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REVIEW

Electrospinning production of nanofibrous membranes

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Abstract

Electrospinning has attracted a worldwide interest as a technique for the production of nanofibrous membranes with diameter ranging 2 nm to several microscales using natural and synthetic polymers. The electrospun nanofibres have advantages such as high surface area, easy surface modification, functionalization of polymeric chains, inexpensive and tunable thermo-mechanical properties. Moreover, electrospinning is one of the simplest techniques for the incorporation of nanofillers into polymeric nanofibres. Herein, we review the preparation and applications of natural and polymer-based nanofibrous membranes. We focus on applications of the electrospun membrane for energy storage, water purification and biomedical. Furthermore, we show surface morphologies of nanofibrous membranes using fast emission scanning electron microscopy, transmission electron microscopy, atomic force microscopy, Brunauer–Emmett–Teller and micrographs.

Keywords Electrospinning · Polymer nanofibre materials · Electrospun nanofibres · Nanofillers · Surface engineering · Tissue engineering

Introduction

Recently, the use of nano- or micron-scale fibres derived from natural and synthetic polymers has increased. The progress made in the fabrication of nano- and microfibrous membranes has resulted in the increased production of such fibres for several biomedical purposes including tissue engineering, wound dressing and protein absorption. The applications of natural biomaterial-based nano- and microfibrous membranes increased as a result of their inherent characteristics such as (1) increased porosity in sub-micrometre scale (geometry and morphology with nanodimensions), (2) biocompatible nature (3) barrier effect to bacterial species and (4) reasonable mechanical stability (Kumar Mishra et al. 2017). The final characteristics of such nano- or microfibrous membranes are dependent on certain factors like alignment as well as the orientation of fibres, morphology, geometry, porosity, surface functional entities, etc. (Mishra et al. 2018a). Various methods have been developed for the large- and small-scale synthesis potential materials for the different applications (Mondal et al. 2018; Chaudhary et al. 2017; Sonkusare et al. 2018; Tanna et al. 2016; Mohanty and Mondal 2013; Saha et al. 2015). In this specific respect, electrospinning is a convenient, swift and cost-effective

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technique and is presently in the preliminary stage of commercial-scale production. It provides possible utility infiltration systems (Aguilar-Costumbre et al. 2016), tissue designing scaffolds, injury dressings, medicine delivery system, biomimetic products (Elsayed and Lekakou 2015), composite reinforcement and a lot more (Bognitzki et al. 2001; Ko et al. 2003; Mohammadzadehmoghadam et al. 2015). Because electrospun fibres have practical application in both nanotechnology and biotechnology, this has been considered as an inspiration behind the currently updated attention in an approach that has been recognized since the 1930s (Wendorff et al. 2012).

The theory behind electrospinning is simple and easy: an electrical field is utilized across a polymer solution along with a collector plate, to force a polymer solution jet released from a tiny orifice. As the solution jet moves, the solvent evaporates and simply leaves behind a charged polymer fibre, which goes through stretching and also thinning due to the whipping, finally accumulates on the grounded collector in the form of a randomly oriented web of micro- or nanofibres. The experimental operational situations are recognized to have a considerable impact on the ultimate fibres. Earlier researchers show that the growth and development of beneficial applications of electrospun nanofibres entail an intensive perception of the electrospinning guidelines as the morphology and consequently diameter of the electrospun nanofibre may have an impact on the end product.

The first electrospinning-related patents were issued to Cooley (entitled "Apparatus for electrically dispersing fluids") (Cooley 1902) and to Morton ("Method of dispersing fluids") (Morton 1902), both in 1902 in the USA. Further, this idea followed by many researchers and published a series of patents in a decade from 1934 to 1944, which includes experimental techniques and set-ups for polymer nanofibre productions using polymer filaments charged with electrostatic force. In 1971, DuPont researchers reported the synthesis of acrylic fibres with a diameter below 1 µm using dimethylformamide (Lukáš et al. 2009). The actual era of polymer nanofibre synthesis using electrospinning initiated after 1990, and since this technique has attracted near about every field of research. Now, more than forty different types of organic polymers nanofibres have been prepared using electrospinning technique for applications like engineering, plastics, optical and electronic devices, biopolymer synthesis. Due to the versatility of the electrospinning process and resultant electrospun membranes, researchers have been encouraged to examine the property and application of such membranes (Wei et al. 2018).

The ultimate goal of this review paper is to comprehensively deliberate the principle, materials, methodology involved in the electrospinning method. In addition, characterization techniques used for electrospun membranes and their biomedical applications are mentioned herein.

Fundamentals of electrospinning

The term "electrospinning" is derived from "electrostatic spinning" which mainly consists of a polymer solution; the polymer solution is subjected to an electrical field to form polymer filaments within electrodes of opposite charges. On applying the very high voltage (~ 15 kV), the polymer solution in the syringe get charged and electrostatic repulsion counteracts the surface tension of polymer solution and at certain point liquid erupts from the surface in the form of a liquid jet. Ejected charged solution is evaporated or solidifies collected on round rotating collector in the form of wide stretched nanofibres. The elongation and thinning of the fibre resulting from this bending instability lead to the formation of uniform fibres with nanometre-scale diameters. When the applied voltage is below the critical values, the maximum elongation of the fibre will not form, which may arise breaking of the jet in the form of droplets (Feltz et al. 2017). Figure 1 illustrates the basic set-up for electrospinning experiment.

The patent describes the method for the production of artificial thread from cellulose acetate/acetone mixture. The electrospinning system is illustrated in Fig. 3. It comprises (1) a wheel, (2) two electrodes, (3) a vessel and (4) a rotating collector. Because of the electric field generated by electrodes, the solution containing cellulose acetate is sprayed from the vessel. The charged solution that comes out of the vessel tends to reach the rotating collector in the form of threads. After that, the threads are subjected to cleaning in a customized washing followed by stretching as well as drying (Karakas 2014). Electrospinning has received consideration by the year 1990 during which various researchers agreed the fact that nanofibres can be generated out of several polymers. After this declaration, the popularity of electrospinning technique remarkably increased, which in turn resulted in the significant number of published research papers.

In today's context, electrospinning is recognized as an excellent technology for the generation of nanofibrous materials. The electrospinning process is performed as follows: initially, a desired amount of polymer is dissolved in an

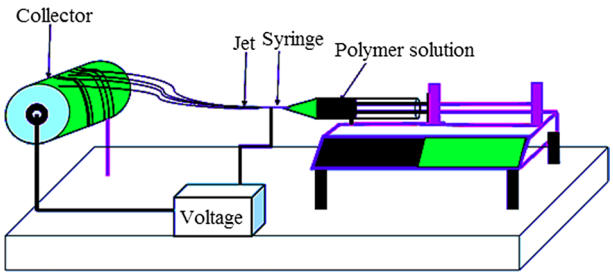

Fig. 1 Schematic set-up for electrospinning

appropriate solvent, and then a high voltage (kV) is applied between the nozzle of the syringe containing polymer solution and the ground collection system (Bognitzki et al. 2001). Electrospinning differs from the other techniques in which mechanical energy is utilized to generate extrusive force via interactive action between the charged polymer solution and external electrical field. When the electrospinning process proceeds, a fluid structure in the conical form named as "Taylor cone" will be generated at the syringe's edge. At that point, where the critical voltage is achieved, the force, which is repulsive in nature exhibited by charged polymer solution, tends to overcome the surface tension (Jirsák et al. 2015). Due to this action, the eruption of a charged jet takes place. As the jet sets to flow towards the area of lower potential, evaporation of solvent occurs. Thereafter, elongation of fibres takes place due to enhanced electrostatic repulsion process of the polymer with due course of evaporation of the solvent. The charged fibres finally deposited onto the grounded collector plate as a random scaffold. The residual surface charge on the nanofibres will dissipate upon the contact with the metal collector if the collector is grounded well. The continuously elongated fibres are produced as the polymer chain strength helps in the prevention of jet break-up (Rutledge et al. 2000). The operating conditions for electrospinning method are usually defined as below: the syringe nozzle size with a gauge of 17–25 (internal diameter 0.26–1.067 mm); the flow rate is in the range of 0.1–5 mL h^{-1}; applied voltage is typically 5–25 kV; and nozzle-to-target distance is 6–20 cm. Collectors can be of different materials, shapes and sizes. Furthermore, rotating collectors can be utilized to fabricate membranes with aligned fibres (Dersch et al. 2004). To obtain the desired nanofibres through electrospinning, it is necessary to draw attention to several parameters such as voltage, the feed rate of solution, spinning distance, type of collector, size of the syringe nozzle, velocity, humidity and temperature of air in the spinning chamber.

Additionally, the properties of polymer solution including molecular weight, conductivity and viscosity characteristics, the vapour pressure of the solvent, dielectric properties of the system and surface tension can affect the formation of nanofibres (Jalili et al. 2006). Zhong et al. described the procedure for the fabrication of collagen nanofibrous scaffolds in an aligned manner. Comparative investigations on the structure as well as in vitro characteristics of aligned and random collagen scaffold were made. Scaffold with aligned pattern showed decreased cell adhesion and greater cell proliferation characteristics for rabbit conjugation fibroblasts as compared to the random scaffold (Zhong et al. 2006). Kim et al. fabricated three-dimensional (3D) nanofibrous sponge-like scaffolds. In this study, the method for obtaining fibres in a dispersed state was developed via a collection of fibres in a coagulation bath. Thereafter, the dispersed fibres were allowed to be solidified via freeze-drying, and the 3D nanofibrous sponge-like structure was formed. The 3D structure was found to be highly porous as compared to the 2D structure since enhanced bone cell adhesion and proliferation were achieved for the 3D scaffold (Kim et al. 2014). Figure 2 represents the SEM images for 2D and 3D nanofibrous sponge-like scaffolds.

Wagner et al. developed a two-stream electrospinning system. Through this set-up, elastic fibres with two different sub-micrometre sizes were formed from poly(ester urethane) and poly(lactide-*co*-glycolide) (Qin et al. 2015). The antibiotic agent, namely tetracycline hydrochloride, was incorporated in poly(lactide-*co*-glycolide) matrix for antibacterial

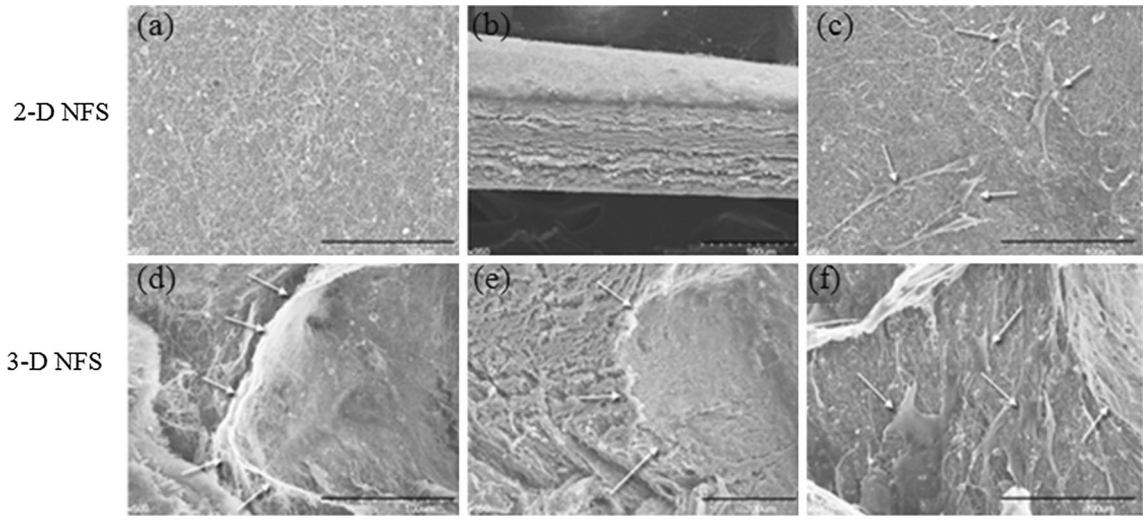

Fig. 2 Scanning electron microscope (SEM) images for **a**–**c** 2D nanofibrous sponge and **d**–**f** 3D nanofibrous sponge structures obtained after the first day of cell seeding. The presence of pores and cells in the sponge is indicated by arrows (Ki et al. 2008)

application. Figure 3 shows the two-stream electrospinning set-up where the fibres generated from the first component presented antibiotic property, whereas the fibres produced from the other component exhibited excellent mechanical properties. The fibrous product developed by the two-stream electrospinning process was used as a temporary closure for the abdominal wall. Therefore, the fibrous product resulted via two-stream electrospinning process offered the benefit of both mechanical and antibacterial properties.

A direct electrospinning set-up was introduced by Kim and Yoon (2008) to prepare micro-/nanofibrous membranes. In this system, a guiding electrode along with an air blower was used for generation of poly(caprolactone)-based micro-/nanofibrous membranes for wound dressing application. The produced membranes were highly porous, and they demonstrated excellent specific surface area and tensile strength. The advantage of the direct electrospinning process is the generation of stable fibres in a steady-state manner with the absence of interruption of charges while depositing on the substrate. The lack of interruption is due to the removal of the solvent in a complete manner (Stano et al. 2008). Figure 4 presents the direct electrospinning system. During the conventional spinning process, the fibres flushed out with a high charge. In addition, the excess solvent that remains during the electrospinning process tends to interrupt the rate of fibre deposition. Such type of limitations can be addressed by the direct electrospinning system. The presence of the guiding electrode helps in minimizing the static charges for the fibres, and the air blower removes the excess solvent. The fibres with minimized charge can be subjected to deposition on conductive or non-conductive-type targets.

With appropriate selection of several polymer blends and conducting the spinning process under different conditions, it is possible to generate nanofibres with beaded, ribbon, porous, core–shell and aligned morphologies (Fong et al. 2001). However, since the electrospinning process is so complicated, comprehensive theoretical models that encompass all the pertinent variables have yet to be developed. Until recently, only certain qualitative general principles have been available to guide the electrospinning operation.

Parameters for electrospinning

Nowadays, there is a requirement for the generation of electrospun fibres with a specific diameter and desired morphology. In spite of the experimental set-up, the electrospinning operation is influenced by numerous parameters, for example, the polymer nature and molecular weight, solution concentration, viscosity, surface tension as well as conductivity, solvent nature, voltage, flow rate, distance between needle tip to collector, and also surrounding variables (temperature, humidity). Therefore, several research activities are promoting to investigate the effect of these parameters on the properties of fibres

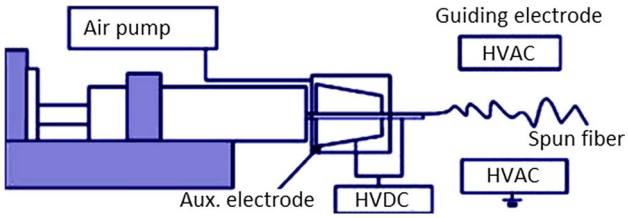

Fig. 4 Direct electrospinning apparatus (*HVDC* high-voltage dc electric field, *HVAC* high-voltage ac electric field) (Kim and Yoon 2008)

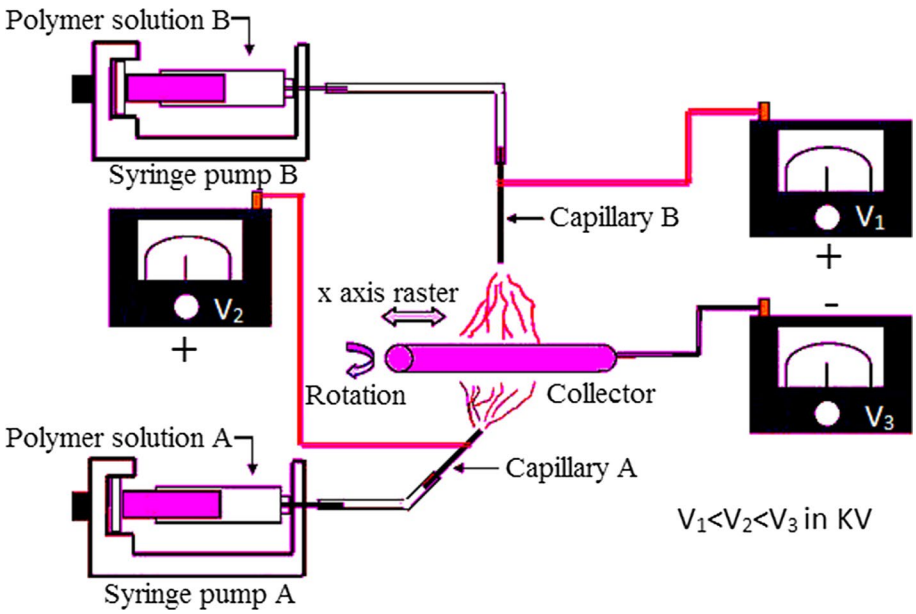

Fig. 3 Two-stream electrospinning system (Hong et al. 2008)

(Raghvendra and Sravanthi 2017). These parameters are classified into the following categories: (1) solution parameters, which mainly deal with viscosity, (2) operational parameters such as working distance, applied voltage and flow rate of the solution and (3) environmental parameters including temperature and humidity. Some of these key parameters that affect the electrospinning process are given in Table 1.

Solution parameter for electrospinning

The morphology and properties of nanofibres obtained by electrospinning process can be influenced by several characteristics of a polymer, such as viscosity, molecular weight as well as the conductivity and surface tension of the polymer solution. Among them, rheological characteristics of polymers are the most important factor regarding fibre spinning and polymer processing (Abraham et al. 2017). Various

Table 1 Electrospinning parameters

Parameters	Electrospinning parameters	Remarks	References
Polymer molecular weight	Solution parameter	Increases viscosity of the solution and shows the effect on fibre diameter	Wang et al. (2006)
The concentration of polymer	Solution parameter	Increasing fibre diameter with higher concentration increases the viscosity of the solution and shows the effect on fibre diameter	Ramakrishna et al. (2005)
Solution viscosity	Solution parameter	Increasing fibre diameter with higher viscosity influences fibre diameter and bead formation	Ramakrishna et al. (2005) and Wang et al. (2006)
Solution surface tension	Solution parameter	Homogeneous fibres at low surface tension, high surface tension leads to bead formation during spinning	Theron et al. (2004)
Polymer conductivity	Solution parameter	Taylor cone, as a result, no electrospinning will be performed at lower conductivity, decreasing diameter with increase in conductivity up to critical value, beyond a critical value of conductivity hinder the Taylor cone and electrospinning	Ramakrishna et al. (2005) and Wang et al. (2006)
Solvent vapour pressure	Solution parameter	Low vapour pressure results in premature evaporation of the solvent and in turn affect the fibre formation, also, higher porosity with higher volatility	Koombhongse et al. (2001)
Applied voltage	Processing parameter	Higher probability of bead formation beyond the critical value of voltage, fibre diameter decreases and the rate at of fibre formation is enhanced up to the critical value of the voltage	Fong et al. (2001) and Zhang et al. (2004)
Type of collector	Processing parameter	Various types of fibres assemblies	Thompson et al. (2007)
Flow rate	Processing parameter	Increasing fibres diameter and bead formation with a higher rate	Thompson et al. (2007)
Tip to collector distance	Processing parameter	Decreasing fibre diameter with larger distance, solidification of fibres takes place with increased distance among spinner jet and collector	Casper et al. (2004) and Thompson et al. (2007)
Temperature	Ambient parameter	Temperature condition is known to affect the viscosity of the solution to be subjected to electrospinning and hence influence fibre properties, decreasing fibre diameter with higher temperature	Ramakrishna et al. (2005) and De Vrieze et al. (2009)
Humidity	Ambient parameter	Affects porosity and solvent evaporation process, higher humidity induces circular pores	Thompson et al. (2007) and De Vrieze et al. (2009)

correlations are provided for describing the viscosity behaviour of the polymer solution. From the "definition" point of view, a polymer solution is termed as concentrated in case if the concentration of solute is beyond 5 wt%. The viscosity of the polymer solution depends on the molecule's shape, molecular weight, hydrophilic nature, the interaction of the polymer with the solvent and concentration of the dissolved polymer. In addition, it is well known that polymeric chain length is a mere representation of molecular weight and entanglement. It is obvious that high viscosity of the polymer solution depends on the radius of gyration of polymer and density of entanglement coupling, which is independent of solvent's nature. The tremendous increase in the viscosity with increase in the concentration of polymer is a result of the formation of an intermolecular linkage between polymer chains (Mishra et al. 2017; Thomas et al. 2017).

In the electrospinning process, nanofibres are generated via a uniaxial stretching process of viscous solution. In the fibre generation process through electrospinning, the polymer solution is stretched under electrostatic forces and it is solidified. The drawing of solution for production of fibres will tend to continue until sufficient feed solution to the spinning jet is available. Hence, fibres will be produced in a continuous manner due to the lack of disruption. However, utilization of appropriately viscous solution for the electrospinning process can result in the formation of homogenous bead-free fibres. It is to be noted that it is tough to pump the highly viscous polymer solution via capillary and such solutions may dry or drip at the tip (Dalton et al. 2006; Luo et al. 2010). The relationship between viscosity and fibre diameter is given in Eq. 1. It is well known that viscosity is a function of concentration or molecular weight of the polymer used for the electrospinning process. If the viscosity of the polymer solution is high, it will interrupt the formation of fibres. In case of high viscosity, fibres with increased diameter are produced. If the adequate viscosity of the polymer solution is maintained, the formation of beads in the electrospun fibres can be avoided (Dhakate et al. 2010).

$$d \sim \eta^{0.41}. \quad (1)$$

The formation of homogeneous fibres is possible when the surface tension of the solvents used is low. When the concentration of polymer solution reaches the threshold limit, it may lead to the generation of droplets rather than fibres (Araújo et al. 2016). On the other hand, the presence of highly concentrated polymer leads to an increase in the viscosity of the polymer solution, which can affect the morphology of fibres. In other words, it can be generalized that a viscous solution can resist elongation of the jet and the formation of thin fibres (Christiansen and Fojan 2016). An earlier work demonstrated the interrelationship between the viscosity of polyethene oxide solution and bead formation. The study revealed the fact that the beads and their density are dependent on the viscosity of the polymer solution. It was confirmed that high viscosity of the polymer solution leads to the formation of spherical and spindle-shaped beads, which is then accompanied by the formation of nanofibres with irregular bead flaws. In the case of polymer solution with high conductivity, the jet will carry a huge quantity of electrical charges. Under such conditions, the addition of polyelectrolyte in small fractional amount will help in enhancing the stretching of jet and thereby forms uniform bead-free fibres with a smooth surface (Tsou et al. 2013). Also, when the conductivity of the polymer solution is high, the enormous tensile force will be created with respect to the voltage applied. This, in turn, helps in the formation of nanofibres with a reduced diameter. In this regard, another study was carried out to investigate the influence of sodium chloride on the production of nanofibres through electrospinning process (Padron et al. 2013). It was declared that the presence of sodium chloride in the polymer solution helps in enhancing the charge density of the jet, which actually increases the production of homogeneously smooth nanofibres. In a similar research, the addition of salts to poly-DL-lactic acid (PDLLA) solution caused the formation of smooth nanofibres with devoid of beads (Kriegel et al. 2009). In addition, further studies demonstrated that the presence of surfactants in the polymer solution could affect the conductivity, which will assist in the formation of fibres with uniformity and nanoscale dimensions (Dong et al. 2012).

Solvent properties

The essential factors to be chosen for the selection of solvent prior to electrospinning are its solubility and boiling point. The solvents with low boiling points result in very fast evaporation, which creates a hindrance at the needle tip during the spinning process, while the solvents with a high boiling point generate ribbon-shaped fibres rather than round shape. This is due to the absence of complete dehydration of the solvent before reaching the collector. Consequently, volatility of the solvents influences the microscopic characteristics of the electrospun fibres, such as diameter, shape and porosity. It is important to consider that the utilization of solvents in the electrospinning process exhibits hazardous effects (Megelski et al. 2002). The properties of several solvents are given in Table 2.

Processing parameters

Effect of voltage

Increasing the applied voltage reduces the drawing stress and hence decreases the diameter of the resultant fibres. Abolhasani et al. investigated the influence of applied voltage on the poly(vinylidene fluoride) nanofibres. It was observed that

Table 2 Properties of solvents used in the electrospinning process (Haynes 2014)

Solvent	Surface tension (N m^{-1})	Boling point (°C)	Remarks
Water	73.05	100	High specific heat, high polarity, high heat of vaporization, neutral pH, high surface tension and it is a universal solvent
Hexane	18.43	69	A constituent of gasoline, cheap, largely unreactive, a non-polar solvent and highly flammable
Chloroform	27.14	61	Inflammable, non-formation of explosive products under ambient conditions, easy miscibility with several organic solvents, solubility in water and potential carcinogen
Acrylonitrile	29.30	82	Toxic, volatilize rapidly, explode when exposed to flame and causes inhalation problem
Acetone	23.70	56	Easily miscibility with water and evaporates quickly in air
Dimethylformamide	37.1	158	Polar(hydrophilic) aprotic solvent with a high boiling point, creates irritation to sensory organs
Toluene	28.5	111	Flammable, no action of corrosion, insoluble in water, exhibits solubility in solvents such as acetone, alcohol, benzene, petroleum-based ethers.
Ethanol	22.75	79	Colourless, hydroscopic, exhibits miscibility with water and solvents of organic nature
Methanol	22.61	65	Rapidly volatile in the air, highly flammable and colourless
Acetic acid	27.8	118	Corrosive

the diameter of the electrospun fibres decreased gradually with increase in the applied voltage (Li et al. 2016a). However, maintenance of the control over the electrospun fibres is highly challenging at high voltage. This is owing to the fact that increased drawing stress can result in the breakage of fibres. Thus, the employment of an optimal voltage during the spinning process will be appropriate for the generation of Taylor cone (Yarin et al. 2001).

Volumetric flow rate

The presence of an optimal flow rate is required for the generation of Taylor cone in the electrospinning process. In fact, slower flow rate leads to the creation of a vacuum inside the syringe. On the contrary, higher flow rates will result in the build-up of the solution near the edge of the needle (Chowdhury and Stylios 2011). Both the conditions will have a definite effect on the formation of Taylor cone during the electrospinning process. Furthermore, in order to reduce the formation of beads in the resultant electrospun fibres, it is necessary to maintain a persistent and steady flow rate (Oliveira et al. 2013). Thus, the morphology of the electrospun nanofibres is affected by the flow rate of the polymer solution.

The distance between the tip and the collector

If the distance between the tip of the needle and the collector is increased, a decrease in the elongation of fibres will occur, which is owing to the exponential relationship between the surface charge density of polymer and the distance. In this case, lesser will be the magnitude of the electrical field generated which leads to the formation of a minor amount of charged ions (Luo et al. 2010).

The diameter of the needle tip

The fibre diameter is examined to get increased with respect to increase in needle's tip diameter. In this respect, no correlation has been found between the diameter of the needle tip and electrospun fibre diameter in a separate contribution (Dalton et al. 2006).

Fibre assemblies

Several methods are described for the production of fibres with different patterns or assemblies. In order to obtain fibres with different assemblies, modifications in the electrospinning systems are introduced. The modifications are made not only to obtain fibres with different assemblies but also to overcome the limitations of conventional electrospinning set-up (Teo and Ramakrishna 2006). Also, modifications help in improving the efficiency of the spinning process and thereby production of optimized fibres is made possible. Information about different types of electrospinning systems is provided in Table 3.

Application of electrospinning for various types of nanofibres

Nowadays, polymer nanofibres are employed in a wide range of applications in diverse industries and also in other areas. Natural polymers are preferable over artificial polymers in medical and biological services because of their low immunogenicity and finer biocompatibility. Investigators have investigated the employment of electrospinning process of natural polymers such as gelatin, collagen and silk fibroin (Le Corre et al. 2013). Moreover, synthetic polymers are

Table 3 Various types of electrospinning systems

Type of set-up	Remarks	References
Rotating drum	The set-up is simple; fabrication of aligned fibres with a large amount is possible. However, it is difficult to obtain highly aligned fibres and high rotating speed can lead to breakage of fibres	Matthews et al. (2002)
Parallel electrodes	The set-up is customized with simplicity, allows fabrication of fibres with high alignment. The obtained fibres can be readily transferred onto different substrates. The drawback lies in obtaining aligned fibres in a thick mat; it is not possible to obtain lengthy fibres	Li et al. (2003)
Rotating wire drum collector	It is customized with a simple set-up, fibres with high alignment can be obtained, and fibres in thick layer remain as the drawback. In the entire assembly, fibres may not be oriented or aligned appropriately	Katta et al. (2004)
Drum collector wrapped with wire wound	It is customized with a simple set-up; fibres with high alignment can be obtained. The thickness of the wire can be varied such that the area of deposited fibres is controllable. The aligned fibres form on the wire rather than the drum	Bhattarai et al. (2005)
Rotating tube collector containing knife-edge electrodes	Fibres with high alignment can be obtained. As the entire tube is covered by highly aligned fibres, it is easy to obtain electrospun mat containing a thick layer of deposited fibres. In order to make the system efficient, the negative electrode is required. The utilization of rotating tube with only smaller diameter remains as the drawback	Teo et al. (2005)
Disc-type collector	It is customized with a simple set-up; the preparation of fibres with high alignment is possible. Fibres can be fabricated via attachment of rotating table to the disc edge. The drawback lies in the lack of possibility for retaining fibres with high alignment when the rotating speed is maintained at a high rate. Only smaller area of aligned fibre mat is possible	Inai et al. (2005)
Rotating drum containing sharp pin	It is customized with a complex set-up for operation; larger area of aligned fibre mat can be obtained. Since the area of deposition is large, it is difficult to obtain a thicker assembly	Sundaray et al. (2004)
Ring collector in parallel position	It is customized with a simple set-up; it is possible to fabricate yarn with the twisted pattern. In order to obtain yarn with the twisted pattern, it is required to rotate one of the two rings available in the set-up. However, the obtained product exhibits limitation in length	Khil et al. (2005)
Multi-spinnerets	It is customized with the relatively simple operation; this set-up offers the possibility of obtaining mixed fibres originated from different sources. The source materials can be mixed in the desired proportion. Interference occurs among the jets originating from multi-spinnerets	Kim et al. (2006)
Bi-component spinneret	In this set-up, it is possible to blend two different polymers and obtain single fibre. The polymers used for the spinning process need to be selected with care in order to avoid incompatibility issue between the source materials	Lin et al. (2005)
Gas jacket electrospinning	This set-up is used for obtaining fibres with smooth texture due to the presence of gas jacket. This can be possible if gas is injected at a controlled speed	Um et al. (2004)
Coaxial spinneret	In this set-up, it is possible to obtain a single fibre made from two dissimilar sources. This set-up also offers the possibility for fabrication of hollow fibres. This can be obtained via the removal of the core. The materials with flexibility can be shaped into nanofibres using this set-up	Loscertales et al. (2004)
Pointed tip electrospinning	This set-up helps in avoiding clogging of polymer solution when originating from the source position during the time of the electrospinning process. The jet and collector are closer to each other during the spinning. Therefore, fibrous mat with different pattern can be obtained, if the speed of moving collector is maintained at a controlled rate. In addition, it is possible to conduct spinning even with a smaller quantity of solution	Sun et al. (2006)
Multiple spikes electrospinning	It is customized with a complex set-up; this set-up also avoids clogging of polymer solution during spinning. The fibres can be fabricated at a higher rate of production. There would be a large deviation in the diameter of the fibres	Yarin and Zussman (2004)

Table 3 (continued)

Type of set-up	Remarks	References
Porous electrospinning	Through this system, fibres can be fabricated with a higher rate of production. There would be a large deviation in diameter of the fabricated fibres	Dosunmu et al. (2006)

preferred over natural polymers in certain needs because synthetic polymers can be tailored to develop the mechanical and degradation properties. Certain synthetic polymers can be used in biomedical applications including polylactide (PLA) and polyglycolide (PGA) in the manner of electrospun nanofibrous scaffolds (LeCorre-Bordes et al. 2016). In addition, copolymers look like an attractive opportunity to obtain new structures with desirable features from electrospinning and also have better efficiency than that of homopolymers. In some cases, the mechanical, thermal, morphological and biodegradability properties of polymers can be customized by using copolymers in the electrospinning process. Incorporation of the hydrophilic polymer of hydrophobic polyesters enhances the cell affinity of polyesters (Mussa Farkhani and Valizadeh 2014). It is worth mentioning that electrospinning is also the most common technique, which is used for the preparation of one-dimensional materials. One-dimensional nanostructures exhibit a long axial aspect ratio, which has a great influence on the physical and chemical properties of materials. Using electrospinning, nanofibres are fabricated by electrostatic stretching of a viscous solution of polymer composites by applying a high voltage (Szilágyi and Nagy 2014). In the recent years, researchers have focused on the fabrication of metal oxide nanofibres such as tin oxide (SnO_2), zinc oxide (ZnO), titanium oxide (TiO_2) and nickel oxide (NiO) through the electrospinning of polymer solution containing metal precursors and followed by annealing procedure (Ochanda 2010; Krupa et al. 2012; Dorneanu et al. 2014). Depending on the thermal degradation of polymers, certain polymers such as polyvinyl alcohol (PVA) and polyacrylonitrile are chosen as a sacrificial template for the fabrication of metal oxide nanofibres (Annamalai et al. 2017). After the annealing process, the organic components will be degraded and the metals will be oxidized by inorganic precursors giving nanofibres with the desired metal oxide.

Cellulose and its derivative-based electrospun fibrous membranes

One of the inexhaustible organic polymers, which are present in nature, is cellulose. It remains as a structural component for plant cells. Wood remains as the principal resource and comprises around 47% of cellulose. Other than the plants, the presence of cellulose can be evidenced in the biomass of vegetables. Organisms like algae, aquatic animals and bacteria exhibit the ability to synthesize cellulose. In addition to this, the extraction of cellulose is possible from several annual crops. The presence of raw materials for the extraction of cellulose is abundant in nature, and also cellulose exhibits biodegradability and biocompatibility characteristics (Mishra et al. 2018b). Due to these reasons, demand for the production of eco-friendly materials from cellulose biopolymer is ever increasing. The backbone of cellulose contains a linear and semi-crystalline polymeric material called cellobiose, which is made up of two glucose units linked by glycosidic linkages (C–OC) at C_1 and C4 locations. The degree of polymerization (DOP) factor determines the figure of repeating glucose units that vary from 20 to 10,000 for chemically synthesized cellulose and naturally available bacterial or wood cellulose, respectively. Cellobiose is the dimer of glucose, and this serves as the repeating unit of natural cellulose polymer. The degree at which the polymerization occurs for cellulose depends on the source from which the monomer is derived. The cellulose derived from wood source is known to contain 10,000 glucose units.

On the other hand, cellulose derived from cotton contains 15,000 units of glucose. The presence of three hydroxyl groups in each glucopyranose molecule is responsible for imparting chirality and biodegradation characteristics for cellulose due to their high reactivity. The presence of hydroxyl groups in cellulose help in the formation of the hydrogen bonds. This leads to the formation of micro-fibrillated structure, crystalline as well as amorphous fractions and cohesive properties of cellulose polymer. In general, cellulose is found to be hydrophilic in nature as it contains both inter- and intramolecular hydrogen bonding in the framework. The hydrophilic property of cellulose enables it to be difficult to be dissolved in hydrophobic solvents (Mishra et al. 2018c). Thus, utilization of cellulose-based derivatives for the production of industrial products came into practice in order to overcome the poor dissolving capability of natural cellulose. However, the cellulose is an abundant and renewable resource found in most parts of the world, which makes it a cheap raw material for various applications. The electrospinning technique offers the advantage for the production of cellulose-based fibres. The electrostatic forces, as well as shear forces, help in the spinning process in order to obtain aligned polymeric chains and nanocellulose phase. In addition, the smaller the fibre diameter, the greater will be the degree of alignment. The removal of the solvent can

occur in a faster manner when the diameter of spun fibres is small. This, in turn, helps in the rapid alignment of fibres and polymeric phase such that extensive drying period can also be avoided (Shin et al. 2012). There are various approaches, which are tried for spinning of nanocellulose solutions or the suspension of nanocellulose in polymers. The techniques used so far include electrospinning, melt spinning and dry spinning (Kenawy et al. 2009). Different types of techniques used for the continuous production of cellulose fibres are shown in Fig. 5.

An important parameter in polymer electrospinning is the selection of a proper solvent since cellulose has a highly crystalline structure that makes it highly insoluble. What makes it even more difficult is the requirement that the solvent should not degrade its structure (Ohkawa et al. 2009). Commonly used solvents for cellulose are not very volatile and are not completely removed during electrospinning. Special instruments will be needed for removing them from the fibres through coagulation steps. This requirement is one limitation in the cellulose electrospinning process (Rezaei et al. 2015). Nanofibres have been obtained from the electrospinning of native cellulosic solutions, but they are mostly produced from cellulose derivatives. Ionic liquids are salts with relatively low melting points often employed for electrospinning of cellulose and can form constant liquids at temperatures below 100 °C (Clough et al. 2015). Qi and others employed polyol binders such as poly(ethylene glycol) (PEG) to improve the electro-spinnability of cellulose. Poly(ethylene glycol) with high molecular weights (HMPEG) is a long-chain polymer which can easily form very thin fibres by electrospinning. Increasing the HMPEG content decreases the viscosity of the polymer solution because of the interactions between inter- and intramolecular cellulose chains (Qi et al. 2010). The direct electrospinning of pure cellulose from cotton and bamboo in combination with chitosan is described in another study. They mixed trifluoroacetic acid–acetic acid and used it as the solvent to obtain nanofibres with an average diameter lower than 100 nm (Devarayan and Kim 2015). Poly(vinyl alcohol) (PVA) is a semi-crystalline, completely biodegradable, non-toxic, water soluble, chemo- and thermo-resistant, and the biocompatible polymer produced industrially by hydrolysis of poly(vinyl acetate). It can be easily processed and is highly penetrable by water (Krumova et al. 2000). PVA readily interacts with a wide variety of cross-linking agents to form a gel. These properties of PVA have resulted in its use alone or in combination with other polymers in producing nanofibres and in such applications as in food technology, the packaging industries; and in producing medical, cosmetic, pharmaceutical, filtration and drug release materials (Nune et al. 2017). A survey of nanofibres composites obtained by electrospinning from PVA and cellulose nanofibre (CNF) solutions is reported (Šutka

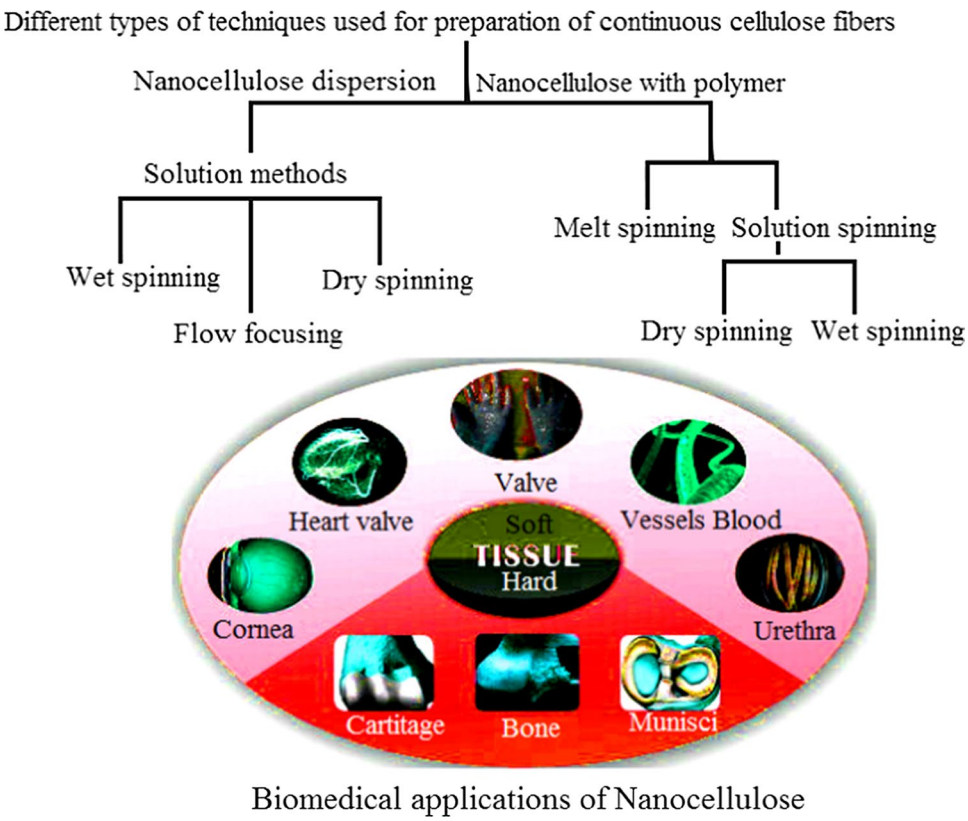

Fig. 5 Different types of techniques used for the preparation of continuous cellulose fibres

et al. 2017). Authors have obtained cellulosic nanofibres by mixing cellulose and PVA in the presence of NaOH with urea used as the solvent. The mechanism of the PVA effect on cellulose structure is similar to that of HMPEG (Song et al. 2017).

In recent years, many micro-/nanofibres with bionic structures have been fabricated by the combination of the electrospinning and bionic technologies, such as lotus-leaf-like fibres (Lim et al. 2013), spider-like fibres (Pant et al. 2010), peapod-like fibres (He et al. 2015), porous fibres (He et al. 2012), tubular fibres (Teo et al. 2005), necklace-like fibres and tree-like nanofibres (Huan et al. 2015). Tree-like nanofibres, as its name implies, are composed of trunk fibres and branch fibres, the thick trunk fibres act as a skeleton support which can improve the mechanical property, and the thin branch fibres act as connection props which can increase the surface area-to-volume ratios and decrease the pore size. It has been noted that the dispersion of nanocellulose has not yet been completely achieved even in polymers, which are soluble in water (Xu et al. 2013; Wang et al. 2014; Spinella et al. 2015; Fox et al. 2016). Approaches like chemical grafting, modification with surfactants and solvent exchange process are used to ensure dispersion of nanocellulose in polymer matrices. The modification techniques helped in improving the interfacial adhesion between nanocellulose and the polymer matrix. The selection of suitable technique usually depends on the type of matrix used and targeted application due to the complexity in the dispersion of nanocellulose in the polymer matrices. Hydrothermal modification of cellulose is a process that treats cellulose in water at elevated temperatures to depolymerize cellulose and decrease the degree of polymerization to the level of 400. Wawro and others used hydrothermally modified cellulose pulp for the manufacture of cellulose fibres. The pulp thus obtained exhibited solubility in aqueous alkaline solutions, while its electrospinning also became easier (Wawro et al. 2009). In another study, Frenot used the cellulase enzyme obtained from a genetically modified *Trichoderma reesei* strain to electrospun enzymatically treated cellulose (Frenot et al. 2007). Cellulose esters are a group of modified cellulosic materials. Nonenteric cellulose esters (such as cellulose acetate propionate, acetate butyrate and acetate) are insoluble in water and may be suggested as carriers of active components in some viscose food dispersions. Enteric cellulose esters, such as hydroxypropylmethylcellulose phthalate (HPMCP) or cellulose acetate phthalate (CAP), are soluble in mildly acidic to slightly alkaline solutions but insoluble in acidic conditions and can be used as carriers of acid-sensitive bioactive materials such as some vitamins, probiotics and prebiotics. Cellulose has a low surface charge in its native form and by chemical modification or combination with highly charged material could increase its surface charge to become favourable for electrospinning (Rezaei et al. 2015).

The physical modification of cellulose into different types of micro- and nanostructures has been reported in the literature (Chauhan and Chakrabarti 2012). Nanoscale materials are attracting increasing attention due to their superior properties such as tensile strength, elasticity modulus and density compared to their macro-sized counterparts. Addition of nanocellulose has been found to improve the conductivity of the spinning jet since negatively charged sulphate functional groups are present in the unmodified nanocellulose. This, in turn, helped to achieve a reduced diameter of the electrospun fibres. However, higher loadings of nanocellulose may increase the diameter of the electrospun fibres. Thus, dilution of the spinning jet is being practised for easy processing during electrospinning. The dilution becomes mandatory while especially performing the electrospinning for a solution with high nanocellulose loadings (Deitzel et al. 2001; Ureña-Benavides et al. 2010; Wanasekara et al. 2016). Several studies have been carried out to investigate the influence of nanocellulose loading and surface modification on the difficulty associated with the electrospinning process. Apart from the changes made in nanocellulose, modifications performed in functional groups of polymers also affect the electrospinning process (Agarwal et al. 2008; Bhardwaj and Kundu 2010).

Cellulose acetate (CA) is one of the common derivatives of cellulose and hence falls under the category of the semi-synthetic polymer. It is derived through esterification process of cellulose with an acetic acid. Based on the degree of esterification, the cellulose derivative contains a different degree of the substituted acetyl group. Thus, cellulose acetate differs in properties in accordance with the degree of acetyl functionality substitution in the chemical framework. The two important categories of cellulose acetate generally used for commercial purposes include cellulose diacetate and cellulose triacetate. The acetyl values for cellulose diacetate and cellulose triacetate are 55 and 61%, respectively. Similarly, they are different in the degree of substitution (DOS) (Zugenmaier 2004; Cerqueira et al. 2009; Tang et al. 2013). The solubility of CA in solvents is dependent on acetyl value. In many research studies that employed cellulose acetate as the starting material, the post-spinning deacetylation of the resulting cellulose acetate–electrospun non-woven fabrics using an alkaline solution produces cellulose–electrospun non-woven fabrics. A two-step method, which involves the conversion of cellulose acetate–electrospun non-woven fabrics to cellulose–electrospun non-woven fabrics via a post-spinning deacetylation, has been applied by many researchers. Herrera et al. (2011) reported a ten-fold increment in storage modulus for cellulose acetate mats reinforced with nanocellulose. The storage modulus was

found to increase upon the addition of 5 wt% of nanocellulose. With further increment in nanocellulose loadings, the modulus decreased because of agglomeration. Consequently, several routes were exploited in order to attain the ordered orientation of fibres in the polymer matrices such that it is possible to improve the mechanical properties (Teo and Ramakrishna 2006). The approaches explored are (1) utilization of rotating drum-based collector (Lee and Deng 2012) and (2) utilization of two metal sheets as collectors with gap among them (Herrera et al. 2011). Furthermore, the incorporation of nanocellulose was found to largely affect the characteristics of spun mats. The mats with unique characteristics, namely (1) ultra-fine thickness, (2) improved surface area and (3) adequate porosity, find potential in biomedical, sensors, separation and catalysis applications. Dong et al. (2012) used the nanoindentation technique to study the mechanical property for PMMA fibres reinforced with nanocellulose obtained via electrospinning. It has been found that the storage modulus of PMMA fibres increased upon addition of nanocellulose up to 17 wt%. In comparison with fibres, the mechanical properties were found to highly improve for electrospun mats made from biopolymers.

Certain researches for the preparation of cellulose acetate-based nanocomposites upon addition of fillers have been reported. When iron oxide (Fe_2O_3) nanoparticles were added to the cellulose acetate matrix, homogeneous suspension and smooth electrospun fibres were obtained, and an improvement in properties has been found. Fabrication of nanoporous bio-composite membrane was carried out by mixing cellulose acetate with finely chopped polyaniline nanoparticles using the electrospinning method. It was found that the membrane exhibited a wide range of porosity and biocompatibility characteristics (Ahmed et al. 2015). Similarly, an electrospun silver nitrate ($AgNO_3$) nanoparticle-incorporated cellulose acetate membrane showed excellent antimicrobial characteristics. In a separate contribution, different varieties of cellulose-based membranes (pure cellulose, cellulose/chitosan blends, cellulose/polymethyl methacrylate blends) were designed using the electrospinning process (Son et al. 2004, 2006). We summarized the various study based on the electrospun fibre from nanocellulose, as mentioned in Table 4.

Chitosan-based electrospun fibrous membranes

The natural biopolymers such as chitin and chitosan gained a significant deal of attention regarding medical and pharma-based applications owing to their excellent biocompatibility, non-toxic nature and biodegradable aspect (Zhong et al. 2006). The inflammatory reaction, as well as toxicity problems due to the utilization of synthetic polymers, can be surpassed largely by eco-friendly chitin and chitosan biopolymers. Also, these biopolymers are known to possess anticancer, antimicrobial, analgesic, haemostatic and antioxidant characteristics (Pillai et al. 2009; Kumirska et al. 2010). Chitosan is a significant derivative of biopolymer chitin and is acquired through partial deacetylation of chitin when subjected to alkaline or enzymatic hydrolysis treatment process. The degree of deacetylation is defined as the ratio of glucosamine to the sum of glucosamine and *N*-acetylglucosamine units. If more than 50% degree of deacetylation is achieved, a partially de-acetylated form of chitin is considered as chitosan (Synowiecki and Al-Khateeb 2003; Aranaz et al. 2009). The degree of deacetylation is an important parameter that determines the biological characteristics of chitosan. In certain conditions, molecular weight also seems to play a significant role in terms of biological properties. In addition, chitosan seems to be enzymatically degradable, which is an attractive property for medical applications. When chitosan-based implants are incorporated, enzymes that occur naturally in the human body can cause degradation of the implants with due course of time. The enzymes that are responsible for the degradation of chitosan include lysozyme, pepsin and papain. Moreover, the rate of degradation is associated with the degree of acetylation and cross-linking effect. The kinetics for degradation of chitosan also depends on the percentage of crystallinity, a factor controlled by the degree of crystallinity. Hence, it is clear that chitin degradation can be more influenced by enzymes compared to chitosan due to the fact that chitin contains a number of *N*-acetyl glucosamine residues. Since chitosan remains in de-acetylated form, it can withstand in vivo conditions without prominent chain degradation (Mourya and Inamdar 2008; Younes and Rinaudo 2015).

Moreover, investigation of the suitable solvents to produce electrospun chitosan fibres was carried out (Ohkawa et al. 2004). Chitosan (8 wt%) dissolved in trifluoroacetic acid solvent when subjected to electrospinning-formed nanofibres. However, beads were also noticed in certain instances in the chitosan fibres. Thus, the research group tried to optimize the dissolution of chitosan using a mixture of solvents in order to obtain a smooth texture for the resultant electrospun fibres. In this respect, chitosan was dissolved in a combination of two solvents, i.e. trifluoroacetic acid/dichloromethane at altered ratios. It was found that the utilization of dichloromethane as a co-solvent assisted in enhancing the production of more homogenous fibres. Appropriate results were noticed when the ratio of trifluoroacetic acid/dichloromethane was maintained at 70:30. The same group also attempted to fabricate electrospun chitosan fibres with the diameter less than 100 nm (Ohkawa et al. 2006). In this study, commercially obtained chitosan samples with different molecular weights were used for the electrospinning process. It was observed that

Table 4 Electrospun fibres from nanocellulose

Nanofibres via electrospinning	Comments	Application	References
Protein A/G functionalized electrospun regenerated cellulose (RC) nanofibre mesh	High ligand binding capacity	Antibody purification	Ma and Ramakrishna (2008)
Non-ionic cellulose ethers/polyvinyl alcohol nanofibres	Controlled release of an antimicrobial drug, nontoxicity	Tissue engineering, drug delivery	Wali et al. (2018)
Porous composite membranes based on cellulose acetate and cellulose nanocrystals	Excellent mechanical properties (tenfold better than nonporous) and negative surface zeta potentials	Adsorption of dyes	Nair and Mathew (2017)
Thermoplastic carboxymethyl cellulose/poly (ethylene oxide) nanofibres	Antibacterial materials	Tissue engineering and pharmaceutical science	Esmaeili and Haseli (2017)
Silver nanoparticles incorporated into bacterial cellulose nanofibres	Strong antimicrobial potential against *E. coli* and *S. saureus* bacteria	Pharmaceutical science	Yang et al. (2013)
T4 bacteriophage incorporated into core/shell electrospun fibres of poly(ethylene oxide) (PEO), cellulose diacetate and their blend	Prevent bacterial growth on contaminated food surfaces	Food processing and packaging	Korehei and Kadla (2014)
SiO_2-cellulose acetate nanofibre	Average fibres diameter is found about 598 nm, influenced of wetting property of nanofibre via SiO_2	Lithium-ion battery separator	Nasir et al. (2017)
Ultrathin fibrous cellulose acetate membranes	Water filtration efficiency increased with rising areal weight of the membranes, high-flux water filtration	High-flux water microfiltration	Zhou et al. (2016)
Dyed regenerated cellulose nanofibre	Good colour fastness increased crystallinity	Apparel applications	Khatri et al. (2017)
Cellulose nanofibres from cellulose acetate	Deacetylation of cellulose acetate nanofibres via ultrasonic	–	Ahmed et al. (2017)
Polybenzoxazine based cross-linked cellulose acetate nanofibre	Superior tensile strength and Young's modulus, high thermal properties	Water treatment	Ertas and Uyar (2017)
Co-polyamide/cellulose nanocrystals nanofibres	The higher contact angle of water, maximum tensile strength and Young's modulus with 1 wt% of cellulose nanocrystals	Separation of oil from water	Sobolčiak et al. (2017)
Cellulose acetate nanofibres	Uniform diameters and their distributions via a modified coaxial process	–	Yan and Yu (2012)
Non-woven structures of cellulose acetate (CA) fibres	Fibre networks of high packing density via alcohols/MEK solvent mixtures, a low degree of fibre cross-links via alcohols/acetone solvent mixtures	Scaffolds for tissue engineering	Haas et al. (2010)
PLA/cellulose nanowhiskers composite nanofibres	Formation trend of PLA α crystal by cellulose nanowhiskers, low crystallinity, improved in mechanical properties, heterogeneous nucleation of PLA	–	Liu et al. (2012)
Polystyrene and poly(vinyl alcohol) nanofibres containing cellulose nanocrystals (CNCs)	The orientation of the CNCs within the fibres	–	Wanasekara et al. (2016)
Aerosol filtration using electrospun cellulose acetate filters	Better quality factors for filtration	Air filtration application	Chattopadhyay et al. (2016)

there is a linear relationship between polymer concentration and fibre diameter. As the polymer concentration reduced, the fibre diameter decreased. The optimal viscosity range for obtaining uniform fibre was determined to be 0.8–1.0 Pa s. The electrospun fibres with an average diameter of 60 nm were obtained for chitosan polymer with higher molecular weight and at the solution concentration of 2 wt% (Van Der Schueren et al. 2012).

The effect of operating conditions on the average diameter of the fibres was also examined (Sencadas et al. 2012a, b). It was observed that the average diameter of the electrospun chitosan fibres increased with respect to increase in distance (5–20 cm) between the tip of the needle and the collector. The applied voltage also had an influence on the uniformity of the produced fibres. More uniform fibres were obtained when the applied voltage was increased. In addition, when the applied voltage was increased from 20 to 30 kV, it was found that the average diameter of the fibres tends to decrease. The only meagre effect was noticed on the average diameter of chitosan fibres with regard to the inner diameter of the needle. However, the feed rate had no effect on the average diameter of the electrospun chitosan fibres (Jafari et al. 2011; Chowdhury and Stylios 2012). In a further study, the factorial design was carried out to explore the possibility of obtaining homogenous chitosan fibres by optimizing the factors that affect the electrospinning process. The interactions among parameters such as the concentration of chitosan, solvent ratio and electric field strength were studied. It was observed that the interaction between chitosan concentration and field strength, as well as a solvent ratio and field strength, played a prominent role to obtain homogeneous nanofibres. Other studies revealed that apart from trifluoroacetic acid, acetic acid is an effective solvent for the fabrication of fine chitosan fibres (Ohkawa et al. 2004; Geng et al. 2005; Jacobs et al. 2011).

An approach reported that the properties of chitosan fibres can be improved by blending it with a second polymer. For this purpose, polymers such as PLA, PVA, PEO and collagen are suggested. All these polymers exhibit biocompatibility and biodegradability nature, and hence, biomedical applications of the resultant electrospun fibres will not be affected. It has been found that the electrospun fibres exhibited a mean diameter of 124 nm (Duan et al. 2004). Along with nanofibres, microfibres were also visualized after the electrospinning process. The structural and calorimetric characterization techniques confirmed that the microfibres resulted from the secondary polymer polyethylene oxide. The formation of microfibres took place due to the phase separation among chitosan and polyethylene oxide. Different grades of polyethylene oxide were also examined for blending with chitosan, and it was found that molecular weight has no effect on the diameter of the resultant electrospun fibres (Bhattarai et al. 2005; Yang et al. 2006). Different polymers and nanoparticles-based chitosan electrospun fibres and their applications are tabulated in Table 5.

Polycaprolactone (PCL)-based electrospun fibrous membranes

Apart from the type of polymers used for designing a scaffold, the important characteristics such as biodegradable as well as biocompatible nature and mechanical stability of the polymer membranes should also be considered. In addition, the growth behaviour of cells on the scaffold will be affected by its design and morphology. Another class of biopolymer which is widely used for the biomedical application is PCL which is a semi-crystalline polymer and it is hydrophobic in nature. PCL can be produced through ring-opening polymerization of the ε-caprolactone polymer. It exhibits good solubility along with tunable mechanical characteristics, which makes it attractive for blending with other natural as well as synthetic polymers. PCL cannot be biodegraded by enzymes, and it undergoes hydrolytic degradation into low molecular weight compounds which makes it an attractive biopolymer for utilization where the slow rate of degradation is essential (Ali Akbari Ghavimi et al. 2015). PCL possesses a glass transition temperature (T_g) of − 60 °C (Matta et al. 2014).

The food and drug administration (FDA) approved the utilization of PCL for biomedical applications in 1970. The biomedical applications of PCL are mainly due to its significant features such as high elongation-at-break (%) as well as elastomeric properties, high solubility in a variety of solvents, processing ability at low-temperature conditions and production of materials resulted from degradation which are non-toxic in nature (Wang et al. 2005b). It has been confirmed in an in vitro study that PCL tends to lose half of its strength after 8 weeks when subjected to degradation via hydrolysis (Yoon and Ji 2003).

In a recent study, PCL was blended with starch via copolymerization technique with the aim to reduce the cost of the product and motivate the growth behaviour of cells when a naturally derived biopolymer is present (Little et al. 2009). It has been found that after the addition of starch to the PCL matrix, the rate of the non-isothermal crystallization process for PCL blends tends to increase. The damping characteristics of PCL/starch blends make them suitable for a biomedical application like orthopaedic implants, where it is required for the implant to undergo excessive mechanical strain. In order to enhance the rate of degradation, the blending of PCL with an increased quantity of starch has been carried out. When the content of starch present in the PCL matrix was increased, it has been found that PCL becomes highly susceptible to degradation by proteinase K49 enzyme (Wang et al. 2005b). For PCL, the hydrolytic degradation which is an auto-catalytic

Table 5 Electrospun chitosan fibres and their applications

Primary polymer	Secondary polymer and nanoparticle	Solvent used	Application	References
Chitosan	–	Trifluoroacetic acid/dichloromethane	Tissue engineering	Sangsanoh et al. (2010)
Chitosan	Poly(vinyl alcohol) (PVA)	Acetic acid	Wound dressing	Zhang et al. (2007a)
Chitosan	Polyethylene terephthalate	Trifluoroacetic acid	Wound dressing	Jung et al. (2007)
Chitosan	Polycaprolactone (PCL)	Hexafluoroisopropanol (HFIP)	Bone tissue engineering	Yang et al. (2009)
Chitosan	Polycaprolactone (PCL)	HFIP/trifluoroacetic acid/dichloromethane	Neural tissue engineering	Mohammadi et al. (2007)
Chitosan	PVA/PCL	Acetic acid/chloroform	Bone tissue engineering	Duan et al. (2006)
Chitosan	PVA/Poly Lactic-co-Glycolic Acid (PLGA)	Acetic acid/tetrahydrofuran/dimethylformamide(DMF)	Tissue engineering	Duan et al. (2007)
Chitosan	Collagen	HFIP/trifluoroacetic acid	Tissue engineering	Chen et al. (2008)
Chitosan	Collagen/polyethylene oxide (PEO)	Acetic acid	Wound dressing	Zhang et al. (2008)
Chitosan	Hydroxyapatite/polyethylene oxide (PEO)	Acetic acid/dimethyl sulfoxide (DMSO)	Bone tissue Engineering	Shen et al. (2010)
Chitosan	Hydroxyapatite/PVA	Acetic acid/DMSO	Bone tissue engineering	Yang et al. (2008)
Chitosan	Silver nanoparticle/polyethylene oxide (PEO)	Acetic acid	Wound dressing	An et al. (2009)
Chitosan	Ag nanoparticle/gelatin	Acetic acid	Wound dressing	Zhuang et al. (2010)
Chitosan	Alginate/PEO	Acetic acid and deionized water	Drug delivery	Nista et al. (2015)

reaction is initiated at the ester linkage. However, the hydrophobic domains present in the PCL are susceptible to hydrolytic degradation process and hence seem to be highly preferable for its utilization as implantation materials. When hydrolytic degradation proceeds, breakage of ester link leads to the formation of fragmented oligomers. These oligomers are lower molecular weight compounds, which are then engulfed by macrophages as well as giant cells. The hydroxy caproic acid produced as a by-product of the hydrolytic degradation process can either be metabolized by tricarboxylic acid cycle or excreted via renal secretion (De Jong et al. 2001; Tsuji et al. 2005). Investigation of the enzymatic degradation of PCL by esterases and lipases was also conducted (Gan et al. 1997). A study has reported the utilization of PCL/collagen composite blends for skin graft application. Monitoring for the investigation of the degradation behaviour of collagen as well as its cell adhesion performance with respect to time was carried out (Shah et al. 2008). PCL exhibits a resorption rate of 1 year which renders it a promising material for making suitable skin grafts for patients with burn injuries. It is also declared that PCL demonstrates essential stability properties required for a skin graft. Unique for this study was the ability to control cell growth and adhesion by the amount of collagen in the initial mixture with PCL. The scaffolds with higher content of PCL showed enhanced cell adhesion properties. This result also paved the way for the utilization of PCL/collagen blends for drug delivery application in order to heal the wound site (Heydarkhan-Hagvall et al. 2008; Chen et al. 2011; Lu et al. 2011).

Poly(lactic acid) (PLA)-based electrospun fibrous membranes

Poly(lactic acid) (PLA) can be produced from a lactic acid monomer which is derived from natural resources such as corn, wheat, sugarcane and starch (Karande et al. 2016). Among various techniques used for the production of PLA, the most generally practised methods are (1) direct polycondensation of lactic acid and (2) ring-opening polymerization (ROP) of lactide (Inkinen et al. 2011).

Through direct condensation method, PLA chains ranging from low to intermediate molecular weights can be produced due to the presence of water produced by the polymerization reaction. The molecular weight of PLA chains can be increased by removing water generated in the reaction. However, this is possible under high temperature assisted with high vacuum conditions which can possibly increase the risk of racemization process (Signori et al. 2009; Wu and Hakkarainen 2015). The low molecular weight PLA chains can then be coupled by utilization of chain-extending agents such as peroxide and isocyanates for the production of various varieties of high molecular weight compounds of PLA (Signori et al. 2009). In case of ROP technique, it is possible to control the polymerization process and produce PLA

with definite molecular weight as well as the desired ratio of D and L sequence in its structure (Tsuji 2005; Murariu et al. 2008). The two leading commercial producers for PLA include (1) Cargill Dow polymers and (2) Mitsui Chemicals; both the companies follow different methods to produce PLA with high molecular weight. Cargill employs condensation polymerization technique to produce PLA chains of low molecular weight. This compound is further subjected to depolymerization for the formation of lactide. Then, the lactide produced undergoes purification process via distillation technique. Later, the purified lactide is converted into PLA of desired molecular weight through the ROP process. Like Cargill, Mitsui also follows the direct condensation route for the production of PLA with high molecular weight (Kim et al. 2003; Vink et al. 2003). The difference adopted in this technique includes the simultaneous removal of water from the polymerization reaction through azeotropic distillation (Wang et al. 2008; Li and Wang 2010; Arlt 2014).

The parameters of PLA, such as crystallinity, composition, molecular weight and stereochemistry, control its thermal and mechanical characteristics (Carrasco et al. 2010; Wang et al. 2012). Conducting the polymerization reaction with various lactides with the help of catalyst can help in the production of stereospecific PLA. The stereospecificity, thermal history as well as techniques used for processing of PLA play important roles in affecting its crystallinity properties (Lim et al. 2008; Inkinen et al. 2011). The three important types of PLA are (1) poly(D-lactic acid), (PDLA), (2) poly(L-lactic acid) (PLLA) and (3) poly(D,L-lactic acid) (PDLLA). The polymer PDLLA exhibits amorphous nature while PLLA, as well as PDLA, possesses semi-crystalline property. The degree of crystallinity for PLA is known to be well affected by the L-lactic acid content.

Initially, hollow fibres of small length are fabricated from PLLA for drug delivery purpose and it has been found that the biopolymer undergoes degradation with respect to the controlled release of the impregnated drug (Tsuji and Miyauchi 2001; Hiemstra et al. 2006; Xu et al. 2006; Chang et al. 2016). High molecular weight PLLA was also produced and implanted in the abdominal wall of guinea pigs. It was found that PLLA exhibits tissue receptive characteristics and slow degradation under in vivo conditions (Bos et al. 1991; Yang et al. 2005). The excellent biocompatible nature exhibited by PLLA enables it to be used as a prospective material for surgical sutures. In spite of this, the application of PLLA as a bioresorbable suture is relatively limited, since PLLA shows only half of its weight loss in 1 or 2 years of degradation time (Wang et al. 2005a; Walton and Cotton 2007; Raghavendran et al. 2014).

Even though PLA is an excellent biomaterial with attractive features, it exhibits certain drawbacks that restrict its application. PLA possesses significant mechanical properties, which are comparable with that of commercial synthetic polymer polyethylene terephthalate (PET). The tensile strength of PLA is 53 MPa, which is nearly equal to PET (54 MPa). The tensile modulus (3.4 GPa) of PLA is even slightly higher than that of PET (2.8 GPa). However, the major disadvantage of PLA is its elongation-at-break (%) properties, which is only 6% for PLA and 130% in the case of PET (Hamad et al. 2015). The poor elongation-at-break (%) property for PLA makes it very brittle in nature which in turn impedes the application of PLA wherever high toughness is an essential factor. Upon consideration of this drawback with PLA, research activities are progressed to develop strategies for the modification of PLA. In general, bulk modification technique such as blending, copolymerization and surface modification approaches including entrapment, photograph grafting and the coating is carried out. Through these modifications, it is possible to tune the hydrophobicity, biodegradability, toughness and reactive functionality properties of PLA such that targeted application can be satisfied (Gref et al. 2000; De Delgado Sousa et al. 2001; Ravi Kumar et al. 2004).

Modification of electrospun membranes

The dealings with the treatment of the electrospun membranes are usually performed to incorporate functionality in order to enhance inherent membrane properties, for example, pore dimensions distribution, mechanical or thermal features (Ahmed et al. 2015; Aslan et al. 2016). Thermal treatment has proven to change the pore dimensions along with enhancing the hydrophilicity of electrospun fibres. Among the groups of people formerly produced the electrospun polyvinylidene fluoride-*co*-hexafluoropropylene membranes. Polymer content was changed from 10 to 15 wt%. They analysed the consequences of hot pressing on the porosity, pore dimensions and contact angle (Lee et al. 2013). Authors applied a swift contact approach to hot-press the membranes with an iron at a surface temperature of 200 °C. Two sheets of the electrospun membranes were additionally hot-pressed collectively as a way to examine the influence of thickness on membrane properties. Hot pressing induced the fibres to stick at intersections which therefore played a role in the mechanical durability of the membranes. Hot pressing as well led to lower contact angle as well as teenier pores. Membranes produced with 10 wt% polyvinylidene fluoride-*co*-hexafluoropropylene and hot-pressed with two sheets experienced pores of 0.26 µm, as well as that, maintained their hydrophobic effects with a water contact angle of 125 °C (Mighri et al. 2005; Park et al. 2016b). The membranes displayed an elevated salt rejection rate of 98% along with a water flux between 20 and 22 L h^{-1} m^{-2}. Authors applied an annealing operation to enhance the mechanical features of poly(lactic acid). Annealing at 90 °C

for 30 min resulted in reduction in pore size in the range of 2.8–0.9 µm and a rise in the elastic modulus by 2500% (Liao et al. 2014). Solid rejection rate improved significantly from 10% for as-spun poly(lactic acid) to 85% for thermally modified membranes, showing the reason for heat treatment in enhancing the capabilities of the electrospun membranes (Li et al. 2013). Researchers formulated polytetrafluoroethylene nanofibre membranes by means of electrospinning and then a sintering operation. Electrospinning has been performed with a 26 wt% solution accompanied by the polytetrafluoroethylene: poly(vinyl alcohol) mass ratio of 7:3. The poly(vinyl alcohol)/polytetrafluoroethylene membranes were sintered at different times as well as temperatures. An electrospun membrane was hydrophilic (water contact angle of 28.8°) as a result of the hydrophilic behaviour of the PVA. Nevertheless, sintering at 380 °C for 30 min considerably increased the contact angle (150°); it expresses a substantial improvement in the hydrophobicity of the membrane (Yin et al. 2013). The purification capability of polyamide 6 (PA-6) nanofibre membranes has also been analysed. The membranes accompanied by a thickness of 71 µm possessed an average pore dimension of 113.7 nm.

However, the untreated membranes were prone to cracking throughout wetting or washing; the membranes were heat-modified over their glass transition temperature in possibly wet or dry situation to enhance their dimensional constancy. The derived PA-6 membranes were employed for air purification, eliminating dust contaminants with a rejection rate of approximately 99.98%. In a different research, authors performed heat treatment process for electrospun PES membranes at 190 °C (Homaeigohar et al. 2012). They noticed that inter-fibre adhesion in the heat-treated membranes has been achieved, which resulted in superior mechanical features. It has also been found that the modified membranes have better mechanically consistency; however, they exhibited inferior permeation as well as a flux in comparison with unmodified at the similar feed pressure. The productions of the composite from electrospun polyethersulfone (PES) nanofibres on a PET non-woven help the pre-purification of wastewater. They noticed that improving the working pressure triggered the pore structure of the membrane to collapse, leading to considerable flux reduction. This tendency is usual of electrospun mats in hydraulic flow since pressure-generated compression leads to change the porosity and therefore permeability of the membrane to reduce. To eliminate this problem in order to enhance interfacial stability within the PES and PET layers, the samples have been exposed to constant heating for 6 h at 190 °C in an air environment (Choong et al. 2014). Heat treatment temperature has been selected above the boiling point of the solvent as well as underneath of the glass transition of PES. After a 24 h, they observed that heat-treated membranes showed a minor decline in flux in comparison with untreated membranes. Hence, heating led to much better adhesion in between the pair of layers and also avoided distortion of the membrane framework under the applied pressure (Shirazi et al. 2013). Significantly, efforts have actually been performed to improve the hydrophilicity of polymeric membranes for fluid penetration since hydrophobic membranes tend to be more susceptible to fouling. Plasma modification has been employed to include hydrophilic groups on the membrane surface; therefore, lesser water contact angle on the surface has been achieved. Authors tailored the polypropylene fibril membranes by introducing plasma via the cross section instead of the surface for enhancing their hydrophilicity. They employed long-distance plasma excitation along with Ar, and then acrylic acid modification in aqueous solution has been performed. The overall performance of the membrane has been considerably improved because water flux improved from 732 to 1763 kg m^{-2} h^{-1} and adsorptions fouling as a result of bovine serum albumin (BSA) reduced by 67% in the tailored membrane. This enhancement is related to enhancement in hydrophilicity because water droplets were capable to entirely wet the tailored membrane (Zhao et al. 2012). Authors additionally established composite membranes through coating PVDF-HFP nanofibre membranes together with cellulose. Cellulose perforates in the structure of the porous membrane, which leads to altering the hydrophobic fibres into super-hydrophilic (Liao et al. 2013a). Cellulose has been employed to restrict the pore size and also decrease the average pore size of the electrospun membrane from 0.9 to 0.3 µm. These composite membranes are designed for purifying oil in water having efficiencies 99.98% as well as permeate flux of 1781 L m^{-2} h^{-1} (Ejaz Ahmed et al. 2014).

Application of electrospun fibrous membranes

Nanofibres offer various applications such as biotechnology, medicine delivery, injury healing, microelectronics, ecological safety, energy harvest as well as because of their huge surface area-to-volume ratio, in surface functionalities and also excellent mechanical functionality (Hosseini Ravandi et al. 2013). Improvement in electrospinning has presented an increase to numerous nanofibrous structures over the ordinary non-woven membrane. Electrospun fibre bundle and also consistent yarn have been applied for several applications, and twisted type usually provides more desirable mechanical durability and uniformity in comparison with untwisted yarns (Vitchuli et al. 2010). Authors wrapped electrospun ZnO yarn together with NiO yarn to develop free-standing p–n junctions. Apart from the textile field, there are numerous additional possible applications for electrospun fibre yarn of confined length collectively in its

twisted as well as untwisted structure (Lotus 2009). Electrospun fibres are often produced from conductive materials so that they can be employed in applications wherein its conductivity is a desired useful feature. In this way, the authors developed polyvinylidene fluoride (PVDF)/carbon nanotube (CNT) nanofibre-wrapped ropes via electrospinning (Zheng et al. 2015). The huge specific surface area helps electrospun membranes to work as useful scaffolds for growing cells, carrying medicines, rectifying harmful gases or functioning as sensors for selected molecular species (Liu et al. 2010). The minimum solidity along with substantial interconnectivity of pores tends to make electrospun membranes as an excellent candidate for purification media as the resistance to movement and also reduced flux because particle retention is very low (Desai et al. 2009; Domenjó 2014). Past few years, many studies have been reported on the electrospun membrane and related potential applications, as given in Table 6.

Purification

Developed electrospun fibres have been stipulated with consideration to their application in purification by calculating fibre diameter as well as purification efficiency of fibre. Fibre purification is among the relevant areas in engineering. As an example, fibre filtration systems possess the benefit of substantial purification performance as well as minor air resistant (Geise et al. 2010). According to the works of the literature, as specified in Fig. 6, the electrospun membranes are classified based on the application as well as overall performance mode.

The efficiency of filters is linked to fibre fineness which is probably the most important aspects of filtration systems. Electrospinning nanofibres are able to capture oil droplets when tiny as 0.3 µm, and this is the crucial character in purification sector. Therefore, electrospinning fibres are excellent applicants for the elimination of adverse tiny contaminants. The effectiveness of electrospun nanofibre filtration systems is enhanced according to the incredible surface area-to-volume ratio which leads to improving surface cohesion. Several researchers have discussed that electrospun polyacrylonitrile (PAN) possesses outstanding purification effectiveness (Patil et al. 2017). Nevertheless, purification is usually a pressure operating procedure. Because electrospun membranes are minimal in solidity and also are comprised of fibres which are flexible together with very small in diameter, they are usually extremely compressible. The desirable features of the high specific surface area and

Table 6 Types of electrospun membrane and their applications

Types of membrane	Solvent	Applications	References
Polyurethane	Dimethylformamide	Filter and protective cloths	Sathish Kumar et al. (2015) and Sheng et al. (2016)
Polycarbonate	Dimethylformamide and tetrahydrofuran (1:1)	Filter, sensor, protective cloths	Kim et al. (2007) and Kunzo et al. (2013)
Polylactic acid	Dimethylformamide, dichloromethane	Drug delivery system, filter, sensor	Nobeshima et al. (2016)
Polyethylene oxide	Distilled water/ethanol (3:2)	Microelectronics, filter	Kazemi Pilehrood et al. (2014)
Polyaniline/polystyrene blend	Chloroform	Conductive fibres	Qavamnia and Nasouri (2015)
Polystyrene	Tetrahydrofuran, toluene, DMF	Enzymatic biotransformation, catalyst, filter	Alayande et al. (2012) and Wu et al. (2013)
Polyamide	Dimethylacetamide	Glass fibre filter	Cai et al. (2013)
Polyvinyl phenol	Tetrahydrofuran	Antimicrobial agent	Kenawy and Abdel-Fattah (2002)
Cellulose acetate	Acetone	Membrane, fabrics	Anitha et al. (2013)
Polyvinylidene fluoride	Dimethylformamide	Fibre ribbon	Liao et al. (2013b)
Chitin/chitosan	Dimethylacetamide	Wound dressing	Dobrovolskaya et al. (2016)
Polyaniline/gelatin	Hexafluoroisopropanol	Biocompatible scaffold for tissue engineering, sensors	Lin et al. (2012) and Oktay et al. (2015)
Ethylene–vinyl alcohol copolymer	Isopropanol/ water	Electrospun mat for cell culture, purification	Shen et al. (2014) and Wang et al. (2018)
Polyacrylic acid	Water/ethanol	Gas sensor	Hu et al. (2018)
Polyacrylonitrile	Dimethylformamide	Hydrogen storage	Zhang et al. (2014)
Polyacrylonitrile/nanofillers	Dimethylformamide	Hydrogen storage, Photovoltaic application	Zhang et al. (2014)
Polycaprolactone	Chloroform/methanol	Scaffold and tissue engineering, packaging	Kenawy et al. (2009) and Nhi et al. (2016)
PHBV	Trifluoroethanol	Biomimicking composite	Zhang et al. (2007b)

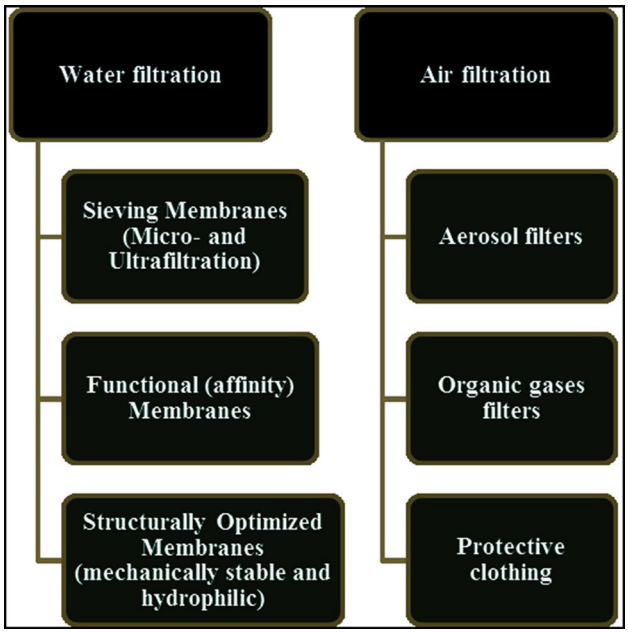

Fig. 6 Electrospun nanofibre membranes for purification

also low solidity are decreased due to compression of the electrospun membranes (Goetz et al. 2018). This result is further important for functions with high pressure including reverse osmosis (up to 7 MPa). Consequently, a concept of the compressive feedback of electrospun membranes is crucial as a way to examine their application as filtration media or even separation membranes. This possible issue is not restricted to electrospun fibre membranes; however, it can be present in other forms of polymer filtration systems or membranes in which solidity is actually less (Liao et al. 2018). Compared to traditional filtration fibres at the identical pressure drop, nanofibres with a diameter possess a higher capacity to absorb the fine particles as the slip flow close to the nanofibres enhances the diffusion, interception and also inertial impaction performance. Experimental analysis, as well as theoretical measurement, verified that electrospun nanofibres are extremely beneficial for trapping airborne contaminants (0.5–200 µm) (Zhu et al. 2017). An extremely fine layer of electrospun nanofibres coated onto a porous template is satisfactory to remove the contaminated penetration. The circulation of air resistance and aerosol purification features connect with the attachment weight of the electrospun fibre coating (Wang et al. 2017a). Additionally, electrospun layers display negligible impedance to moisture vapour diffusion that is crucial for shielding clothing in decontamination functions. A nylon-6 electrospun membrane (thickness 100 µm, pore dimensions 0.24 µm) and an industrial high-efficiency particulate air filtration system (thickness 500 µm, pore dimensions 1.7 µm) having 300 nm suggested that the thin nanofibre membrane has a pretty greater purification efficiency (99.993%) in comparison with the high-efficiency particulate air filtration system (99.97%) (Li et al. 2016b). Polystyrene nanofibres (diameter nearly 600 nm) have been electrospun based on reused expanded polystyrene and blended with micro-glass fibres to develop a filter system for the elimination of water droplets in a water-in-oil emulsion. The inclusion of a little quantity of polystyrene nanofibres has been discussed to considerably improve the capturing efficiency (from 68 to 88%). In an additional study, electrospun nylon nanofibres have been additionally mixed with the glass fibres (diameter 5 µm) for the coalescence filtration system, along with the inclusion of an appropriate quantity of nanofibres (1.6 wt%) to the coalescence filtration system which enhanced the capture performance (Boo et al. 2016).

Wound dressing and drug delivery

Electrospinning can produce a medium to shield the injuries. The researches have shown that employing electric field in the ultra-fine nanofibres may be perfectly spun onto the wounded location of skin to develop a fibrous mat dressing. These types of nanofibres have pore dimensions between 500 and 100 µm which are ideal for shielding the injuries from germs (Mirzaei et al. 2016). A variety of polymers, for example, collagen/chitosan, silk fibroin and also ABA kind poly(dioxanone-*co*-L-lactide)-block-poly(ethylene glycol) block copolymer, is electrospun and also recommended for wound dressing functionality. Figure 7a–c shows scanning electron microscope (SEM) microstructure of spun PVA nanofibres without any treatment and treated with methanol and heat correspondingly. The PVA nanofibres received from the heat treatment method have a split and fine structure and can maintain their web structure better than the nanofibres produced from the other techniques (Hong et al. 2006).

Authors have likewise produced antibacterial electrospinning nanofibres of poly(ε-caprolactone) with small nanoparticles of silver-loaded nanozirconium phosphate which has possible application in injury dressing. The result illustrates that the electrospun fibres have antimicrobial features (Mogoşanu and Grumezescu 2014). Additionally, authors have described an electrospinning instrument that employs a guiding air blowing equipment and electrode to allow the generation of injury dressing cover of poly(ε-caprolactone) nanofibres. Furthermore, authors discussed that electrospinning of polyvinyl–pyrrolidone iodine complex and also polyethylene oxide/polyvinyl-pyrrolidone iodine complex system in the form of a potential path to antimicrobial injury dressing materials. Electrospun nanofibres are additionally useful templates for nervous tissue maintenance. Electrospinning is mentioned in the form of a standard approach for producing

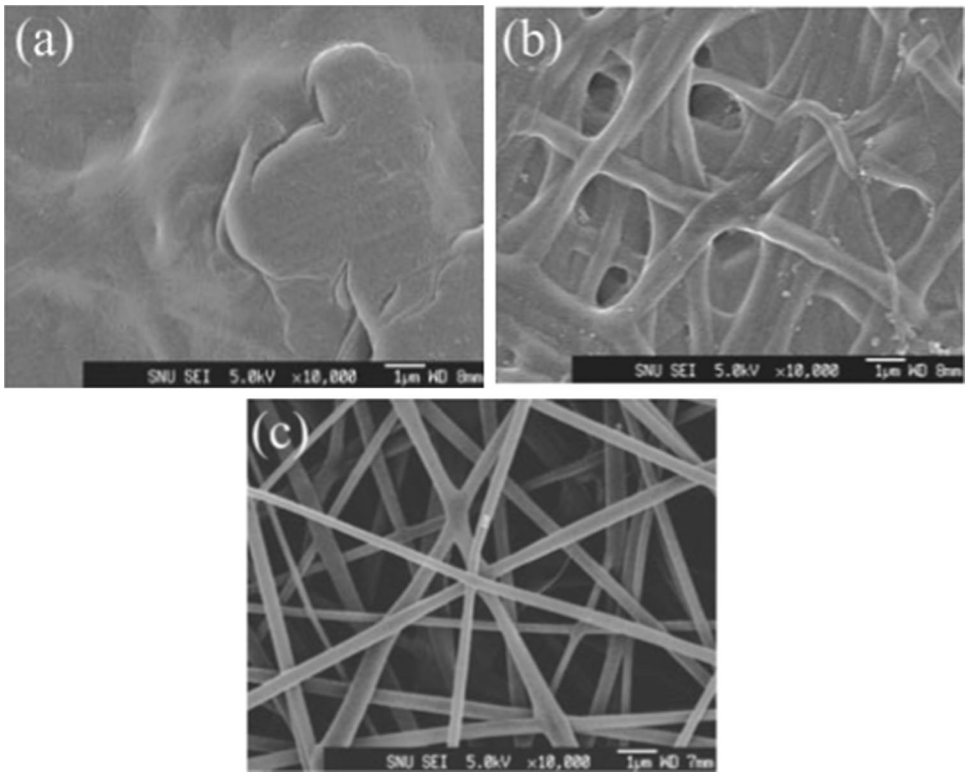

Fig. 7 Scanning electron microscopy (SEM) images of **a** as-spun, **b** methanol-treated, and **c** heat-treated PVA/$AgNO_3$ nanofibres after water immersion at 37.88 °C for 5 h (Hong et al. 2006)

polymeric nanoscale fibres. Different types of synthetic as well as natural polymers have already been effectively electrospun into tiny and high-quality fibres. The higher ratios of surface to volume of developed fibres are able to improve medicine loading and cell connection qualities (Megelski et al. 2002). A variety of medicines, for example, antibiotics, anticancer, ribonucleic acid and deoxyribonucleic acid, are employed by electrospun fibres. Making use of electrospinning is able to create capsules nanofibre having medicines for regulating medicine delivery system. Authors stated that electrospinning of methacrylic acid copolymer is an excellent approach for medicine delivery for both polar and nonpolar medicines (Zamani et al. 2013).

Energy storage

In the majority of batteries, the porous structure is an important factor. A sponge-like electrode has superior discharge current as well as capacity, and a porous separator between the electrodes is able to efficiently prevent the short circuit; however, it enables the exchange of ions easily. Solid electrolytes employed in portable batteries, for example, lithium-ion battery, are usually made up of a gel or porous host to maintain the liquid electrolyte within (Deimede and Elmasides 2015). To gain superior ion conductivity, the host material, known as a separator, must have a permeability to ions. A porous membrane with properly interconnected pores, appropriate mechanical strength as well as good electrochemical stability can be a possible applicant. Authors designed an anode membrane by means of electrospinning slurry of titania nanoparticles, conductive carbon black nanoparticles as well as poly(acrylic acid) in the role of the binder. The subsequent anode material displayed excellent charge/discharge cycling constancy with only a 5% reduction in capacity after 450 cycles at 0.5 °C (Goriparti et al. 2014). To enhance cyclability as well as capacity retention, authors developed electrospun C-Mo_2C fibre membrane with inserted junctions. The existence of MoO_2 throughout the carbonization operation triggered a reaction between MoO_2 and C to develop Mo_2C which enhances mass transfer between fibres and which are linked with each other to develop fused junctions. The fused junction possibly decreases charge transfer as well as sodium diffusion prevention (Zhang et al. 2018b). The hybrid architectural structures of nanocellulose/SnO_2 have been established via hydrothermal growth of SnO_2 nanoflowers on top of nanocellulose nanofibres. The existence of nanocellulose nanofibres functioned in the role of a structure to reduce agglomeration of SnO_2 nanoflowers as well as in the role of a conductive network to speed up the electronic transmission (Jiang et al. 2009). The membrane must show thermal stability, high

porosity for decent electrolyte penetration and allows swift Li-ion transport. Authors developed a multicore–shell electrospun separation membrane that contains several cores of polyimide (PI) in the shell of polyvinylidene fluoride for improved thermal stability. The multicore–shell structure has been produced via a phase-separated polymer-blended solution. The electrospun multicore–shell membrane has been identified to display excellent thermal as well as electrochemical stabilities at around 200 °C although polyethene membrane displayed considerable shrinkage. Additionally, electrospun fibres with flames retardant ingredients are known to stop fire during catastrophic battery malfunction (Park et al. 2016a). Certain situations, such as lithium-ion battery capturing fire, are owing to the malfunctions in the membrane, which separates the combustible electrolytes in the battery that picks up an exothermic reaction once they touch each other. Authors developed a core–shell electrospun fibrous membrane with a flame retardant, triphenyl phosphate, a well-known organophosphorus-based fire retardant in the core. This micro-thin membrane can be employed in the role of the separation layer in the lithium batteries. The shell is created of poly(vinylidene fluoride-hexafluoropropylene) because of its chemical inertness to the battery electrolytes along with a comparatively lower melting point of 160 °C. Their studies indicated that the electrospun membrane is capable to effectively extinguish the fire (Liu et al. 2017). Additionally, as-prepared Si/PAN paper along with the carbonized Si/PAN paper (3D Si/C fibre paper) displayed decent flexibilities, as presented in Fig. 8a, b, correspondingly. Figure 8c–f is the SEM microstructure of 3D Si/C fibre paper. The unique structure of the 3D Si/C fibre paper has been employed in the form of an anode for LIB; the LIB manifested an excellent capacity (1600 mAh g^{-1}), an outstanding rate capability efficiency along with a low capacity loss (0.079% after 600 cycles) (Xu et al. 2015).

Sound absorber

Nanofibres displayed outstanding ability to absorb sound. The electrospun nanofibre exhibits extraordinary sound absorption features having only one-third of the weight of conventional sound absorption components. It is capable to absorb sounds over a broad range of frequencies, particularly frequency sounds below 1000 Hz. The performance of a fibre-based sound absorbance material requires various parameters, for example, porosity, tortuosity, fibre diameter, density, airflow and dimension. In addition to the absorbance, coefficient of a material relies upon the quantity of energy absorbed through it. The scientist noticed a considerable enhancement in sound absorption ability of

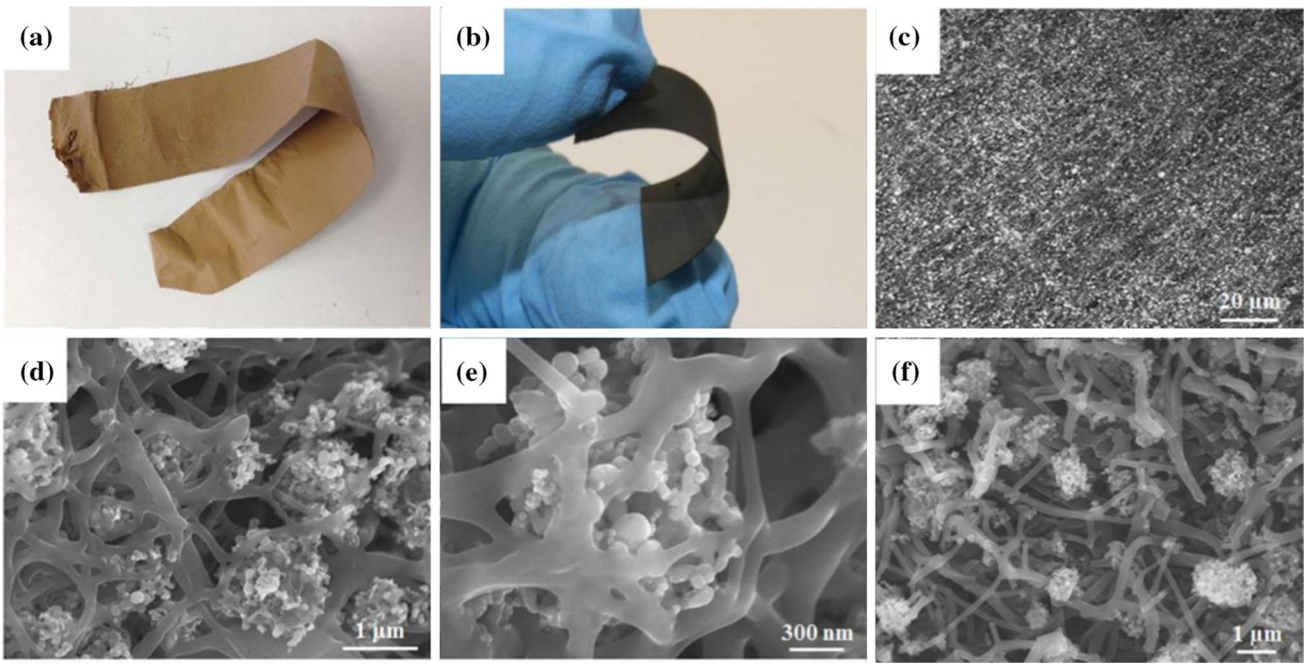

Fig. 8 Photographs of the electrospun/sprayed flexible paper electrode **a** before and **b** after carbonization with 72 wt% Si; SEM images of the 3D Si/C fibre paper electrode: **c–e** top view and **f** cross section (Xu et al. 2015)

electrospun fibres in comparison with glass wool at a frequency of 1600–6400 Hz (Liu et al. 2014). Additionally, there is a basic enhancement in sound absorption with fibre diameter from 8.24 µm of glass wool. A small decrease in sound absorption has been reported for electrospun fibres with a diameter of 520 nm even though it depicts that ideal fibre diameter is about that particular range. When sound waves strike on the porous materials, three kinds of transformations happen for the sound energy: reflection, absorption and transmission.

Authors sandwiched nanofibrous membrane of polyacrylonitrile together with polyurethane between a pair of non-woven layers of polyethylene terephthalate combined with wool. Almost all materials having an electrospun membrane(s) has been found to notably increase its absorbance behaviour from the range 500 Hz to 6000 Hz (Iannace 2014). Authors analysed the sound absorbance feature of electrospun polyvinyl chloride mat of various dimensions and having fibre diameters which range from 100 nm to microns.

Fibre diameters of around 200–500 nm together with the thickness of 0.5 mm are capable to absorb sound at the greater frequency (> 5000 Hz). Since the thickness of electrospun fibre raises, the sound absorbance moves in the direction of the lower frequency. Nevertheless, the absorption coefficient falls as well. While the fibre diameter is above 500 nm, the sound absorbance relocates in the direction of the lower frequency together with thicker mesh; however, absorption coefficients stay similar (Xiang et al. 2011). The overall performance of a number of stacked layers of electrospun PVP fibres membrane (typical diameter of 2.8 µm) using a minimum of 6 layers in the form of sound absorbers in aeroplanes has already been examined (Rabbi et al. 2013). If the layers of PVP membranes raise, the peak absorption relocated in the direction of a lower frequency (about 300 Hz) while the weight is 18 g. Using six layers at a weight of 7 g, the peak absorption is at around 700 Hz (Kucukali-Ozturk et al. 2017). The sound absorption coefficient has been constantly over 0.8 at its peak across almost all samples. Conversely, glass wool fibres at 12 g presented much better sound absorbance at a greater frequency. The sound absorption coefficient of 12 g electrospun fibres having multi-layer membranes functions much better than aerogel (12 g) and also polyester (10 g) throughout the whole frequency range between 300 and 1600 Hz (Yahya and Sheng Chin 2017). For glass wool fibres (12 g), sound absorption begins to exceed electrospun PVP layers at a frequency over 650 Hz. The inclusion of nanoparticles into the electrospun fibre matrix is also noticed to provide a substantial influence on its sound absorption abilities (Gao et al. 2016). A number of tests using polyvinyl alcohol (PVA) with a distinct level of TiO_2 as well as ZrC nanoparticles have already been carried out. Applying ZrC nanoparticles, sound absorption characteristics of the composite relocated to the greater frequency over 2500 Hz. Nevertheless, for TiO_2 nanoparticles, the enhancement has been identified at the lesser frequency range between 500 and 1500 Hz. The dimensions of nanoparticles affect the sound absorption features; it has been mentioned that with TiO_2 nanoparticles size of 200 nm shows much better sound absorption in comparison with 10-nm nanoparticles in the lower frequency range (Kalinová 2011; Mohrova and Kalinova 2012). Current development in the research of porous sound absorption materials is outlined, that is, mentioned by the category of material classification as well as structure manner (Fig. 9).

Sensors

Sensors are commonly used to identify chemicals for surroundings safety, manufacturing process control, health care analysis, as well as military usages. A quality sensor must have a compact size, minimal manufacturing expense and also several different functions, apart from the superior sensitivity, selectivity and also accuracy. Good sensitivity and also swiftly response call for the sensor have a huge specific surface area as well as a remarkably porous structure. The properties held by electrospun nanofibres fit properly with such specifications (Ding et al. 2010a; Bracco et al. 2014). Consequently, a nanofibrous structure must have a potential physical structure to develop an extremely sensitive as well as swift response sensor. A number of strategies have already been employed to deliver nanofibres with a sensing

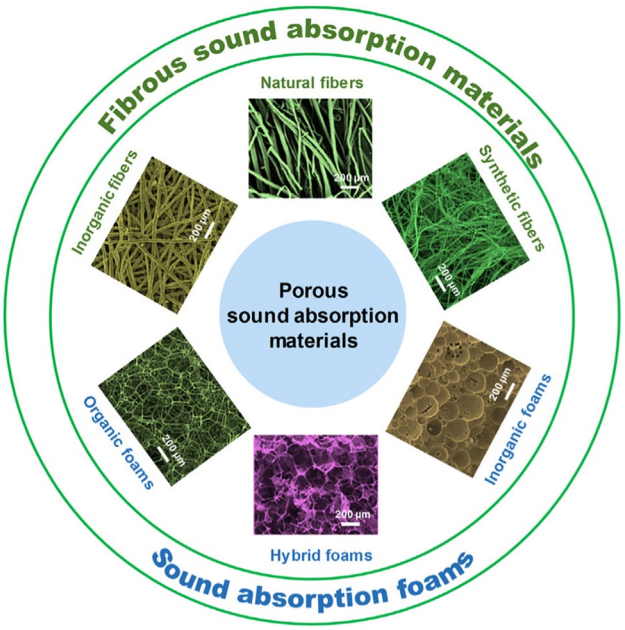

Fig. 9 Porous materials for sound absorption (Cao et al. 2018)

ability, for example, employing a polymeric sensing material to electrospun nanofibres, including sensing molecules into nanofibres or even using sensing material on nanofibre surface by means of coating/grafting method (Li et al. 2015). A PM-grafted poly(methyl methacrylate) nanofibres confirmed greater sensitivity to target analyte 2,4-dinitrotoluene in comparison with its cast film counterparts. Fluorescence optical sensors have been additionally produced via a layer-by-layer electrostatic assembly approach to pertain a conjugated polymer on top of nanofibre surface for the identification of methyl viologen and cytochrome in aqueous solution (Wang et al. 2002). Porphyrin-doped silica nanofibres have been applied to identify the 2,4,6-trinitrotoluene vapour. These types of nanofibre-based sensors presented good sensitivity as well as a swift response. Apart from fluorescent properties, conjugated polymer-based electrospun nanofibres have been additionally discussed, which is able to sense volatile organic compounds via optical absorption properties (Tao et al. 2007). A gas sensor having a particular absorption interaction within ammonia and poly(acrylic acid) nanofibres has been discussed, and weight dissimilarity caused via the gas absorption has been calculated through a quartz crystal microbalance. This particular sensor is able to find ppb degree NH_3 in an air environment, and consequently, the sensitivity is several times greater in comparison with the poly(acrylic acid) cast film (Hu et al. 2018).

Quartz crystal microbalance, one of the acoustic wave strategies, was first introduced in 1880 based upon the piezoelectric effect. The quartz crystal microbalances in the form of an analytical tool can detect extremely little mass variations of less than a nanogram deposited on the crystal surface. Present efforts have been concentrated on the development of nanostructured coatings on quartz crystal microbalances to enhance sensor sensitivities (Wang and Yan 2010). Using the benefits of the huge specific surface area, excessive porosity and also excellent interconnectivity of the electrospun fibrous assemblies, NH_3, H_2S, formaldehyde (Wang et al. 2010a) and moisture (Hu et al. 2011) are being successfully identified under more difficult situations at the room temperature in flow-type (Fig. 10a) or static gas testing strategies (Fig. 10c) by evaluating the resonance frequency shifts of quartz crystal microbalance due to the extra mass loading. The PAA nanofibre-covered quartz crystal microbalance sensors displayed ultra-high sensitivity in the direction of small concentrations of NH_3, for example, 130 ppb at the relative humidity of 40% (Fig. 10b; Ding et al. 2005). Moreover, a humidity sensor is constructed by electrospinning deposition in a network of PAA nanowebs on quartz crystal microbalances (Wang et al. 2010b). The fibrous coatings develop an impulse amplified by greater than two orders of magnitude as relative humidity enhances from 6 to 95% (Fig. 10d). The level of responsiveness of the fibrous membrane-coated quartz crystal microbalance sensors seemed to be many times greater than that of the flat film-coated quartz crystal microbalance sensors. These types of tests have verified the chance of via electrospinning method to control structures of the membrane for greater surface activity as well as gas sensitivity. Additional analysis using arrangements together with structures of fibres are anticipated to increase the features of this system in the coming years.

Conducting nanofibres have been generated from the semiconducting oxides, conducting polymers as well as non-conductive polymers. Oxides nanofibres have been created via electrospinning of oxide and polymer solution, accompanied by calcining treatment method to eliminate the polymer. The identification of gas molecules by means of oxide nanofibres is dependent on the conductivity alterations because of the doping consequence of analyst gases to the oxide. These types of sensors displayed better sensitivity, quicker response and lesser detection limit as compared to sol–gel-based films (Abideen et al. 2017). Additionally, Co-doped ZnO nanofibres have been applying in the form of a photoelectric oxygen sensor having a swift response (Bai et al. 2014). The electrospun polyaniline (PANI)/PS nanofibres which contain glucose oxidase have already been mentioned to possess an excellent sensitivity to glucose (Razak et al. 2015). Organic/inorganic semiconductor Schottky nanodiode has been made by PANI nanofibres (Zhang et al. 2004) as well as an inorganic n-doped semiconductor. The device offers a swift response as well as supersensitive to ammonia (Pinto et al. 2006). Apart from the conducting or even semiconducting materials, insulating polymers have been furthermore employed to generate electrical sensors. In this instance, ions or conductive nanofillers have been included in the polymer for enhancing the conductivity. If the carbon black concentration with the percolation threshold, the composite fibres altered their resistance in volatile organic materials. Applying various polymer matrices, the sensor is used to identify toluene, trichloroethylene, methanol and also dichloromethane vapours. Furthermore, carbon nanotubes/poly(vinylidene fluoride) composite nanofibres displayed a higher strain sensing capability (Tarus et al. 2016). We introduce some recent progress and predominant developments of several sensing approaches such as

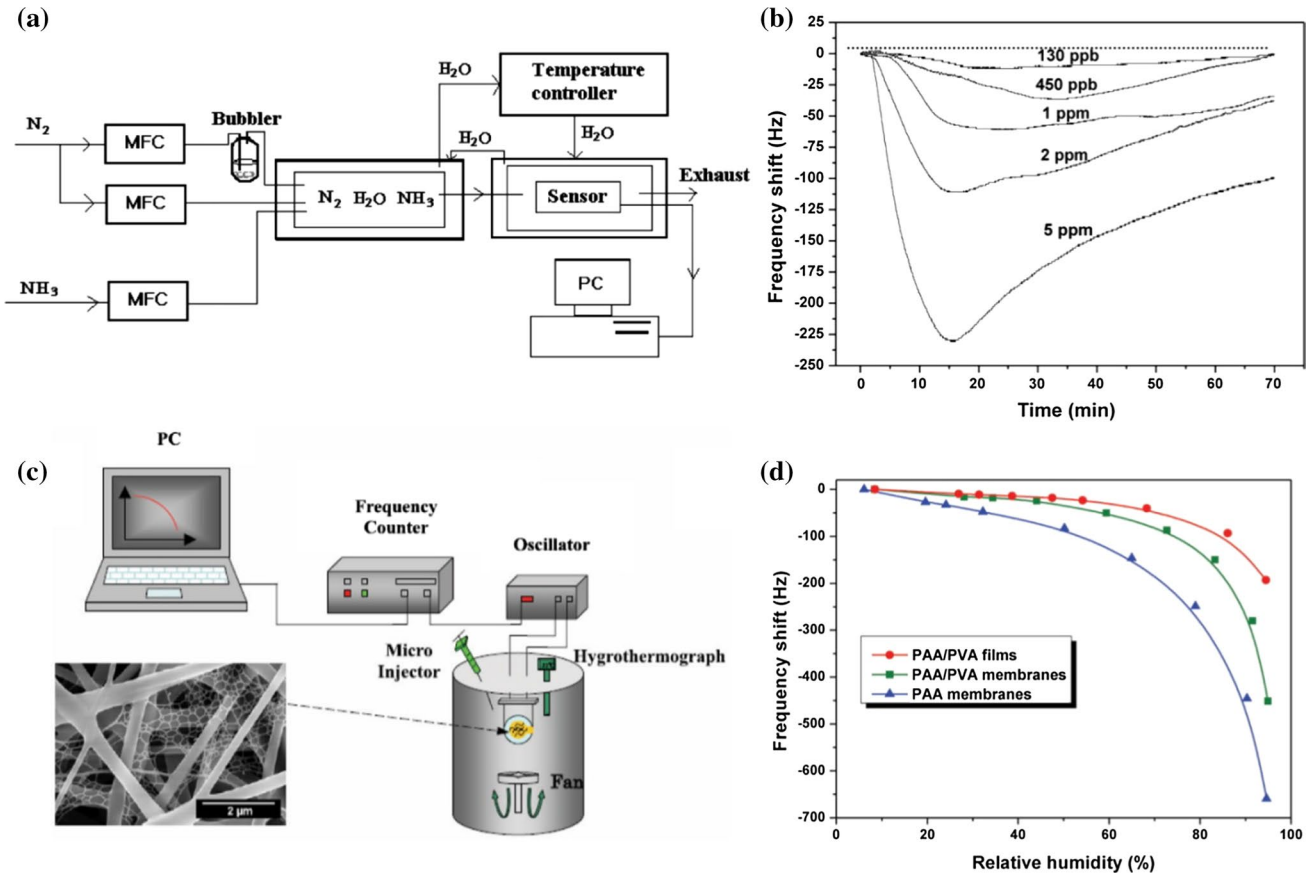

Fig. 10 **a** Schematic of a flow-type gas testing system for NH_3 detection. **b** The response of the PAA fibrous membrane-coated QCM sensors exposed to various concentrations of NH_3, **c** schematic diagram of a static-type testing system for humidity detection. **d** Frequency shifts of polyelectrolyte-coated QCM sensors as a function of the relative humidity (Ding et al. 2005)

resistive, photoelectric, optical, acoustic wave and amperometric sensors. A summary of sensors based on the electrospinning technology is mentioned in Table 7.

Conclusion

The main concerns on electrospinning are a fabrication of nanofibres from natural or artificial polymers with desired morphology and its potential applications. There are several efforts, which have been applied to control the morphology, parameters, and their interaction of electrospun fibres. This review article has been described the fibre formation-based synthetic or natural polymers, metals, ceramics and organic/inorganic, inorganic/inorganic composite system via an electrospinning process. The poetical application of functional electrospun nanofibres in the various fields has been mentioned. It is found that innovating modification in electrospinning units will open further opportunities for electrospun fibres. For this purpose, coaxial electrospinning, mixing and multiple electrospinning, core shelled electrospinning, blow-assisted electrospinning have been pointed in this paper. Research efforts to up-scaling and also enhancing the nanofibre properties have reviewed. Finally, it has been found that processing, as well as the application of electrospun, would be broadened in near future.

Table 7 Types of electrospun nanomaterials-based sensors

Materials	Type of sensor	Remarks	References
Polyethylenimine (PEI)-PVA Fibres	Acoustic wave	Fibre diameter 0.04–1.8 µm, sensing of the HCHO, operating temperature room temperature	Wang et al. (2010a)
Polyvinylpyrrolidone (PVP)/urease	Amperometric	Fibre diameter ~ 100 nm, Urea, operating temperature room temperature	Sawicka et al. (2005)
10,12-Pentacosadiynoic acid (PCDA)	Optical	Fibre diameter ~ 3 µm, sensing of the α-CD, operating temperature 30 °C	Chae et al. (2007)
Gallium nitride (GaN)	Photoelectric	Fibre diameter 32–48 nm, wavelength, operating temperature room temperature	Wu et al. (2009)
Poly(epichlorohydrin) (CB)-Poly(epichlorohydrin) (PECH), PEO, poly(isobutylene) (PIB), PVP	Resistive	Fibre diameter ~ 3 µm, CH_3OH, operating temperature room temperature	Kessick and Tepper (2006)
PEI-PVA	Acoustic wave	Fibre diameter 200–400 nm, H_2, operating temperature room temperature	Wang et al. (2010a)
Haemoglobin	Amperometric	Fibre diameter 70–250 nm, Glucose, operating temperature room temperature	Ding et al. (2010b)
PEO-PANI	Resistive	Fibre diameter 110–140 nm, H_2O, operating temperature room temperature	Li et al. (2009)
Poly(acrylic acid) (PAA)	Acoustic wave	Fibre diameter 11–264 nm, NH_3, operating temperature room temperature	Wang et al. (2010b)
PAA-PVA	Acoustic wave	Fibre diameter 100–400 nm, NH_3, operating temperature room temperature	Ding et al. (2004)
Cobalt (Co)-ZnO	Photoelectric	Fibre diameter 50–400 nm, NH_3, operating temperature room temperature	Yang et al. (2007)
Polyaniline (PANI)/PVP	Resistive	Fibre diameter 1–10 µm, NO_2, operating temperature room temperature	Low et al. (2015)
Zinc oxide (ZnO)-SnO_2	Resistive	Fibre diameter 100–150 nm, C_2H_5OH, operating temperature room temperature	Song et al. (2009)
Stannic oxide (SnO_2)	Resistive	Fibre diameter 700 nm, H_2O, operating temperature room temperature	Wang et al. (2007)
Titanium dioxide (TiO_2)	Resistive	Fibre diameter 120–850 nm, CO, NO_2, operating temperature room temperature	Landau et al. (2009)
Polymethyl methacrylate (PMMA) fibre membrane ($d \approx 400$ nm) encapsulated with CsPbBr3 perovskite quantum dots	Fluorescence	Fibre diameter 400 nm, biological proteins, metal ions, pH	Wang et al. (2017b)
Polyvinyl alcohol/poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate)	Resistive	Fibre diameter 68 nm, ammonia	Zhang et al. (2018a)
Polyurethane/polyacrylonitrile nanofibre yarn	Resistive	Strain sensing	Yan et al. (2018)

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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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