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Nanofibers and Electrospinning Method

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Abstract

As a result of their peculiar features like extremely high surface area to weight ratio, low density, as well as high pore volume and controllable pore size, which may not be present in other structures, nanofibers have taken centre stage in nanotechnology. The indicated properties, consequently, make non-woven nanofibers as appropriate materials for wide-spread applications. Electrospinning, because of its high productivity, simplicity, low cost, reproducibility and its potentialities of being utilised at the industrial level is regarded as one of the most potential processes in nanotechnology. This method implies the application of high voltage electric field aiming to extract very thin fibres from a polymeric fluid stream (solution or melt) potentially deliverable through a millimetre-scale needle. Electrospinning, as a technique, is reliant on various processing standards like solution properties and processing parameters. Consequently, altering these parameters could exert a considerable degree of influence on the nanofiber size, shape and morphology. Thus, by controlling those parameters well, specific fibres can be produced to benefit various applications.

Keywords: nanofibers, application, electrospinning, nanostructure

1. Introduction

Electrospinning is a simple and comprehensive process for generating an ultrafine fibre from varieties of materials which include polymer, composite and ceramic. The electrospinning setup consists of three major components namely, high voltage power supply, syringe with metal needle and a conductive collector. It is, in fact, very sophisticated, but a simple, processing mechanism of producing nanofiber. The electrospinning process can be classified into several techniques like vibration electrospinning, magneto-electrospinning, siro-electrospinning and bubble electrospinning, according to Liu et al. [1]. As the charge liquid jet moves from the

syringe tip to the collector, the mode of current flow changes from ohmic to convective flow as the charge moves instead to the fibre surface.

A slow acceleration is a characteristic of the ohmic flow, since the geometry of the Taylor cone is controlled by the ratio of the surface tension to electrostatic repulsion [2]. After successfully addressing the ohmic flow, the jet travels at a rapid acceleration, which includes the transition zone from liquid to dry solid. In the end, the jet penetrates the collector [3–5]. The name ‘Taylor Cone’ simply represents the conical shape formed at the needle tip see (Figure 1).

In 1964, Sir Geoffrey Ingram Taylor described this cone [7] as a continuation of the study by Zeleny [7] on the formation of a cone-jet of glycerine exposed to high electric fields. Several others including Wilson and Taylor, Nolan and Macky [7] continued research in this area. However, it was Taylor who investigated further into the reactions between droplets and electric fields. Taylor’s result is based on two assumptions: (1) that the surface of the cone is an equipotential surface and (2) that the cone exists in steady state equilibrium. Immediately after being discharged and the Taylor cone activated, the polymer jet goes through a whipping process [8] in which the solvent evaporates, precipitating a charged polymer fibre, which lays itself at random on a grounded collecting metal screen. As far as the melt is concerned, the discharged jet solidifies when it travels in the air and is collected on the grounded metal screen [7]. Fridrikh et al. [9] theorised that the terminal diameter of the ‘whipping’ jet (h_t) is controlled by flow rate (Q), electric current (I) and fluid surface tension (γ) as given by the equation

$$h_t = \left(\gamma \bar{\epsilon} \frac{Q^2}{I^2} \frac{2}{\pi(2 \ln x - 3)} \right)^{\frac{1}{3}} \quad (1)$$

where $\bar{\epsilon}$ is the dielectric constant, (x) is the displacement, Eq. (1) offers a prediction that the terminal diameter of the whipping jet is controlled by the flow rate, electric current and the surface tension of the fluid, disregards the elastic effects and fluid evaporation, and also makes an assumption about the minimal jet thinning after the saturation of the whipping instability takes place.

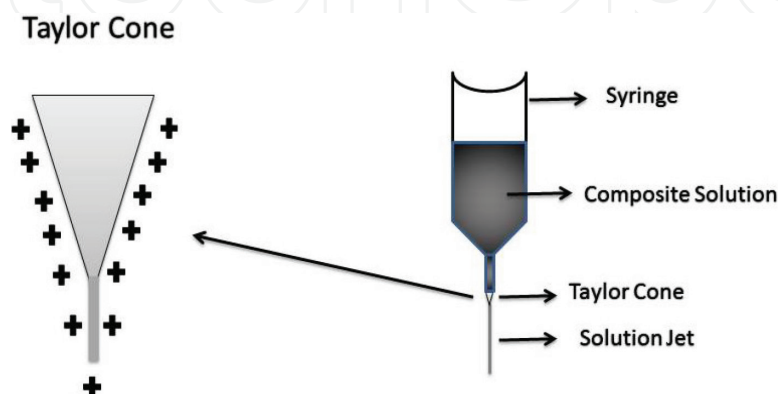


Figure 1. Illustration of Taylor Cone formations from the Syringe Needle Tip [6].

2. Electrospinning setups

2.1. Electrospinning process

The electrospinning apparatus is really a simple idea, carrying only three main components: a high voltage power supply, a polymer solution reservoir (e.g., a syringe, with a small diameter needle) with or without a flow control pump, and a metal collecting screen. A high voltage power supply with adjustable control can well provide up to 50-kV DC output and, depending on the number of electrospinning jets, the multiple outputs that function independently, are necessitated. The polymeric solution is kept in a reservoir and connected to a power supply to establish a charged polymer jet. Charging the polymer solution could be done either with a syringe with a metal needle or a capillary with a metal tip in the polymer solution. If the syringe is not placed horizontally, polymer flow can be driven by gravity. However, to remove the experimental variables, a syringe pump is engaged to control the precise flow rate. The fibre collecting screen is expected to be conductive and it can either be a stationary plate or a rotating platform or substrate. The plate can produce non-woven fibres, whereas a rotating platform can produce both nonwoven and aligned fibres.

Presently, two standard electrospinning setups are available namely the vertical and horizontal, with three new electrospinning setups with different angles for the study of the effect of the gravity. As a result of the increasing interest in this technology, many research groups have developed sophisticated mechanisms by which more complex nanofibers structures, can be fabricated in a more controlled and efficient manner [10, 11], see (Figure 2). For instance, motor-controlled multiple jets and fibre-collecting targets provide avenue for producing a single nanofibrous scaffold consisting of multiple layers, with each layer obtained from a different polymer type. Furthermore, this technology can be used to manufacture polymer composite scaffolds where the fibres of each layer represent a combination of various polymer types.

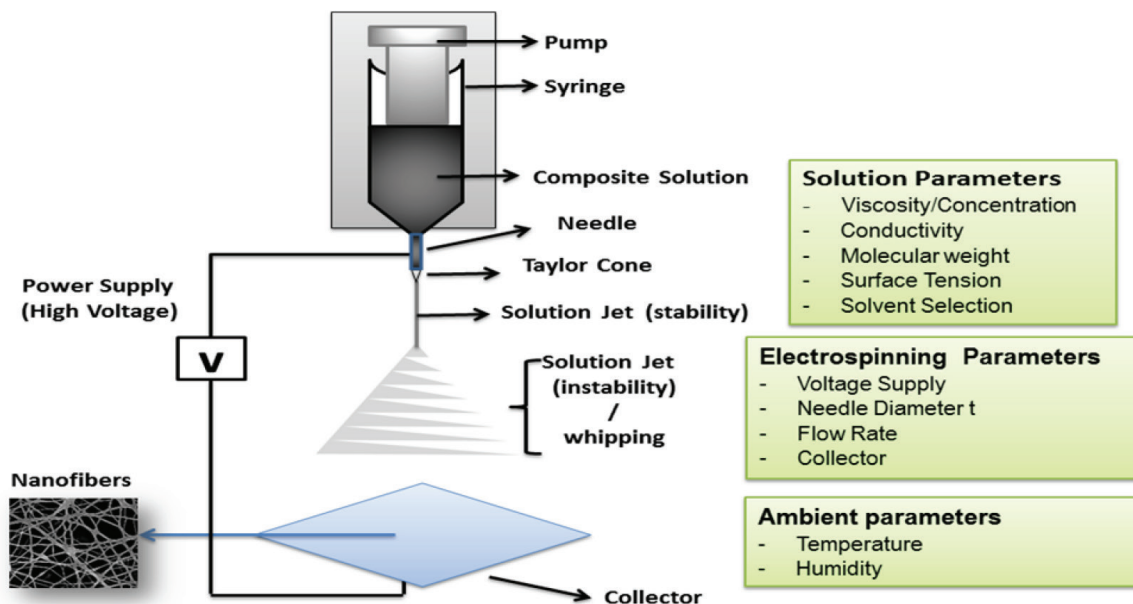


Figure 2. Electrospinning setup and controllable electrospinning process parameters [12].

3. Mechanism and technique for nanofiber formation

Electrospinning process has been studied extensively [13]. The mechanism takes place when the surface tension of the solution is overcome by an applied electric field, thereby ejecting tiny jets from the surface. Taylor [14] identified a critical voltage at which this breakdown would occur:

$$V_c^2 = 4 \frac{H^2}{L^2} \left(\ln \frac{2L}{R} - \frac{3}{2} \right) (0.117\pi\gamma R) \quad (2)$$

where V_c is the critical voltage, H is the separation between the capillary and the ground, L is the length of the capillary, R is the radius of the capillary and γ is the surface tension of the liquid. A similar relationship by Carson et al. [15] had progressed for the potential electrostatic spraying from a hemispherical drop pendant from a capillary tube:

$$V = 300 \sqrt{20\gamma r} \quad (3)$$

where v is electric field, γ is the surface tension of the liquid and r is the radius of the pendant drop [15]. As he investigated a small range of fluids, Taylor determined a 49.3° equilibrium angle-balanced surface tension with electrostatic forces, and he had manipulated this value in his derivation. Taylor cones are required for electrospinning because they define the onset of subtle velocity gradients in the fibre forming process. When $V > V_c$, a thin jet of solution will explode from the cone surface and travel towards the nearest electrode of opposite polarity, or electrical ground. As a way to describe this, electrospinning jet is a string of charged elements connected by a viscoelastic medium, with one end attached to the point of origin and the other end is let free. When a polymer solution, held in a capillary by its surface tension, is subjected to an electrical field, a charge is induced on the liquid surface [16]. Mutual charge repulsion occurs in a force opposing the surface tension forces and shear stresses are set up in the fluid. With increased intensity in the electrical field, ions in the like-polarity solution will be forced to aggregate at the surface of the drop. The length of the stable jet increases with increasing voltage. After the viscoelastic jet starts flowing away from the Taylor's cone, initially it traverses a linear path. The jet gradually starts to bend away from this linear path and complex shape changes may occur from repulsive forces generated in the charged elements inside the electrospinning jet [17]. The jet may undergo substantial reductions in cross sectional area and spiralling loops may grow from it. This phenomenon is often referred to as whipping instability. Consequently, the hemispherical surface of the solution at the tip of the capillary elongates to form a cone, called the Taylor cone (**Figure 3**). At remarkably high electrical fields ($V > V_c$), a charged jet of solution is ejected from the tip of the Taylor cone and will travel to an electrode of opposite polarity (or electrical ground).

A dimensionless parameter called the Berry number (B_e) [18, 19] was used by various research groups as a processing index for controlling the diameter of fibres. B_e number is defined as:

$$B_e = \eta C \quad (4)$$

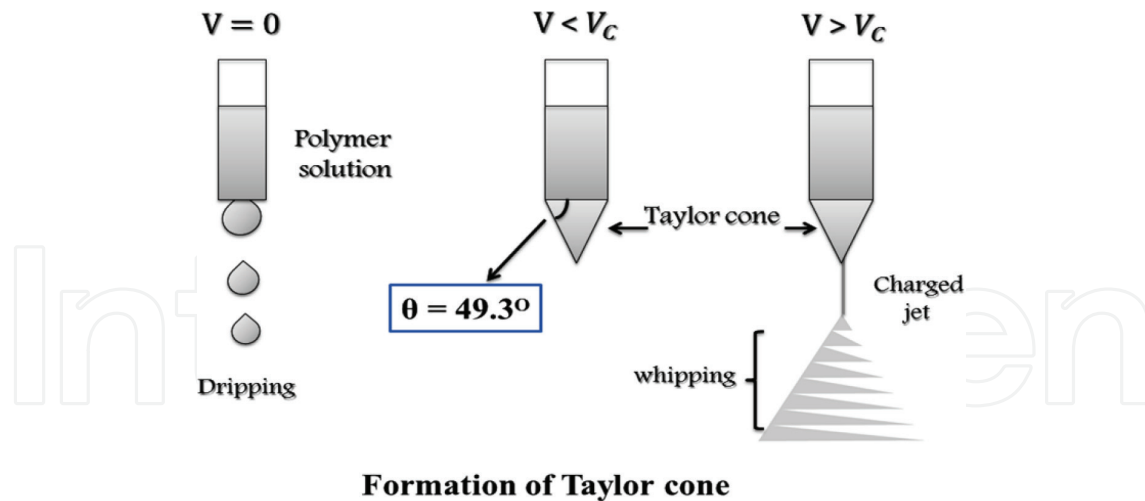


Figure 3. Schematic illustration of the effects by electric field applied to a solution in a capillary.

where $[\eta]$ is the intrinsic viscosity of the polymer which is the ratio of the specific viscosity to the concentration at an infinite dilution and C is the concentration of the polymer solution. Intrinsic viscosity is dependent on polymer molecular weight. B_e also describes the level of the entanglement of polymer chains in a solution. As far as highly diluted solutions are concerned, when B_e is less than unity, the polymer molecules are sparsely distributed in the solution. There is low probability for individual molecules to be entangled with each other.

When B_e is greater than one, the polymer concentration as well as the level of molecular entanglement are enhanced, leading to more favourable conditions for the fibre formation [20]. The experiment implied that as the solution viscosity increased the fibre diameter also increased (approximately proportionally) to the jet length. Baumgarten detailed the relationship between fibre diameter and solution viscosity expressed by the following equation:

$$D = \sqrt[2]{\eta} \quad (5)$$

where D is the fibre diameter and η is the solution viscosity in poise. It also proves that fibre diameter is highly dependent on the applied electric field. An increase in the applied voltage increases the electrostatic stress, which, in turn, produces smaller diameter fibres [7, 21]. According to Huang et al. [22] further increase in the electric field, is a critical value achieved when the electrostatic repulsive force deals with the surface tension and the charged jet of the fluid is ejected from the end of the Taylor cone. In the process, the solvent evaporates, contributing to the formation of charged polymer fibre. As for the melt, the discharged jet solidifies when it moves in the air. Based on findings of the study conducted by Pham et al. [23], the shape of the base is dependent on the surface tension of the liquid and the force of the electric field; jets can be ejected from surfaces that are mostly flat if the electric field is high enough. The solvent in the polymer jet evaporates in the movement to the collecting screen, thereby increasing the surface charge on the jet. As it passes via the electric field, this increase in the surface charge induces instability in the polymer jet [24]. The polymer jet divides geometrically, first into two jets, and then into many more as the process repeats itself in order to compensate for this instability. Nanofibers are formed from the spinning force action, given

by the electrostatic force on the continuous splitting of the polymer droplets. They are deposited one layer after another on the metal target plate, forming a non-woven nanofibrous mat. The mechanisms, by which nanofibers are formed, much less controlled, have not been fully elucidated yet, although the electrospaying/electrospinning technology has been used for such a long time. Not much of theoretical clarity has been achieved, although, several studies have been carried out to investigate the mechanism of fibre formation to reproducibly control scaffold design. A uniform fibrous structure is created only under optimised operating during the process electrospinning. The structural morphology of the nanofibers is affected by both extrinsic and intrinsic parameters [16]. In order to produce inform nanofibers, external parameters, like environmental humidity and temperature, in addition to intrinsic parameters, including applied voltage, working distance and conductivity and viscosity of the polymer solution need to be optimised. The intrinsic parameters are more critical in determining the nanofiber structure in general sense.

4. Operating parameters for electrospinning

Three main parameters, which are solution parameters, process parameters and ambient parameters, tend to affect the electrospinning process. These operating parameters play a big role in determining the desired quality of the electrospun fibre produced [25, 26]. The most preferred in many applications is a fibre with diameter within 10–1000 nm in scale and a smooth surface morphology. The solution properties are difficult to alter, according to Lu and Ding [25], since the relationship between one parameter will drag the other parameters; and in addition, they are very difficult to isolate as one controllable parameter. Li and Wang [27] discussed the effects of working parameters that govern the electrospinning process and the process, and discovered that these parameters could affect the fibre morphologies and diameters. In their study on the effects of the parameters on nanofiber diameter, Thompson et al. [28] found out that the jet radius could leave an impact to the production of the electrospun fibre. In their study, a number of parameters significantly affected the fibre formation compared to other parameters. For instance, the first electrospinning method by Formhals [29] had had some technical disadvantages since it was not easy to dry the fibres entirely after electrospinning as the spinning and collection zones have a very short distance; this resulted in a less aggregated web structure [29]. After half a decade, however Formhals [30], in his pioneering work, changed the distance between the nozzle and the collecting device in order to give more drying time for the electrospun fibres at a longer distance [31].

4.1. Polymer/solution parameters

4.1.1. Viscosity/concentration

The most critical factor in controlling the structural morphology of the nanofibrous structure is polymer solution viscosity, a parameter that is directly proportional to the concentration of the polymer solution. For fibre formation, polymer viscosity should be in a particular range, depending on the type of polymer and solvent used. An electrospinning method by Zeng J et al. was used to fabricate PLA nanofiber, with different concentrations or viscosities ranging from

1% to 5% by weight as shown in **Figure 4**, and below 3% for beads or beaded fibres and 3% and above for continuous nanofibers [32]. A bead that contains nanofibers structure was created below this range. Spherical beads had become longer and turned into spindle-shaped ones, with increased viscosity, and the number of beads in the structure was decreased. In the same manner, Liu et al. also talked about that a different particular range of viscosity rendered appropriate for the formation of uniform nanofibers composed of cellulose [33]. Recent studies done by Deitzel et al. [34] and Demir et al. [35], in addition, have illustrated that a more viscous polymer solution can well create larger fibres. To sum up, these studies have been able to prove that there is a polymer-specific, optimal viscosity value for electrospinning.

According to Sill and von Recum [36], polymer concentration determines the spinnability of a solution. For chain entanglements to occur, the solution must have high enough polymer concentration. However, the solution should not be either too diluted or too concentrated. Both, the viscosity and surface tension of the solution are affected by the polymer concentration.

4.1.2. Conductivity

The charge carrying capacity of polymer solutions with high conductivity is greater than solutions with low conductivity. Therefore, the fibre jet produced from a solution of high conductivity will tend to have higher tensile force when exposed to an applied voltage. Through

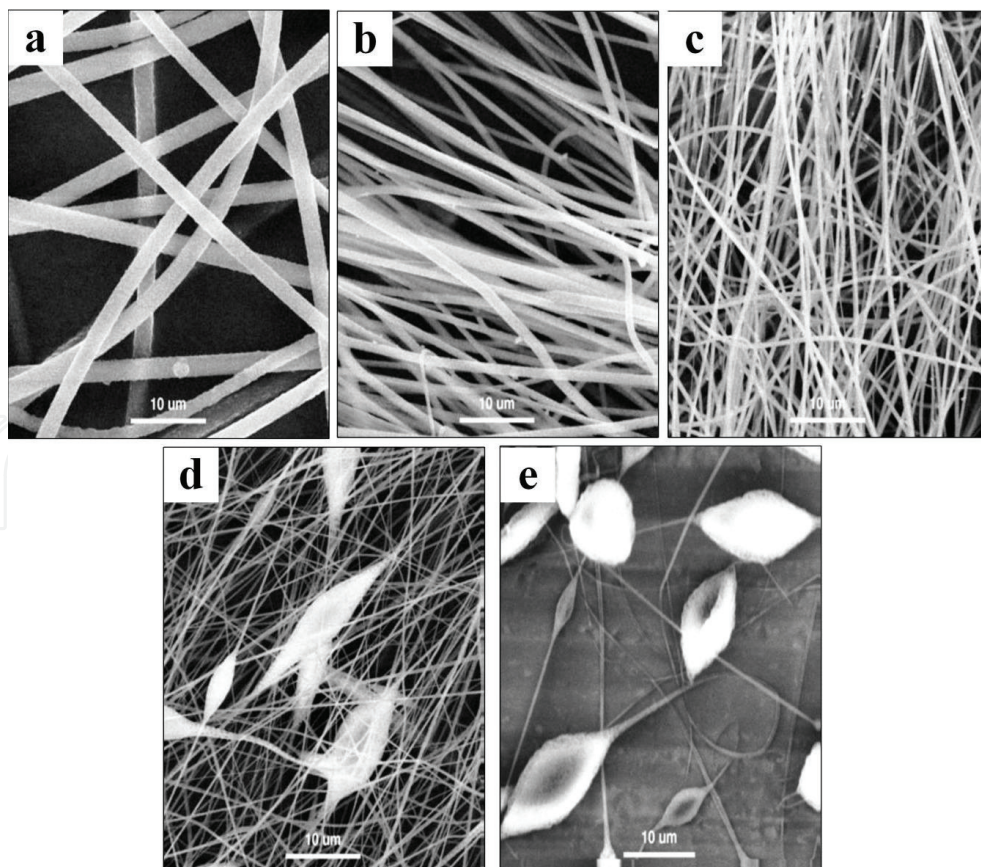


Figure 4. FESEM of electrospinning of nanofibers with different concentrations PLA. (a) 5%, (b) 4%, (c) 3%, (d) 2%, and (e) 1% [32].

observation, an increase in the solution conductivity brings about a substantial decrease in the nanofiber diameter; and also, evidently the radius of the nanofiber jet is inversely related to the cube root of the electrical conductivity of the solution [7, 37, 38].

The conductivity of a given cell has a connection with the molar conductivity following Eq. (6) [39], where k is the conductivity with units of mS/cm, c is the ion concentration with units of mol/L and therefore, the molar conductivity (Λ) has units of S cm²/mol.

$$\Lambda = \frac{k}{c} \quad (6)$$

Chitral and Shesha [40] had published the results of a comprehensive investigation of the effects of change in the conductivity of polyethylene oxide (PEO)/water solution on the electrospinning process and fibre morphology. The effects of the conductivity of PEO solution on the jet current and jet path were elaborated further, with the addition of NaCl to the solution results in the formation of protrusion on the fibre surface, as shown in **Figure 5**. The effects of the conductivity of polyethylene oxide (PEO) solution on the jet current and jet path were also considered.

Zong and colleagues [37] had done a study to see the effect of adding varying kinds of salts to poly(L-lactic acid) (PLLA) solutions in electrospinning. KH_2PO_4 , NaH_2PO_4 and NaCl were studied, and each was added in separation at 1% W/V to PLLA solutions. The resulting electrospun nanofibers were smooth, bead-free and they also had smaller diameters than those of the nanofibers electrospun from solutions that did not have a salt. While KH_2PO_4^- which contains solutions produced nanofibers with the largest diameter, those containing NaCl

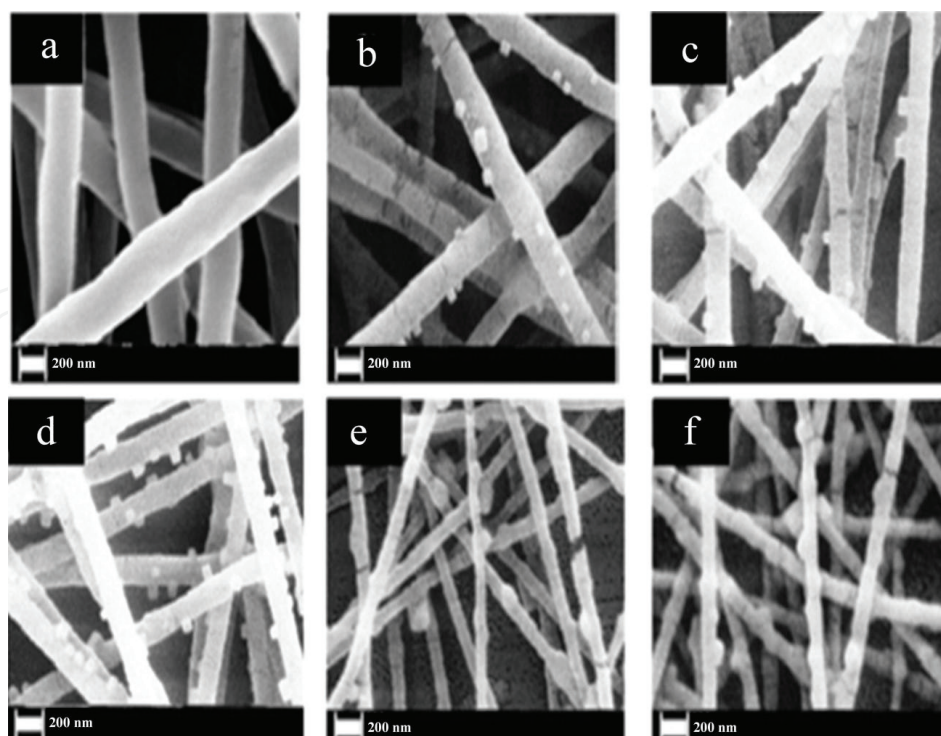


Figure 5. FESEM images of samples of electrospinning PEO/NaCl fibres for a range of conductivities. (a) 5 g/0 g, (b) 5 g/0.1 g, (c) 5 g/0.2 g, (d) 5 g/0.5 g, (e) 5 g/1.25 g, and (f) 5 g/2 g [40].

produced nanofibers with the smallest diameter. The ion size was also found to ascertain the nanofiber diameter. Ions with smaller radii had higher charge density, and thus they gave greater forces of elongation on the electrospun nanofibers [41].

4.1.3. Molecular weight

Molecular weight of the polymer also leaves a great effect on the morphologies of the electrospinning fibre. The entanglement of polymer chains in solutions, namely the solution viscosity, is principally a reflection of the molecular weight. Keeping the concentration fixed, and lowering the molecular weight of the polymer have the ability to form beads instead of the smooth fibre. Smooth fibre will be obtained by increasing the molecular weight. What is also worth noting is that too high molecular weight favours micro-ribbon formation even with low concentration [42, 43]. Çiğdem A et al. [44] studied the impact of the molecular weight (MW) on the fibre structure of electrospun poly(vinylalcohol) (PVA) which has molecular weights that range from 89000 to 186,000 g/mol when dissolved in water, as can be seen in **Figure 6**.

4.1.4. Surface tension

As the function of solvent compositions of the solution, surface tension is an important factor in electrospinning. Yang et al. [45] conducted a study on the influence of surface tensions on the morphologies of electrospun products with PVP as model with ethanol, N,N-dimethylformamide (DMF) and dichloromethane (MC) as solvents. In the process, it was discovered that different solutions may contribute different surface tensions. With the concentration fixed, and the surface tension of the solution, reduced beaded fibres can be converted into smooth fibres.

4.1.5. Solvent selection

For a particular polymer to solubilise and be transformed into nanofibers via the process of electrospinning, the choice of solvent is very important. The solubility of the polymer in the solvent and the boiling point of the solvent, which altogether indicate its volatility, are two major aspects worth considering when it comes to choosing a solvent. Volatile solvents are

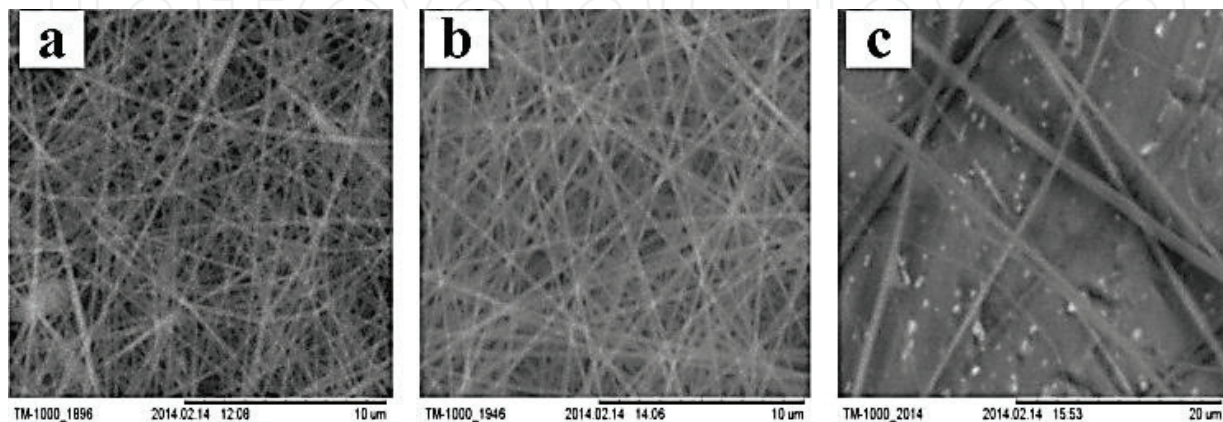


Figure 6. FESEM showing the typical structure in the electrospun PVA polymer for various molecular weights. (a) 89000–98,000 g/mol; (b) ~ 125,000 g/mol; and (c) 146,000–186,000 g/mol (solution concentration: 25 wt.%) [44].

the more favourable choice as they assist the dehydration of the nanofibers during trajectory from the capillary tip to the collector surface, because of their lower boiling point, and thus causing a rapid evaporation rate. Nonetheless, highly volatile solvents that have very low boiling points should be prevented as they may evaporate at the capillary tip and further leading to the clogging and the obstruction of the flow-rate of the polymer solution. Solvents that have high boiling points may not dehydrate entirely before reaching the collector, thus resulting in ribbon-like, flat, nanofiber morphologies or conglutination of nanofibers at the boundaries [36, 46]. The ability of the electrospinning polyvinylpyrrolidone (PVP) by Yang and Coworkers [45], was investigated with different solvents. The solvents examined were MC, ethanol and DMF, while the beaded nanofibers were formed from DCM and DMF solutions of PVP, the use of ethanol produced PVP nanofibers. Nanofibers electrospun from an integration of the ethanol and DMF had small diameters of 20 nm, while a combination of ethanol and DCM resulted in the formation of nanofibers with diameters as large as 300 nm (see **Figure 7**). It is therefore conclusive that nanofiber morphology and porosity may be regulated by the defensible use of solvents or a combination of solvents.

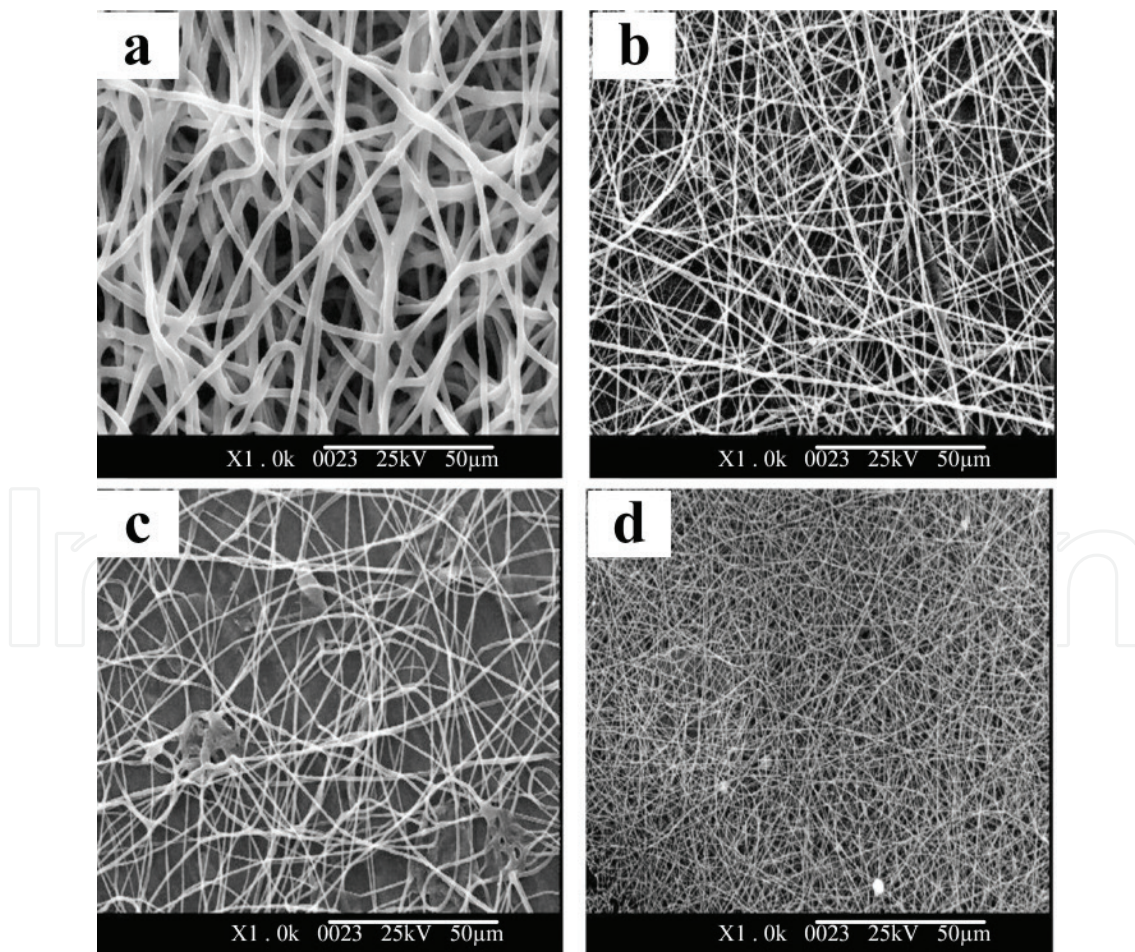


Figure 7. TEM images of PEO nanofibers electrospun different solvent. (a) chloroform (3%), (b) Ethanol (4%), (c) DMC (5%), (d) Water (7%) [47].

4.2. Electrospinning parameters

4.2.1. Voltage supply

The amount of charge per unit surface area of the polymer droplet which constitutes charge density is determined by the applied voltage, working distance and the conductivity of the polymer solution. Applied voltage is used to provide the driving force to spin fibres by imparting charge to the polymer droplet. The working distance which is the distance between the tip of syringe and the collecting plate, in addition to the applied voltage, can influence the structural morphology of nanofibers. Demir et al. [35] suggested that when higher voltages are applied, more polymer is ejected to form a larger diameter fibre. Similarly, high voltage conditions also created a rougher fibre structure. To reduce bead formation, Zong et al. [37] proposed an approach to increase charge density on the surface of the droplet by adding salt particles. However, they concluded that high-charge density produced thinner fibres, a finding not corroborated by Demir et al. [35]. The study by Pham et al. [23] shows that in the state of low voltages or field strengths, typically, a drop is suspended at the needle tip, and a jet will originate from the Taylor cone producing bead-free spinning (under the assumption that the force of the electric field is sufficient to address the surface tension). Hao Shao et al. [48] studied the effect of high voltage, and observed change in the morphology as a result of change in high voltage as shown in **Figure 8**.

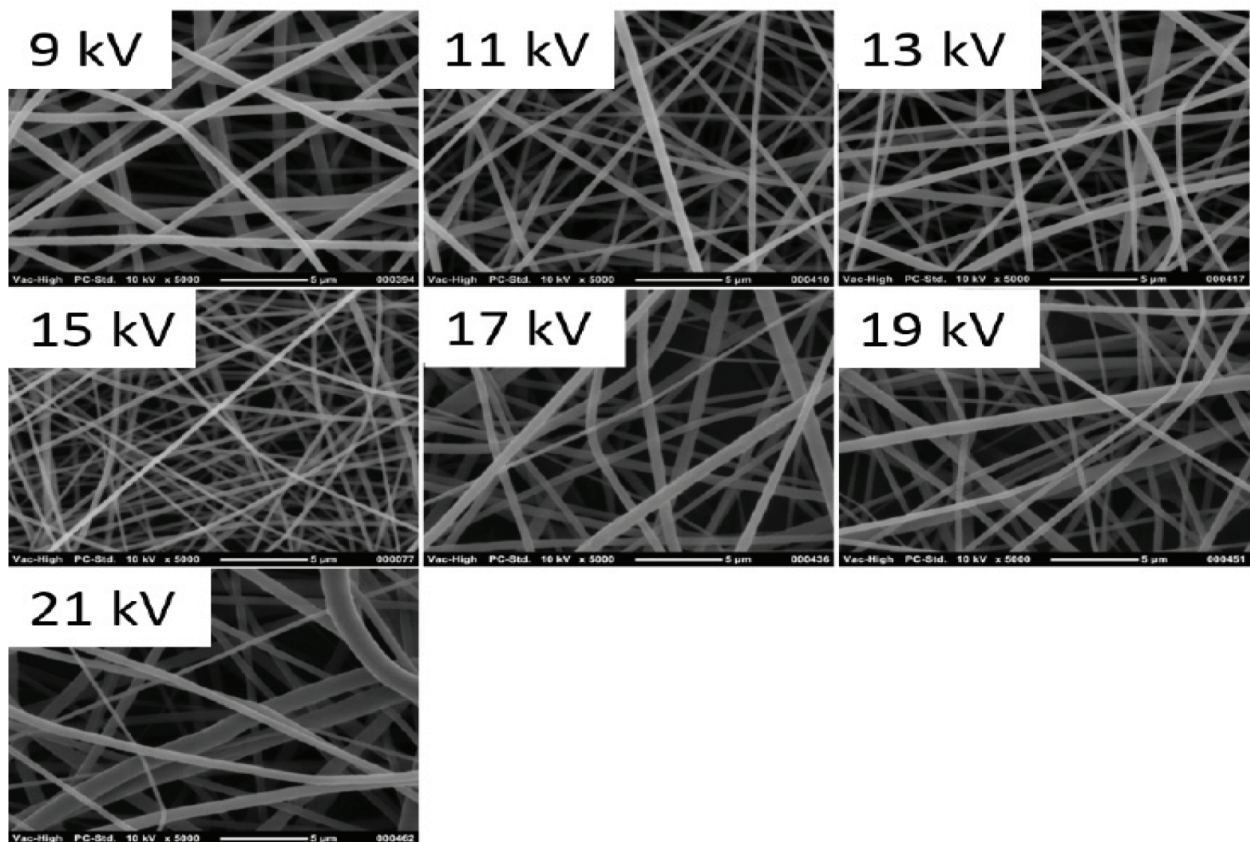


Figure 8. SEM images of the PVDF nanofibers prepared at different applied voltages [48].

4.2.2. Needle diameter (nozzle)

The size of needle has a certain effect on the nanofibers diameters. It was discovered that a reduction in the diameters of the electrospun nanofibers was caused by a decrease in the internal diameter of the needle. The nozzle (usually the syringe needle set up) determines the amount of polymer melt that comes out, which, in turn, affects the size of the drop being formed and also the pressure or the amount of force required by the pump to push the melt out. If the polymer melt is less viscous, it can easily flow out of the nozzle. The polymer melt is usually a thick highly viscous fluid. So, if the nozzle is too small, and the melt is too viscous, the melt cannot be forced out. Therefore, an appropriate nozzle should be used. Different types of nozzles or spinnerets have been used over the years [49]. The effect of needle diameters on the resulting electrospun poly(methyl methacrylate) (PMMA) average nanofiber diameters was evaluated for three different needle gauges by Javier Macossay et al. [49]. These fibres presented regular surface morphologies, with a few nanofiber bundles being evident in **Figure 9**.

4.2.3. Distance between tip and collector

The distance from the needle to the collector is very important, because by decreasing it, the electrical field increases instead; and also the stretching force does and the time at which the fibre undergoes the field is lower, causing sufficient evaporation of the solvent of the fibres. The result is that when there is reduction in the distance between the needle and the collector the fibres grow and may be subject to structural deformities like blobs. The high voltage was determined at 15 kV and the distance from the tip of the needle to the collector is in the range from 9 cm to 21 cm. The fibres' morphology was assessed from the SEM images of **Figure 10**; for the shortest distance (9 cm), the fibres came together at their intersections following the incomplete evaporation of the solvent before the jet arrived at the collector. For the other four distances used, the fibres appeared similar and the mean fibre diameter increased a little with the distance to the collector. The distance established between the tip and the collector exerted a direct influence in flight time and electric field strength. For the fibres to form, the electrospinning jet must be given ample time for most of the solvents to be evaporated. The electric field strength will increase at the same time and this will increase the acceleration of

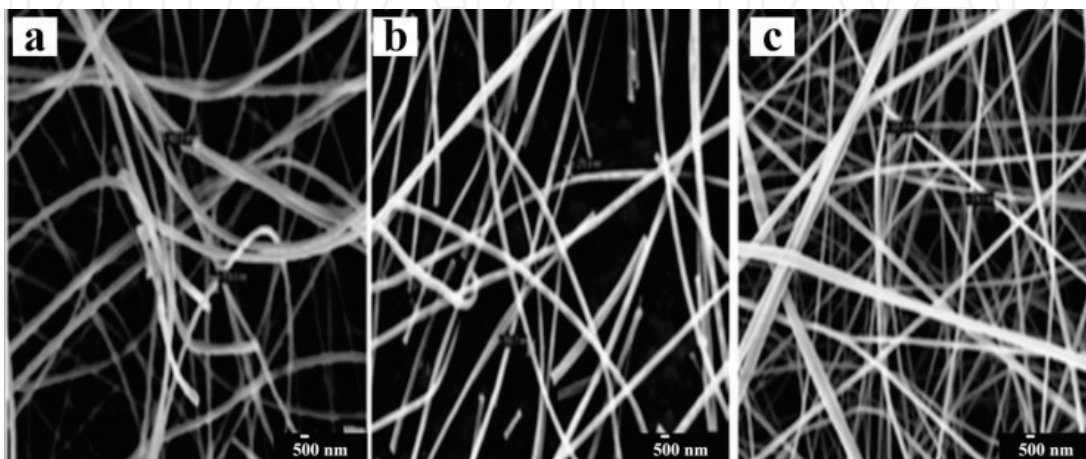


Figure 9. SEM of PMMA nanofibers, utilizing internal diameter needle. (a) 0.83 mm, (b) a 0.4 mm, (c) a 0.1 mm [49].

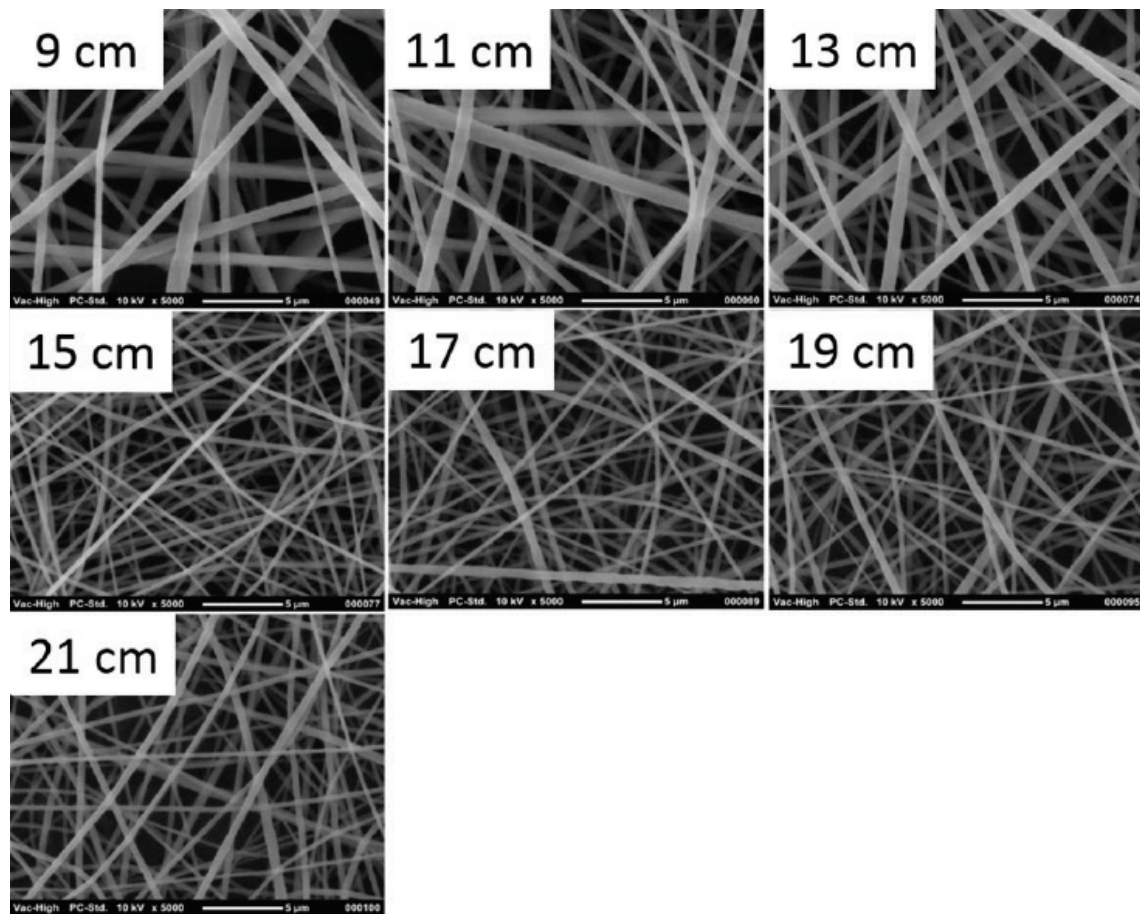


Figure 10. SEM images of the PVDF nanofibers prepared at different spinning distances [48].

the jet to the collector. As a result, there may not be enough time for solvents to evaporate when they reach the collector.

4.2.4. Flow rate

Another important parameter process is the flow rate of the polymer solution within the syringe. For the polymer solution to have enough time for polarization, lower flow rate is more preferred. If the flow rate is very high, bead fibres with thick diameter will form instead of smooth fibres with thin diameters owing to the short drying time before reaching the collector, and also due to low stretching forces. There is a corresponding rise in the fiber diameter or blobs size, as a result of greater volume of solution ejected from the needle tip, when there is increase in the feed rate. As shown in **Figure 11**, Shamim Z et al. [50] indicated that when the flow rate is decreased with other parameters kept constant; there is a decrease in the blobs size and an increase in nanofiber diameter. The inference here is that, with the decrease in flow rate, blobs size could get smaller until the non-beaded structure is obtained.

4.2.5. Collector

The formation of nanofibers can be classified into woven and non-woven nanofibers. The type of collector used plays a big role in differentiating the type or nanofiber alignments. The use

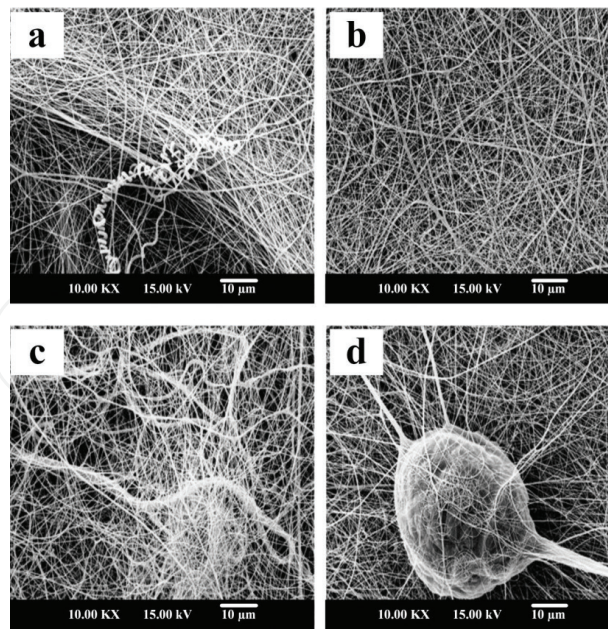


Figure 11. SEM images of PVA different flow rate. (a) 0.1 ml/h, (b) 0.5 ml/h, (c) 1 ml/h, (d) 1.5 ml/h [51].

of oriented collector, as well as static double grounded collector [2], constitutes the methods adopted in developing aligned woven nanofibers. The rotating drum collector is used for collecting the aligned arrays nanofibers, while the rotating disk is used for collecting uniaxially aligned nanofibers. The alignment fibres obtained from the rotating drum correspond to the rotational speed applied on the drum [2]. This type of electrospinning method is more complex because the speed of the rotation needs to be very properly controlled to produce nanofibers with such a good alignment. The rotating disk collector can also serve to collect continuous nanofibers, since they can very much attract the large electrical field applied at the edge of the disk [2].

As seen in **Figure 12**, SEM images of diverse collectors for many reports, have been developed including the wire mesh studied by Wang X et al. [52], pin studied by Sundaray B et al. [53], grids studied by Li D et al. [54], parallel or gridded bar and rotating rods or wheel studied by Xu CY et al. [55], and liquid bath studied by Ki CS et al. [56]. Kim et al. [57] proved that the different types of composition used in the collector affected the structure of the poly (L-lactide) (PLLA) and poly (lactide-co-glycolide) (PLA₅₀GA₅₀) fibres.

4.3. Ambient parameters

Fibre diameters and morphologies such as humidity and temperature could also be affected by ambient parameters. Increasing temperature, as noted by Mituppatham et al. [58] for instance, favours the thinner fibre diameter with polyamide-6 fibres for the inverse relationship between the solution viscosity and the temperature, as shown in **Figure 13**. With regards to humidity, low humidity could dry the solvent totally and increase the velocity of the solvent evaporation. On the contrary, high humidity will lead to thick

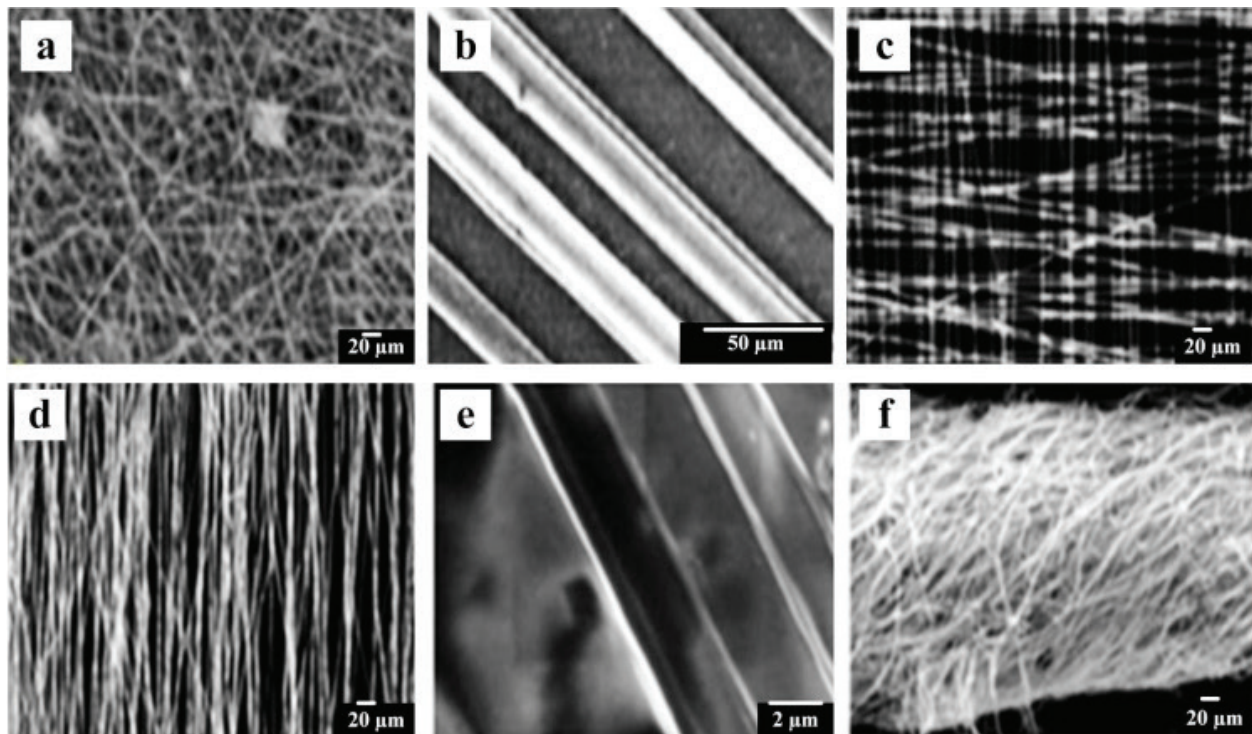


Figure 12. SEM images of the different electrospun products with various types of collectors. (a) Wire Screen, (b) Pin, (c) Gridded Bar, (d) Parallel Bar, (e) Rotating Wheel, and (f) Liquid Bath [52–56].

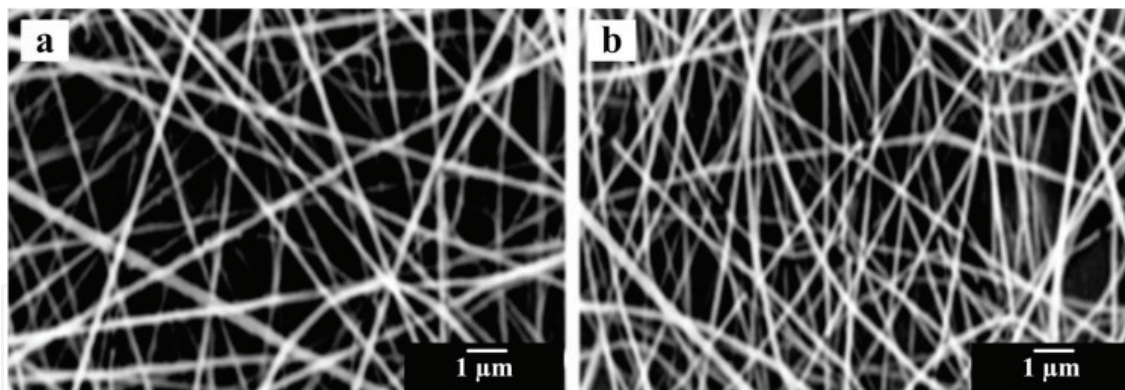


Figure 13. SEM images of the electrospun PA-6-32 fibers under different temperatures. (a) 30° and (b) 60° [58].

fibre diameter because the charges on the jet can be neutralised and the stretching forces become small.

The variety of humidity can also affect the surface morphologies of electrospun PS fibres, as recently show by Casper et al. [59]. Nezarati et al. [60] observed that low humidity (5% RH) resulted in beads connected by thin fibres, but increasing the RH (20–75% RH) resulted in smooth, uniform fibres for poly(ethylene glycol) (PEG). In addition as relative humidity was increased from 50–75%, fibre density decreased, see (Figure 14).

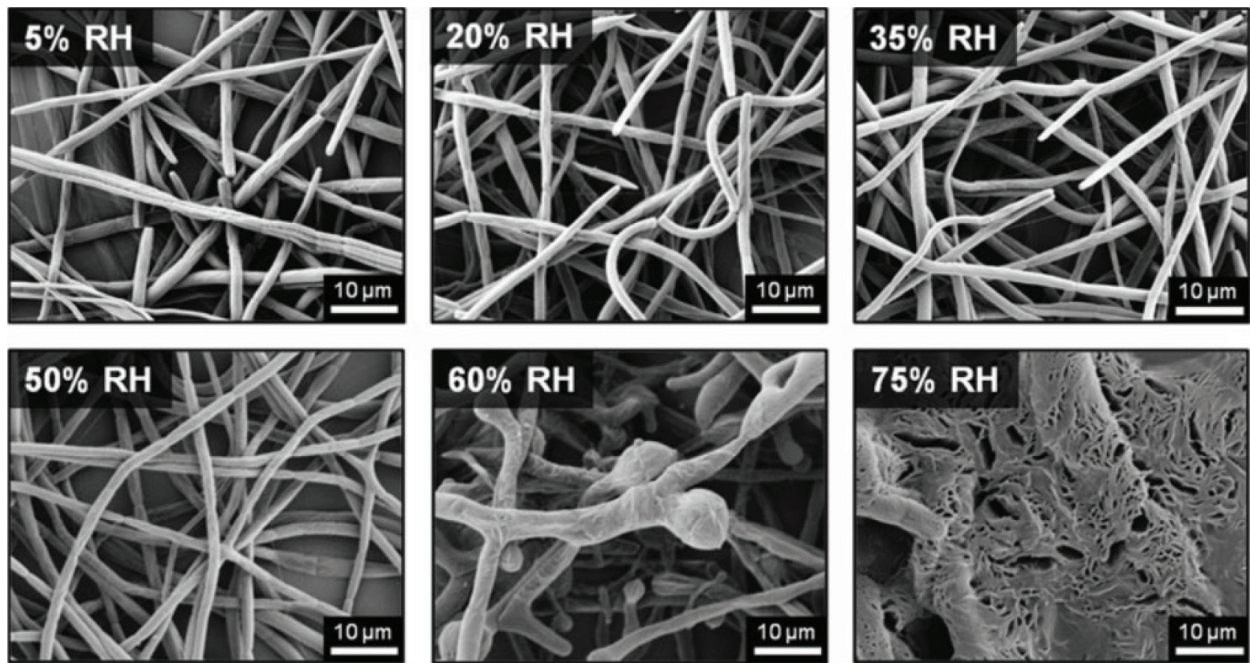


Figure 14. SEM images of poly(ethylene glycol) (PEG) electrospun at relative humidity (RH) ranging from 5 to 75% [60].

5. Conclusions

In this chapter, nanofibers are successfully grown using the electrospinning method at different parameters. These nanofibers, fabricated on several substrates, were investigated using FESEM, observations revealed the formation of nanofibers. Effect of the parameters on the morphology and the diameter was shown. The optimal condition was selected to study the effects of parameters on surface morphology and diameter through the study of characterisation of semiconductor/polymer NFs through the above observations and structural. The semiconductor/polymer nanofibers thin films have offered interesting due to having multi-applications. The sensor, solar cell, supercapacitors, drug delivered, filtering, and more of that its success through been fabricated nanofibers using electrospinning. The electrospinning will not use for fabricating nanofibers only in future work, however, will expand to produce other nanostructures such as nanorods, due to the electronic process has the ability to control the parameters.

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