Chapter

Classification of Electrospinning Methods

Muhammad Waqas Munir and Usman Ali

Abstract

Electrospun nanofibers are being used in a variety of performance apparel applications where their unique properties add to their functionality. Those properties include, small fiber diameter, high surface area, potential to combine chemistry, layer thinness, high porosity, filtration properties, and low basis weight. Electrospinning has been considered as an efficient technique for nanofiber web formation. Polymers have been electrospun into nanofibers mostly after being dissolved in solvent and melted. This chapter presents a comprehensive summary of existing electrospinning methods. Electrospinning methods are classified into different categories depend upon jet formation.

Keywords: electrospinning, spinneret, needleless electrospinning, nanofiber

1. Introduction

Nanotechnology denotes to the science and designing concerning materials, structures, and gadgets which at least one of the dimension is 100 nm or less. Electrospun nanofiber webs can be modified to a desired porous structure, and in these are a huge range of polymers that can be used to make nanofibers [1]. The unique combination of high surface area, low weight, flexibility, and porous structure enables us to control the water resistance level, vapor transmission, and air permeability rate. Consumption of nanofibers in the world is shown in **Figure 1**. Applications of electrospun nanofibers, as shown in **Figure 2**, include tissue engineering scaffolds [2], filtration [3], catalyst and enzyme carriers [4, 5], release control [6], sensors [7], energy storage [8], affinity membranes [9], recovery of metal ions [10–12], wound healing [13], reinforcement [14], protective clothing [15, 16], and energy conversion and storage [17].

1.1 Various ways to make nanofibers

Nanofibers can be processed by a number of techniques such as:

1. Drawing

2. Template synthesis

3. Phase separation

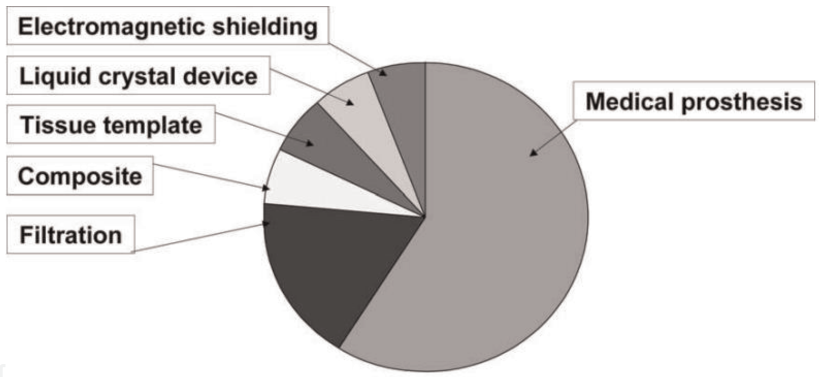


Figure 1.
Consumptions of nanofibers in world [18].

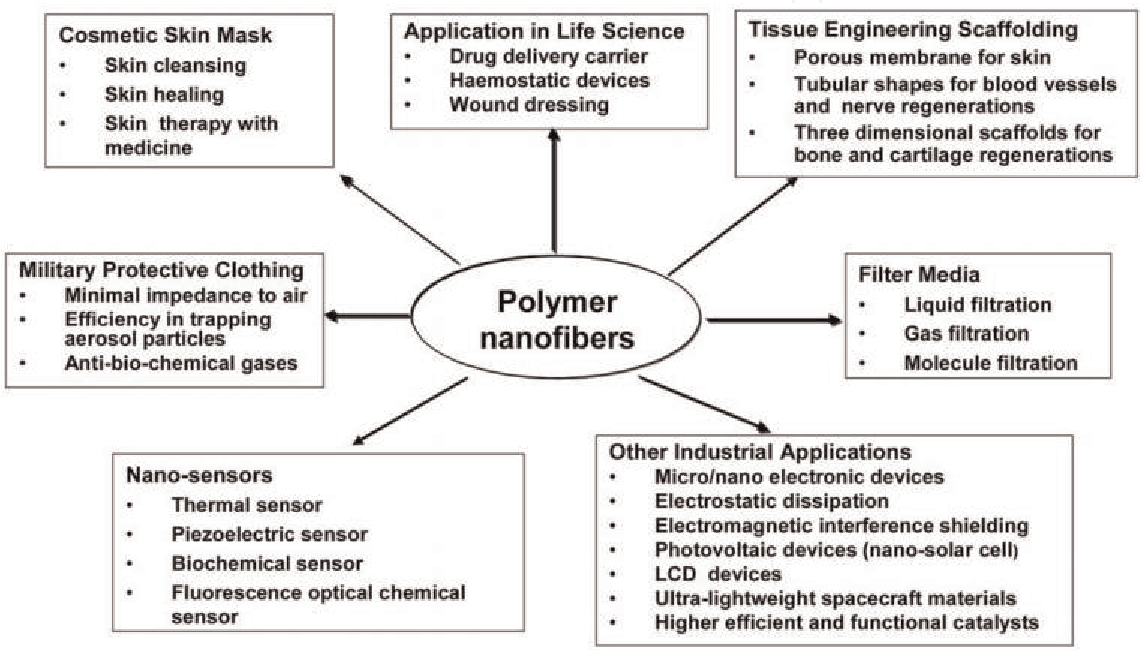


Figure 2.
Potential applications electrospun nanofibers [18].

4. Self-assembly

5. Electrospinning

Commonly nanofiber fabrication is done by electrospinning method [19].

1.1.1 Drawing

In drawing process, single nanofiber is attended by stretching of polymer that is in solution form. With this method only viscoelastic materials have been spun into nanofibers. If polymer is in melt form, then cooling system is necessary to solidify the fiber. On the other hand, if polymer is in solution form, then heating mechanism is necessary to evaporate the solvent. This is a very slow process that is suitable only for lab scale [18]. Process diagram is shown in **Figure 3**.

1.1.2 Template synthesis

In this method, nonporous membranes are used in which pores are in cylindrical form. Diameters of these pores are uniform. Solid polymers are formed

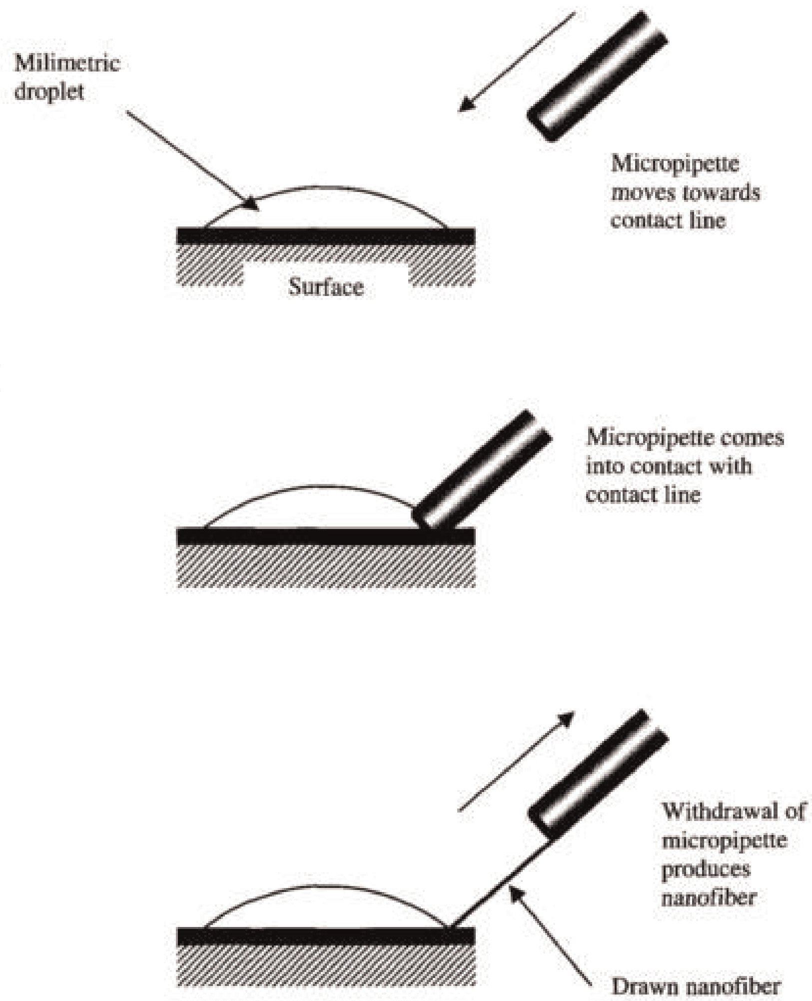


Figure 3.
Drawing in method [19].

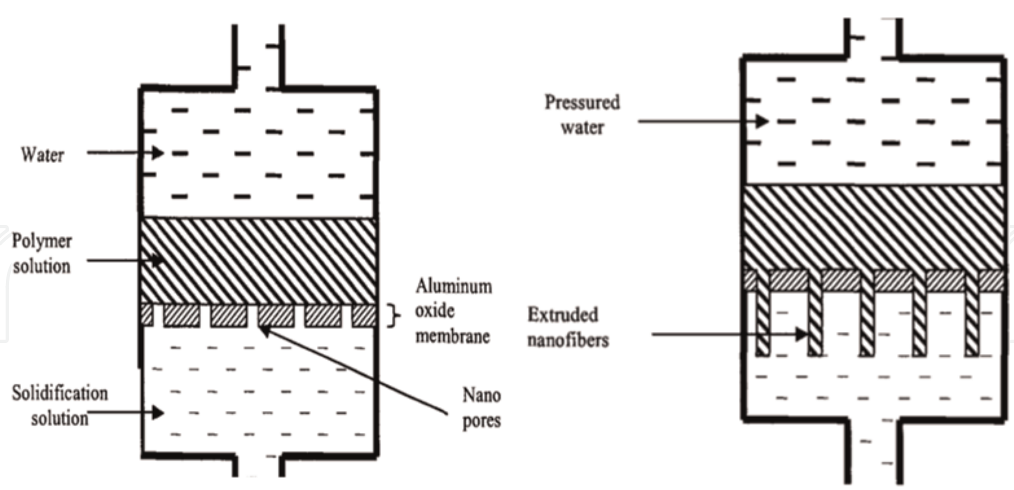


Figure 4.
Temple synthesis [20].

that have diameter equal to size of porous [20]. The process diagram is shown in **Figure 4**.

1.1.3 Phase separation

In this process, five steps are involved: polymer dissolution, polymer gelation, extraction of solvent, freezing, and freeze-drying. Fiber dimensions are not controllable with this process. This proves only suitable for lab scale [21]. The process diagram is shown in **Figure 5**.

1.1.4 Self-assembly

Peptide nanofibers are produced from self-assembly process. This is a very complex process that is only suitable of lab-scale nanofiber production [22]. This is shown in **Figure 6**.

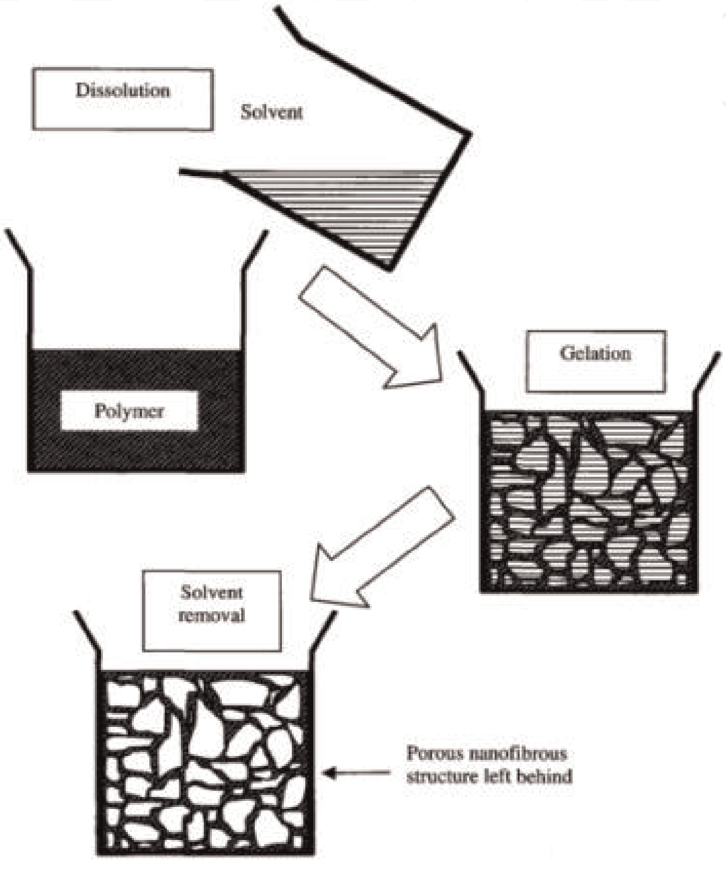


Figure 5.
Phase separation [21].

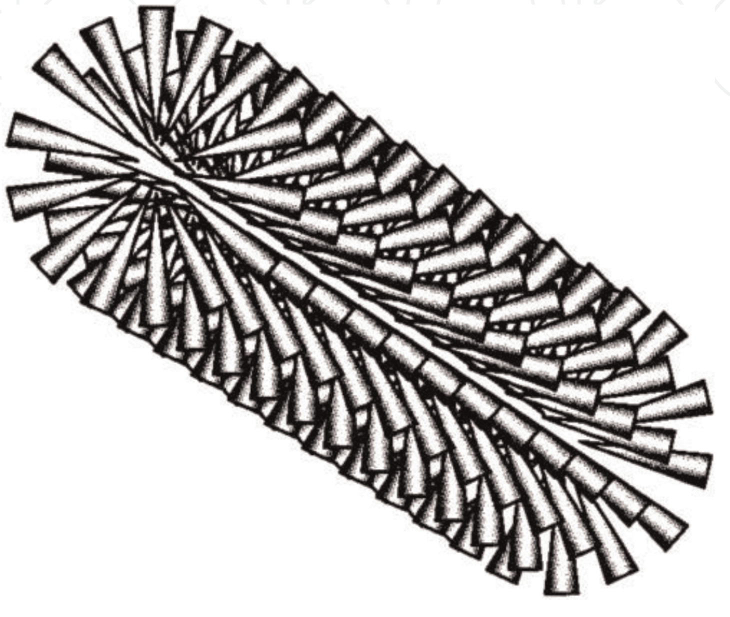


Figure 6.
Self-assembly [22].

1.1.5 Electrospinning

Instruments used for electrospinning are given below:

1. High-voltage DC power supply

2. Syringe pump

3. Spinneret (a small diameter needle connected to the syringe)

4. Metal collector

The polymer is dissolved in a solvent before electrospinning, and when it is completely dissolved, it forms polymer solution. The polymer fluid is then introduced into the syringe tube for electrospinning. The positive terminal of the DC power supply is connected to the hollow needle [23], and the negative terminal is connected to the metal collector. With the increase of intensity of the electric field, the repulsive electrostatic force overcomes the surface tension, and the charged jet of the fluid is ejected from the tip of the Taylor cone. The discharged polymer jet undergoes an instability and elongation process, which allows the polymer in the jet to become very long and reduces the diameter of the extruded polymer fiber. The solvent that is used to dissolve the polymer evaporates, and the polymer in the jet is dried. The solvent evaporation depends on the distance between the tip and collector, the solution vapor pressure, and the inside chamber temperature. Stable environmental conditions are therefore important in getting good quality nanofibers. The maximum applied voltage for a needle electrospinning setup is normally less than 30 kV and is also highly humidity dependent [24]. **Figure 7** illustrates the schematic diagram of the complete electrospinning setup.

Needleless electrospinning presented as an option electrospinning innovation that deliver nanofibers on a substantial scale. Needleless electrospinning is included as electrospinning of nanofibers straightforwardly from an open fluid surface. Many planes are shaped at the same time from the needleless fiber generator (spinneret) without the impact of capillary effect that is regularly connected with needle electrospinning. Since the fly start in needleless electrospinning is a self-composed process which happens on a free fluid surface, the spinning process is hard to control. In needleless electrospinning process, many shapes of spinneret

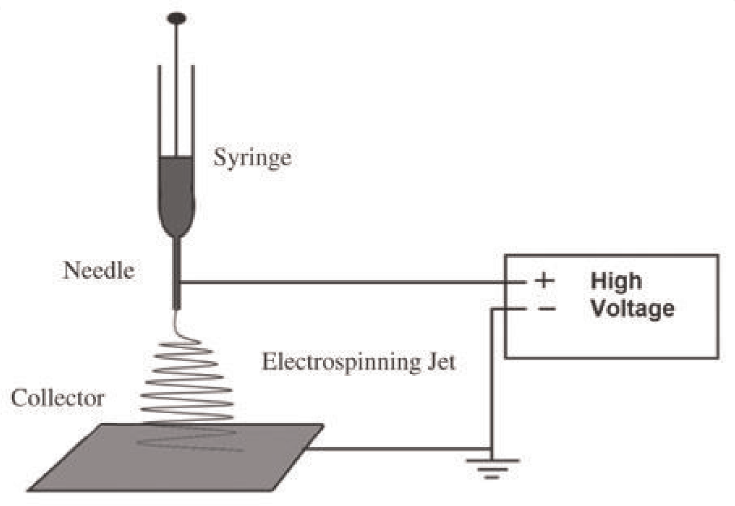


Figure 7.
Needle electrospinning.

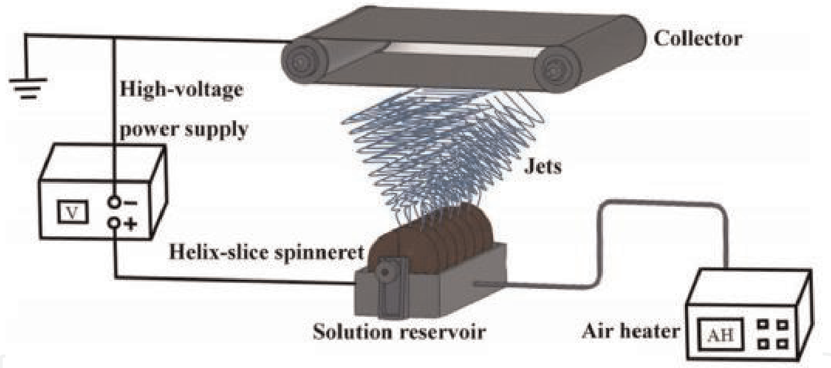


Figure 8.
Needleless electrospinning [33].

have been invented that have different levels of production. **Figure 8** illustrates a schematic diagram of the complete needleless electrospinning setup.

One of the problems also created with needle electrospinning method is low production rate that is typically less than 0.3 g/h [25]. With needleless electrospinning method, production of nanofibers is 250 times [26] more than needle electrospinning. Production depends upon the shape of spinneret used in needleless electrospinning. With different shapes of spinnerets, production rates of 2.5–100 g/h can be achieved.

Different needleless setups, like conical wire coil electrospinning spinneret [25], edge-plate electrospinning setup [27], splashing electrospinning setup [28], rotary cone [29], roller electrospinning process [30], cylinder [31], disk [32], and spiral coil electrospinning processes [33], were made for large-scale production of nanofibers. In all these needleless setups, the spinneret shape is different. Due to this variation in spinneret shape, nanofiber production rate and fiber morphology is different.

1.2 Production of nanofibers

Based on the jet formation and the way of using the needles, electrospinning methods can be classified as:

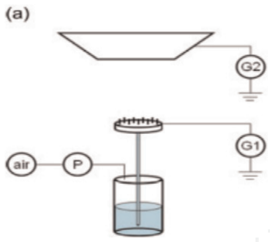
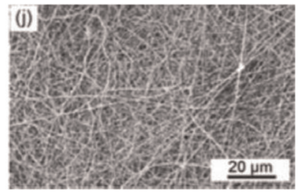
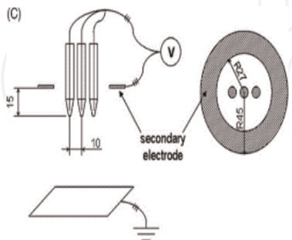
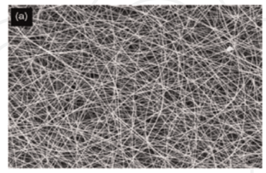
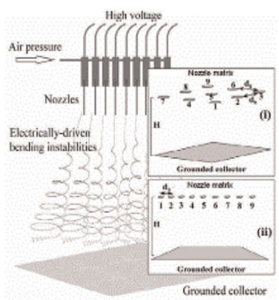
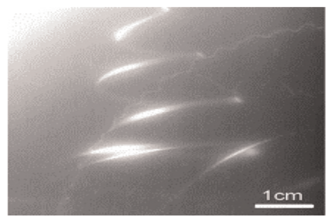
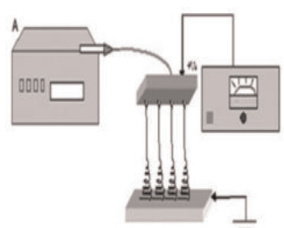
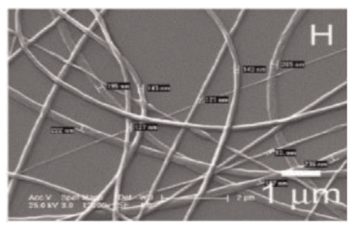
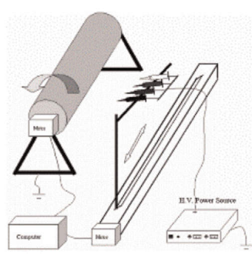
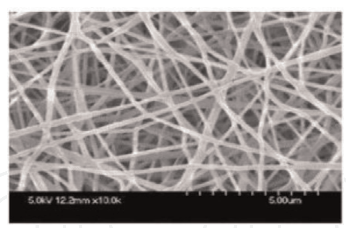
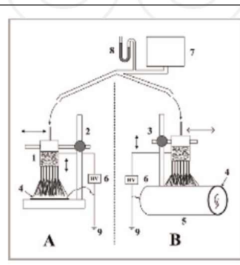
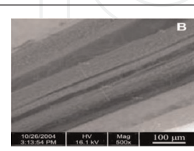
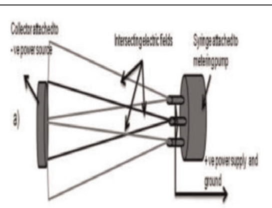
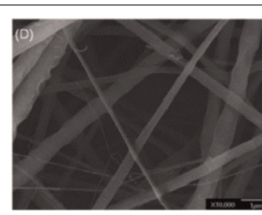
- Multi-jet electrospinning methods
- Multi-needle electrospinning methods
- Needleless electrospinning methods

1.2.1 Multi-jet electrospinning methods

In this electrospinning method, multi-jets were used for nanofiber formation. Production of nanofiber increased as compared to needle spinning. Due to multi-jets, uniform web of nanofiber is not formed; this is due to repletion effect between jets. Some multi-jet electrospinning methods are given in **Table 1**.

1.2.2 Multi-needle electrospinning methods

In multi-needle electrospinning method, a number of needles are used as spinnerets that contain one or different types of polymer solutions. High voltage is

Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2010	Varesano et al.			Ethylene oxide polymer solution was used for nanofiber. Feeding of solution to each nozzle is done at flow rate of about 0.45 g/h
B. 2009	Varesano et al.			Polyethylene oxide solution was made in water with ratio 93:7. Flow rate of polymer solution form nozzle tip is 1 ml/h
C. 2005	Theron et al.			Polyethylene oxide was used to prepare solution for working fluid in this needless setup. The production rate was in the range of 22.5 ml/(cm^2 min) to 22.5 ml/(cm^2 min) per 1 cm^2 of the spinneret plate
D. 2007	Yasmin et al.			Polyvinylpyrrolidone and polypyrrole polymers are used in this experiment. Production of 8-spinneret device is 0.1 g/h
E. 2004	Ding et al.			PVA and cellulose acetate (CA) polymers are used with concentration 10%. Throughput (mg/min jet) PVA solution is 1.9, while CA solution is 2.3
F. 2005	Tomaszewski et al.			PVA was used in this experiment; its concentration was 15 wt%. With elliptic head production is 11 +/− 3 g per min; with concentric head dry nanofiber production is 12+/− 3 g
G. 2010	Kumar et al.			12 wt% of polyethylene oxide was used in this experiment. With 3 jets, production is 0.3 ml/min; with 7 jets, it is 0.45 ml/min

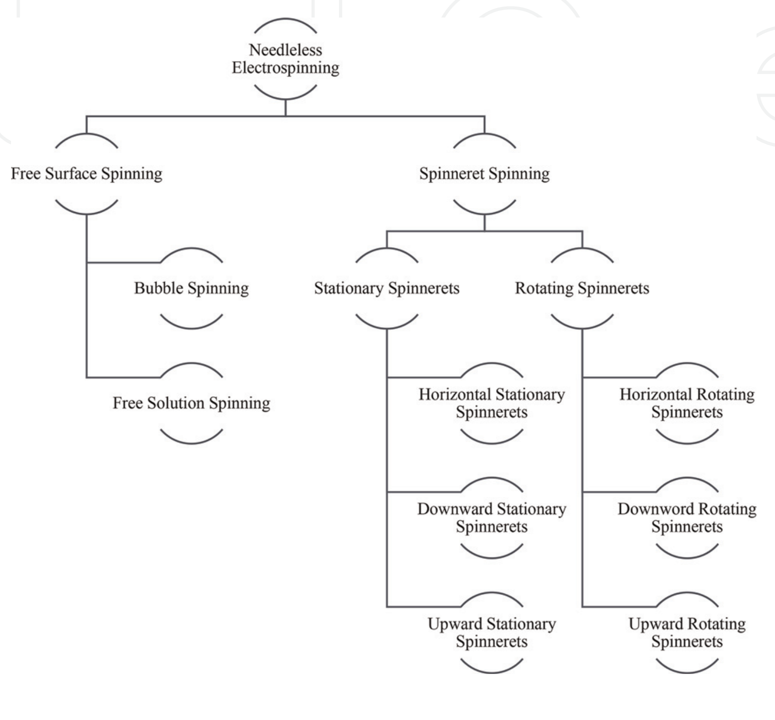
A. In this multi-jet electrospinning setup, a pilot plan was used that consist of spinning head. On this spinning head, nine plastic nozzles are deposited in two rows; each nozzle's internal diameter was 0.43 mm. These nozzles are 2 cm away from each other. The polymer solution was provided to the nozzles at spinning head at 0.2 bar; flow rate of solution was about 0.45 g/h. Nanofibers were collected on the nonwoven substrate. Nanofibers were collected that form nine spots on collector, uniform web not formed [34].
B. High-voltage power supply is attached in multi-jet setup; solution is filled in the tube that ejects downward by gravity flow at the rate of 1 ml/h from plastic tip that have orifice diameter of 750 mm. Tests demonstrated that the disparity angles between polymer jets can be lessened by utilizing an auxiliary electrode. Jets used in this setup are 2–16 that have different arrangements [1].
C. This work portrays the consequences of the test examination and modeling of multi-jet amid the electrospinning of polymer solution. The outcomes exhibit how the outside electric fields and shared electric collaboration of various charged jets impact their way and advancement among electrospinning. In this multi-jet electrospinning setup, nine syringes were arranged, and polymer solution was placed identical in all syringes. When electric field is applied to syringes, nanofibers were produced that collected on metal collector. It is observed that nanofibers are collected at nine spots that show repletion effect in multi-jet electrospinning process [35].
D. This setup was the same as conventional needle electrospinning, only microfluidic device was used instead of syringes. The polymer solution was constantly fed through the microfluidic gadget utilizing a syringe pump. High voltage 10–15 kV was applied with spinning distance of 10 cm. It was shown that the morphology and measurement of the nanofibers can be altered by modifying the polymer focus, surface strain, salt, quality of the potential, and nourish rate [36].
E. In this multi-jet electrospinning setup, polymers (PVA and cellulose acetate (CA)) were physically blended with each other. This setup contained four syringes placed on the setup which moved along the track. Distance between the tips of syringes was 3 cm and rotating collector was used. The speed of the rotatable tubular layer and the mobile stand can be controlled by PC. The PVA and CA arrangements were set in various syringes as indicated by the necessity. The consistent nanofiber mats were gathered on the surface of foil and dried at 80°C in vacuum for 24 h [37].
F. The electrospinning testing done with three sorts of electrospinning heads, series, elliptic, and concentric, demonstrated that the last two enabled the procedure to continue on the premise of minimal multi-jet frameworks utilizing at least 10 turning channels. The concentric electrospinning head, which turned out best as to both the effectiveness and the nature of the procedure, can deliver 1 mg of dry PVA nanofibers from one turning channel amid 1 min [38].
G. The attention was on investigating the fiber repulsion in multi-jet electrospinning. The utilization of multi-jet was hazardous because of fiber repulsion. In this multi-jet setup, a novel spinneret was used to make nanofiber, and increment in the yield has been illustrated. A plastic channel plan with numerous pores exhibited decreased fiber repulsion. This novel plastic channel setup yielded strands with more steady and smaller diameter fibers than with multi-needle electrospinning [39].

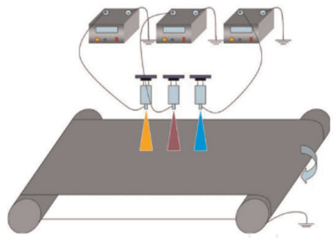
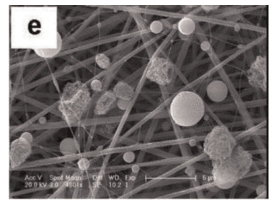
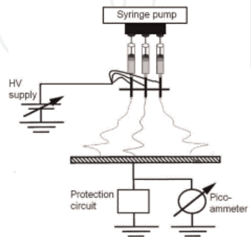
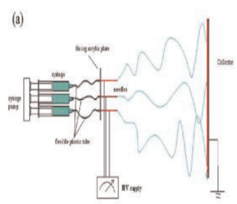
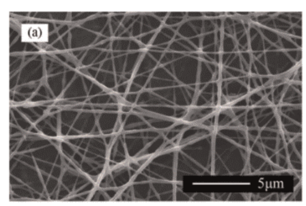
Table 1.
Multi-jet electrospinning methods.

applied to the tip of the needle and nanofibers are deposited on collector. The main advantage of multi-needle electrospinning is we can mix different polymers at our required ratio (**Table 2**).

1.2.3 Classification of electrospinning methods

It may be defined as the method in which fiber jets are produced or generated from the free surface of liquid. It can also be defined as the technique of producing the fibers from open liquid surface. Based on the fiber generating method, the motion of spinneret, and collection direction of fibers, the needleless electrospinning techniques can be classified as:



Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2014	Wang et al.			Polystyrene, polyvinylidene fluoride, and polyacrylonitrile solutions are used in this setup with concentrations of 4, 21, and 12% by weight, respectively
B. 2011	Angammana et al.			Aldrich polyethylene oxide was employed for preparation of solution; concentration of solution was 5% by weight. The solution was forced through syringe pump at the rate of 0.1 ml/min
C. 2012	Sheng Xie et al.			Polyoxyethylene solution concentration 7 wt % was used for experiments. All experiments were carried out at 22 kV voltage, 22 cm collecting distance, and 0.3 ml/h solution flow rate per needle

A. In this multi-needle electrospinning setup, three syringes were used that contain different polymers. Conveyor belt was used as collector. During electrospinning three types of fibers were mixed together very easily. During electrospinning repletion, polymer jets were observed that could be reduced by increasing distance between needle jets [40].
B. Three needles were used in this setup that are mounted vertically. Polymer solution was pumped through syringes at rate of 0.1 ml/min. The point of this paper is to research the electric field bending in various needles by utilizing limited component investigation and to decide its consequences for the electrospinning procedure. It can be presumed that as the quantity of needles in the course of action expands, the electric field at the tip of each needle diminishes essentially because of the impact of the encompassing needles in the needle arrangement [41].
C. In this multi-needle electrospinning setup, three needles were used, which are arranged in triangle. An auxiliary plate anode has been utilized to be associated with a three-needle framework to get a more uniform electric field. This electrospinning investigations and electric field reenactment exhibit that the multi-needle spinneret with an auxiliary plate can deliver better and more uniform nanofibers [42].

Table 2.
Multi-needle electrospinning methods.

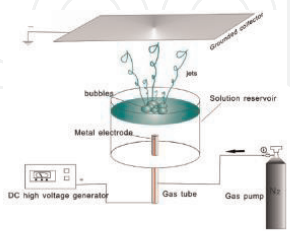
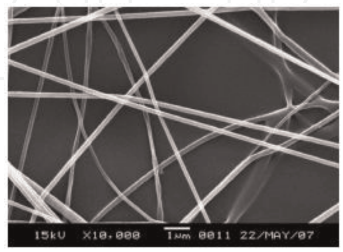
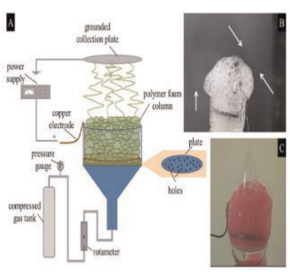
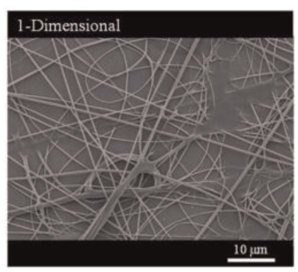
1.2.3.1 Free surface spinning method

1.2.3.1.1 Bubble spinning methods

In bubble spinning method, air is supplied from porous surface that is placed at the bottom of polymer solution. Bubble is made at the surface of polymer solution, and jet is formed at the charged surface of the bubble. Very fine nanofibers are deposited on collector that is placed at the top of the polymer container (**Table 3**).

1.2.3.1.2 Free solution spinning methods

In this electrospinning setup, two layers were used: the lower layer was ferromagnetic and the upper layer was polymer solution (**Table 4**). When electrospinning

Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2008	Ji-Huan et al.			Polyacrylonitrile (PAN) was dissolved in N,N-dimethylformamide (DMF) solvent, and the weight concentration was 12 wt%. Bubble electrospinning leads to different little rises on surface with little surface tension; minimum diameter achieved with this setup was 50 nm
B. 2014	Higham			Polyvinyl alcohol (PVA) was used as polymer. Production rate was 300 times more than syringe electrospinning

A. The polymer arrangement was filled; the supply and the stature of fluid surface were higher than that of electrode and tube. By turning on gradually the pneumatic weight control valve, we could discover a few air pockets created at the pinnacle of tube. The delivered air pockets will be broken down into smaller ones on the arrangement surface. At the point when surface strain of the little air pockets lessens to the basic esteem which can be overcome by the connected electric field, nano-planes discharge from the peak of the air pockets. Nanofibers that are produced from this method have very fine diameter of 50 nm [43].
B. This is a new method to produce nanofiber with a single bubble electrospinning process which is a concept based on keeping the bubble from bursting during electrospinning. Compress gas was supplied to porous surface. This porous surface was placed below the polymer solution. When gas was supplied to this surface, bubbles were produced that formed charged polymer jets [44].

Table 3.
Bubble electrospinning methods.

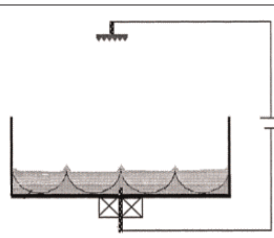
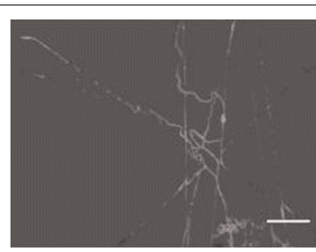
Year	Author	Setup	Morphology	Fiber bundling/polymer
A. 2004	Yarin et al.			Polyethylene oxide in water-ethanol mixture was used in this setup. Production is 12 times more than traditional needle electrospinning

Table 4.
Free solution electrospinning methods.

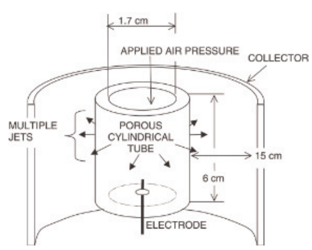
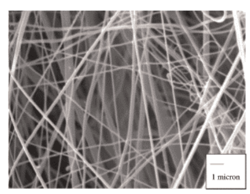
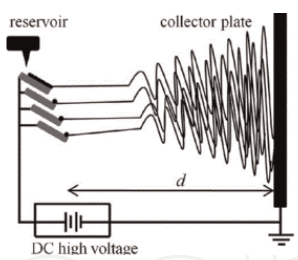
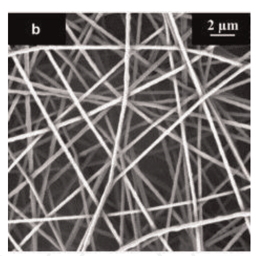
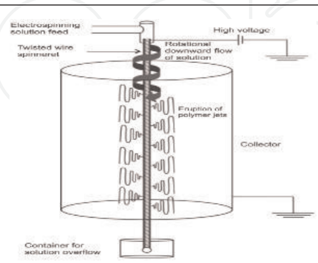
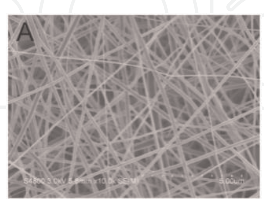
process was started, a customary electric field was utilized to the gadget; steady vertical spikes of attractive suspension were formed. When high voltage was applied, electrified jets undertake strong stretch by the electric field, solvent evaporates, and solidified nanofibers deposit on the upper counter electrode [45].

1.2.3.2 Spinneret spinning methods

1.2.3.2.1 Stationary spinnerets

In this needleless electrospinning method, stationary spinneret is used for nanofiber generation. High voltage is applied to spinneret, and there is special mechanism to feed polymer solution on spinneret. Polymer jets are formed on the edges of stationary spinneret that produce nanofibers. Stationary spinnerets are further classified into three categories depending upon the spinneret position:

Horizontal stationary spinnerets.
Downward stationary spinnerets.
Upward stationary spinnerets.

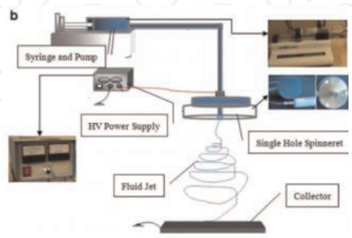
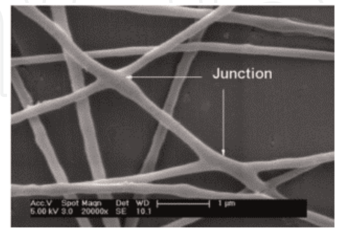
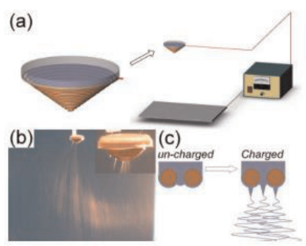
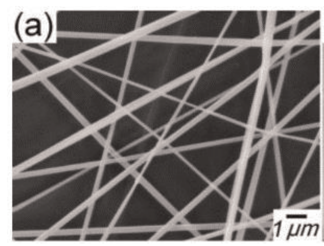
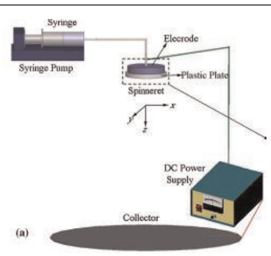
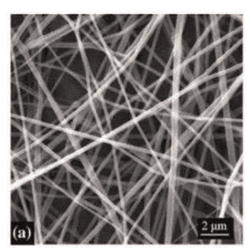
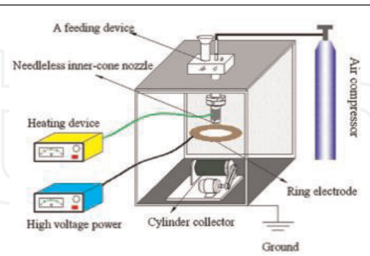
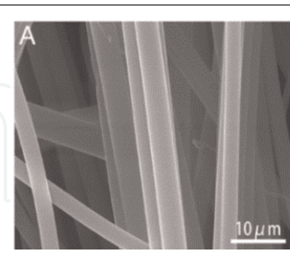
Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2006	Dosunmu et al.			Polyvinylpyrrolidone and nylon 6 were used in ceramic porous tube for this setup. Nanofibers were made at the rate of more than 5 g/h
B. 2010	Thoppey et al.			Polyethylene oxide in water at 6 wt% was used in this experiment. Fabrication rate is 0.11–0.27 g/h
C. 2014	Holopainen et al.			Polyvinylpyrrolidone, hydroxyapatite and bioglass were used as polymers. Production was 5.23 and 1.40 g h^{-1}, respectively

A. In this setup solid porous polyethylene tube was used as a spinneret that fixed vertically inside tube polymer solution was filled that ejected from outside pores by applying pressurized air that formed drops on the outer surface of tube wall. This porous tube was surrounded by circular wire mesh collector. When high voltage was applied, charged drops form nanofibers. When length of the tube increased, production of nanofibers increased by 4.2 g/min per meter length of tube [2].
B. The edge of a flat plate has been utilized as a spinneret onto which polymer solution was set as beads or experiences a gravity-helped stream. When high voltage was applied, nanofibers were ejected from the edge of plates. Collector was placed vertically at a working distance [27].
C. In this electrospinning setup, twisted wire was used that was placed vertically connected with high-voltage power supply. Cylindrical collector was used to collect nanofiber placed around the wire. Polymer solution was flowing downward on the twisted wire. Multi-jets were formed at the wire that produced nanofibers [46].

Table 5.
Horizontal stationary spinneret methods.

1.2.3.2.1.1 Horizontal stationary spinnerets

In horizontal stationary spinnerets, polymer jets are formed in horizontal direction. Nanofibers are collected on vertical mounted plates. Some of these are given in **Table 5**.

Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2009	Zhou et al.			Polyethylene oxide was used as polymer with water as a solvent. With four holes, production is 1.68 g/h with flow rate 28 ml/h
B. 2009	Wang Xin et al.			PVA solution was used, and production of dry nanofibers was found to be 0.86 and 2.75 g/h at 45 and 70 kV, respectively
C. 2013	Zheng et al.			Polyethylene oxide solution with water is used in this setup. Flow rate was 9.5 ml/h
D. 2014	Li et al.			Polypropylene was used that melted before electrospinning

A. In this electrospinning setup, a flat spinneret was connected to the positive point of high-voltage power supply. Polymer solution was pumped by syringe to the hollow cylindrical metallic cavity. There was a hole in the flat end surface where the solution was ejected and formed nanofibers. Nanofibers were collected on the sheet placed below [47].
B. In this novel electrospinning setup, a conical wire coil was used as spinneret. PVA solution was filled in this conical wire coil; when high voltage was applied to this cone, jets were produced from the surface of wire coil. Nanofibers were collected on the metal plate placed below the conical wire coil [25].
C. Multi-hole spinneret was used that contained electrode and thick plastic plate. This plastic plate has 19 holes which produce more uniform electric filed during electrospinning process. The polymer solution was placed between the plastic plate and electrode. Polymer was pumped by syringe. It was found that electric field lines play leading role in jet repulsion during nanofiber production [48].
D. Variable high-voltage power supply was used that is supplied to needleless inner-cone nozzle. Heating device was used to melt polypropylene, and a cylinder collector was used to collect nanofibers [49].

Table 6.
Downward stationary spinnerets methods.

1.2.3.2.1.2 Downward stationary spinnerets

In downward stationary spinnerets, nanofibers are made in downward direction. Polymer solution is placed in shower-like spinnerets, polymer jets are stretched downward due to high voltage, and nanofibers are collected on the plate that was placed in the bottom. Some of these types of spinnerets are described in **Table 6**.

1.2.3.2.1.3 Upward stationary spinnerets methods

In this needleless electrospinning setup, a novel spinneret was used that have a stepped pyramid shape (**Table 7**). When electric field was applied to the system, then nanofibers were generated from the edges of stepped pyramid-shaped spinneret. These nanofibers were collected on the collector that was negatively charged, placed at the top of the spinneret. Nanofiber production increased by increasing applied voltage and keeping working distance and concentration of polymer solution constant [50].

1.2.3.2.2 Rotating spinnerets

In this needleless electrospinning method, the spinneret is rotated in polymer solution that licks polymer solution into its surface. When high voltage is applied to the spinneret, polymer jets are formed on the surface of spinneret, and nanofibers are formed that are deposited on the collector. Rotating spinnerets are further classified into three categories that are given below:

Horizontal rotating spinnerets
Downward rotating spinnerets
Upward rotating spinnerets

1.2.3.2.2.1 Horizontal rotating spinnerets

In this setup a metal roller was used as spinneret that was connected with high-voltage power supply (**Table 8**). Polymer solution was splashed onto metal roller through a hole of the solution provider that was placed above the metal roller spinneret. Nanofibers were collected on a metal collector that was placed horizontally [28].

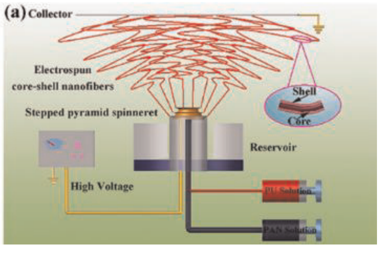
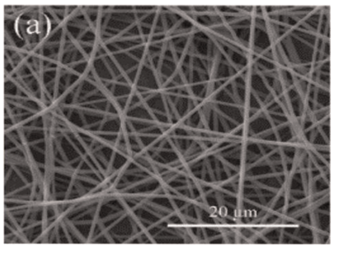
Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2014	Jiang et al.			Polyvinyl alcohol is used as polymer; with concentration 8–10%, production of nanofiber is 2.46–5.84 g/h

Table 7.
Upward stationary spinnerets methods.

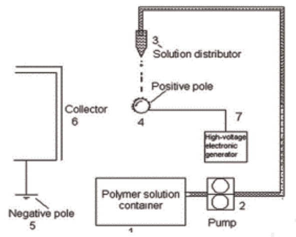
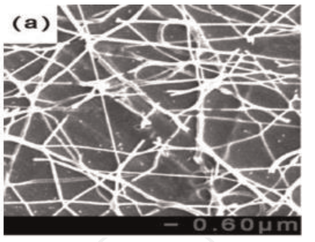
Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2010	Tang et al.			Polyoxyethylene was used with water solvent. Productivity of nanofibers were 24–45 times more than single needle electrospinning

Table 8.
Horizontal rotating spinnerets.

1.2.3.2.2.2 Downward rotating spinnerets

In this electrospinning setup, polymer solution was continuously fed to the rotating cone by a tube (**Table 9**). This cone was connected with positively charged applied voltage. When high voltage was applied to cone, nanofibers were generated from the edges of the cone. These nanofibers were collected on a negatively charged collector placed in a downward direction [29].

1.2.3.2.2.3 Upward rotating spinnerets

This kind of spinnerets is used for more production and uniform nanofiber web formation. Polymer solution is placed in tub and spinneret is rotated in solution. Polymer solution layer is formed on the surface of spinneret. When high voltage is applied to spinneret, then polymer jets are formed that produce nanofiber. These nanofibers are moved in an upward direction and deposited on the collector (**Table 10**).

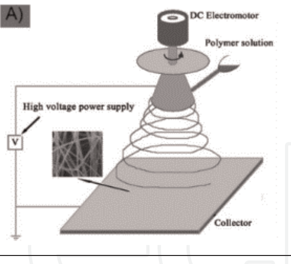
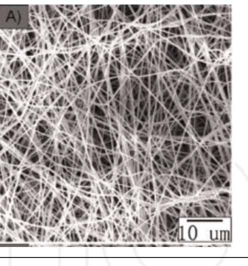
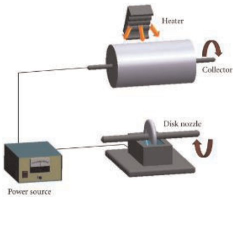
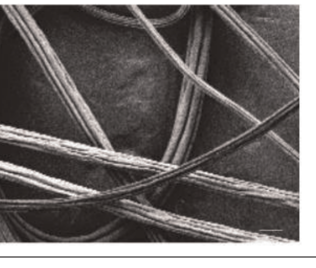
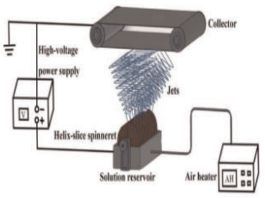
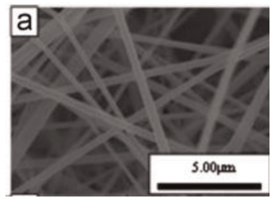
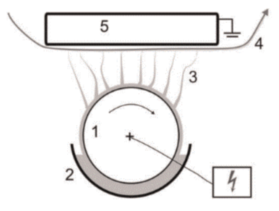
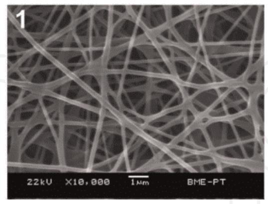
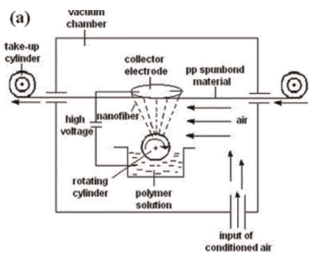
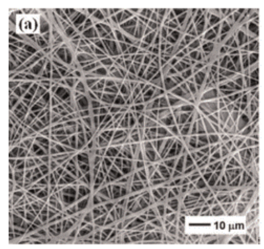
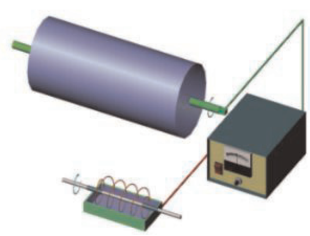
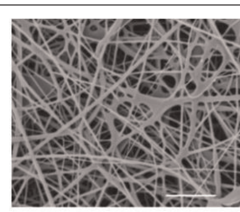
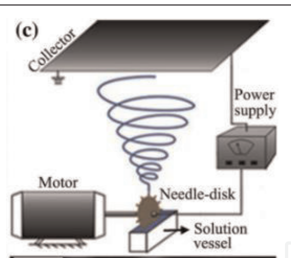
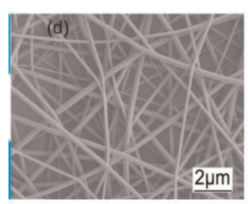
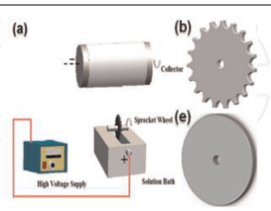
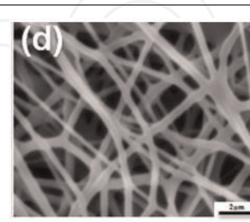
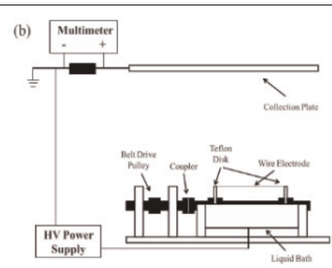
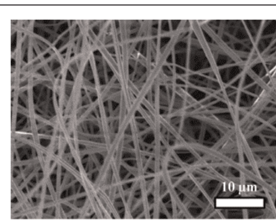
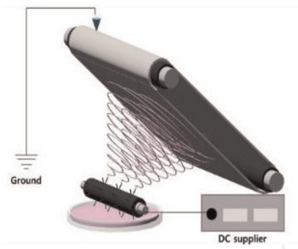
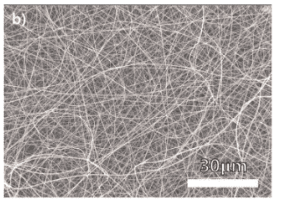
Year	Author	Setup	Morphology	Fiber bundling/polymer
A. 2010	Lu et al.			Polyvinylpyrrolidone is used as polymer. Production of this setup is 10 g/min

Table 9.
Downward rotating spinnerets.

Year	Author	Setup	Morphology	Fiber bundling/ polymer
A. 2012	Chen et al.			Polystyrene with 10 wt % is used in this setup. Production is 6.85 g/h

Year	Author	Setup	Morphology	Fiber bundling/ polymer
B. 2014	Lu et al.			Gelatin powder was used in this setup; solvent is water. Production is this setup was 100 g/h
C. 2009	Kostakova et al.			Polyvinyl alcohol 10 wt % with water solution plus glyoxal 2.5 wt% and phosphoric acid 2.5 wt% of PVA were used. Production capacity of this setup was 2 g/min/m
D. 2010	Cengiz et al.			Polyvinyl alcohol polymer solution is used in this setup; productivity is not mentioned
E. 2012	Xin et al.			Polyurethane is used in this nanofiber production setup. Production of nanofibers is 2.94–9.42 g/h
F. 2016	Liu et al.			Polyvinylidenefluoride-co-hexa-fluoropropylene polymer is used in this setup. Production of nanofibers is 13.5 g/h
G. 2017	Ali et al			Polyvinyl alcohol polymer solution was used; maximum production was 5.24 g/h
H. 2012	Forward Keith et al.			Polyvinylpyrrolidone (PVP) was used as polymer with M_w = 55 kDa and 1.3 MDe. Production was not mentioned

Year	Author	Setup	Morphology	Fiber bundling/ polymer
I. 2017	Seongjun Moon et al.			Poly methyl methacrylate, polyacrylonitrile, polyvinyl alcohol, and lactic-co-glycolic acid were used as polymers; production was 3.2 g/h

A. In this upward rotating spinneret design, rotating disk was used to produce nanofibers. Sharp edges of disk produce high intensity of electric field that causes more productivity and fine nanofibers. In this study ultrafine polystyrene fibers were produced that contain parallel line surface structure, by using highly volatile solvent [32].
B. In this needleless electrospinning setup design for massive production of nanofibers, helix slice spinneret was used that rotates in Teflon solution bath which contains polymer solution. Air heater was used to maintained temperature of polymer solution. When helix slice rotates in polymer solution, edges of spinneret was coated with polymer; when there is high-voltage direct current supply, then polymer jets were formed at the edges of the helix slice that produced nanofibers [33].
C. This needleless electrospinning setup contains positively charged metal roller that rotates in solution bath. This metal roller is licked with solution when electric field exceeded surface tension of the polymer solution; then nanofibers jets were formed, and nanofibers were collected on nonwoven substrate that was placed below the collector electrode that was grounded [51].
D. Roller spinning device was used to produce nanofibers; it contained metal cylindrical roller that rotates in solution bath. High voltage was supplied to the solution; when a thin layer of polymer solution was made on the roller, nanofiber was produced from the edges of the cylinder. Collector electrode was grounded [52].
E. This electrospinning setup was designed to make fine nanofibers and high productivity. Conical wire coil was used as spinneret. This conical wire coil was licked with polymer solution; when electric field was applied. Nanofibers were produced that were collected on the rotating drum [53].
F. In this work, new spinneret was designed, and needle disk was used as spinneret. In this article, comparison between disk and needle disk was done. It was observed that electric intensity of needle disk is 5.33 times more than disk electrode. Productivity of nanofibers is 183 times more than traditional needle electrospinning. In the spinning process, when needle disk was rotated in polymer solution, needle was coated with polymeric solution. High voltage was applied to the system, nanofiber jets were formed at the tip of needles that produced competitive quality of nanofibers by enhancing throughput [54].
G. In this work, new spinneret was designed for massive production of nanofiber. The effect of the spinneret shape on large-scale production of nanofibers was described here. Comparison of disk and sprocket wheel in terms of electric field intensity, fiber production, and fiber morphology was done. Setup consists of rotating spinneret in solution bath. When high-voltage DC power was supplied to the solution, nanofiber jets were formed at the teeth of sprocket wheel that produce nanofibers; these nanofibers were collected on rotating cylinder [55].
H. In this needleless electrospinning setup, a thin wire was used as nanofiber generator. DC voltage was applied to the wire that was placed in solution bath. Wire spinneret was swept with polymer solution, a thin layer was formed on the surface of the wire that produced nanofiber jets, which was collected on the metal collector [56]. In this electrospinning setup, there is no mention of the effect of wire size on production and fiber morphology.
I. In this needleless electrospinning setup rotating, helically probed cylinder was used for nanofiber production. This system gives an easy and flexible method for setting up an electrospun nanofiber web. In this method breadths are placed that have a distance of between 0.1 and 1 mm; DC voltage is supplied that produce a Taylor cone. These changes influence the electrospinning to process a clump-based ceaseless framework and, in this way, abstain from suffering from repetitive streamlining technique. In this syringe less framework, comes about indistinguishable to those of customary electrospinning can be acknowledged generally effectively. Moreover, a few specialized leaps forward are proposed to overcome difficulties introduced by the traditional electrospinning strategy [57]. In this setup there is no optimization of needle distances and effect of needle size on production.

Table 10.
Upward rotating spinnerets.

Author details

Muhammad Waqas Munir* and Usman Ali
College of Textile Engineering, Bahauddin Zakariya University, Multan, Pakistan

*Address all correspondence to: mwaqasmunir786@yahoo.com

References

[1] Varesano A, Carletto RA, Mazzuchetti G. Experimental investigations on the multi-jet electrospinning process. Journal of Materials Processing Technology. 2009; **209**(11):5178-5185

[2] Dosunmu O et al. Electrospinning of polymer nanofibres from multiple jets on a porous tubular surface. Nanotechnology. 2006;**17**(4):1123

[3] Gopal R et al. Electrospun nanofibrous filtration membrane. Journal of Membrane Science. 2006; **281**(1):581-586

[4] Jia H et al. Enzyme-carrying polymeric nanofibers prepared via electrospinning for use as unique biocatalysts. Biotechnology Progress. 2002;**18**(5):1027-1032

[5] Kedem S et al. Composite polymer nanofibers with carbon nanotubes and titanium dioxide particles. Langmuir. 2005;**21**(12):5600-5604

[6] Abidian MR, Kim DH, Martin DC. Conducting-polymer nanotubes for controlled drug release. Advanced Materials. 2006;**18**(4):405-409

[7] Wang X et al. Electrospun nanofibrous membranes for highly sensitive optical sensors. Nano Letters. 2002;**2**(11):1273-1275

[8] Thavasi V, Singh G, Ramakrishna S. Electrospun nanofibers in energy and environmental applications. Energy & Environmental Science. 2008;**1**(2):205-221

[9] Ma Z, Kotaki M, Ramakrishna S. Electrospun cellulose nanofiber as affinity membrane. Journal of Membrane Science. 2005;**265**(1):115-123

[10] Fang J et al. Applications of electrospun nanofibers. Chinese Science Bulletin. 2008;**53**(15):2265

[11] Saeed K et al. Preparation of amidoxime-modified polyacrylonitrile (PAN-oxime) nanofibers and their applications to metal ions adsorption. Journal of Membrane Science. 2008; **322**(2):400-405

[12] Lu X, Wang C, Wei Y. One-dimensional composite nanomaterials: Synthesis by electrospinning and their applications. Small. 2009;**5**(21): 2349-2370

[13] Khil MS et al. Electrospun nanofibrous polyurethane membrane as wound dressing. Journal of Biomedical Materials Research Part B: Applied Biomaterials. 2003;**67**(2):675-679

[14] Bergshoef MM, Vancso GJ. Transparent nanocomposites with ultrathin, electrospun nylon-4, 6 fiber reinforcement. Advanced Materials. 1999;**11**(16):1362-1365

[15] Gibson P, Schreuder-Gibson H. Production and characterization of nanoporous polymer membranes produced by an electrospraying process. In: Symposium on Porous, Cellular, and Microcellular Materials. Orlando, Florida: International Mechanical Engineering Congress and Exposition, Materials Division; 2000

[16] Gibson P, Schreuder-Gibson H, Rivin D. Transport properties of porous membranes based on electrospun nanofibers. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2001;**187**:469-481

[17] Choi SW et al. An electrospun poly (vinylidene fluoride) nanofibrous membrane and its battery applications. Advanced Materials. 2003;**15**(23): 2027-2032

[18] Huang Z-M et al. A review on polymer nanofibers by electrospinning and their applications in

nanocomposites. Composites Science and Technology. 2003;**63**(15):2223-2253

[19] Sarbatly R, Krishnaiah D, Kamin Z. A review of polymer nanofibres by electrospinning and their application in oil-water separation for cleaning up marine oil spills. Marine Pollution Bulletin. 2016;**106**(1):8-16

[20] Martin CR. Template synthesis of electronically conductive polymer nanostructures. Accounts of Chemical Research. 1995;**28**(2):61-68

[21] Vasita R, Katti DS. Nanofibers and their applications in tissue engineering. International Journal of Nanomedicine. 2006;**1**(1):15

[22] Malkar NB et al. Characterization of peptide-amphiphiles possessing cellular activation sequences. Biomacromolecules. 2003;**4**(3):518-528

[23] Li D, Xia Y. Electrospinning of nanofibers: Reinventing the wheel? Advanced Materials. 2004;**16**(14): 1151-1170

[24] Medeiros ES et al. Effect of relative humidity on the morphology of electrospun polymer fibers. Canadian Journal of Chemistry. 2008;**86**(6): 590-599

[25] Wang X et al. Needleless electrospinning of nanofibers with a conical wire coil. Polymer Engineering & Science. 2009;**49**(8):1582-1586

[26] Dosunmu OO et al. Polymer nanofibers from multiple jets produced on a porous surface by electrospinning. Nanotechnology. 2006;**17**(4):1123-1127

[27] Thoppey NM et al. Unconfined fluid electrospun into high quality nanofibers from a plate edge. Polymer. 2010;**51**(21): 4928-4936

[28] Tang S, Zeng Y, Wang X. Splashing needleless electrospinning of nanofibers. Polymer Engineering & Science. 2010;**50**(11):2252-2257

[29] Lu B et al. Superhigh-throughput needleless electrospinning using a rotary cone as spinneret. Small. 2010;**6**(15): 1612-1616

[30] Huang X et al. Needleless electrospinning of multiple nanofibers. In: 2007 7th IEEE International Conference on Nanotechnology—IEEE-Nano 2007, Proceedings; Hong Kong. 2007

[31] Wu D et al. High throughput tip-less electrospinning via a circular cylindrical electrode. Journal of Nanoscience and Nanotechnology. 2010;**10**(7):4221-4226

[32] Huang C et al. Needleless electrospinning of polystyrene fibers with an oriented surface line texture. Journal of Nanomaterials. 2012;**2012**:1-7

[33] Lu W et al. Gelatin nanofibers prepared by spiral-electrospinning and cross-linked by vapor and liquid-phase glutaraldehyde. Materials Letters. 2014; **140**:1-4

[34] Varesano A et al. Multi-jet nozzle electrospinning on textile substrates: Observations on process and nanofibre mat deposition. Polymer International. 2010;**59**(12):1606-1615

[35] Theron SA et al. Multiple jets in electrospinning: Experiment and modeling. Polymer. 2005;**46**(9): 2889-2899

[36] Srivastava Y, Marquez M, Thorsen T. Multijet electrospinning of conducting nanofibers from microfluidic manifolds. Journal of Applied Polymer Science. 2007;**106**(5): 3171-3178

[37] Ding B et al. Fabrication of blend biodegradable nanofibrous nonwoven mats via multi-jet electrospinning. Polymer. 2004;**45**(6):1895-1902

[38] Tomaszewski W, Szadkowski M. Investigation of electrospinning with the use of a multi-jet electrospinning head. Fibres & Textiles in Eastern Europe. 2005;**13**(4):22

[39] Kumar A et al. Controlling fiber repulsion in multijet electrospinning for higher throughput. Macromolecular Materials and Engineering. 2010;**295**(8): 701-708

[40] Wang S, Yang Y, Zhang Y, Fei X, Zhou C, Zhang Y, et al. Fabrication of large-scale superhydrophobic composite films with enhanced tensile properties by multinozzle conveyor belt electrospinning. Journal of Applied Polymer Science. Jan 5 2014;**131**(1)

[41] Angammana CJ, Jayaram SH. The effects of electric field on the multijet electrospinning process and fiber morphology. IEEE Transactions on Industry Applications. 2011;**47**(2): 1028-1035

[42] Xie S, Zeng Y, et al. Industrial and Engineering Chemistry Research. 2012; **51**(14):5336-5345

[43] He J-H et al. BioMimic fabrication of electrospun nanofibers with high-throughput. Chaos, Solitons & Fractals. 2008;**37**(3):643-651

[44] Higham AK et al. Foam Electrospinning: A Multiple Jet, Needle-less Process for Nanofiber Production. AIChE. Vol. 602014. pp. 1355-1364

[45] Yarin AL, Zussman E. Upward needleless electrospinning of multiple nanofibers. Polymer. 2004;**45**(9): 2977-2980

[46] Holopainen J et al. Needleless electrospinning with twisted wire spinneret. Nanotechnology. 2014;**26**(2): 025301

[47] Zhou F-L, Gong R-H, Porat I. Polymeric nanofibers via flat spinneret electrospinning. Polymer Engineering & Science. 2009;**49**(12):2475-2481

[48] Zheng Y, Zeng Y. Electric field analysis of spinneret design for multihole electrospinning system. Journal of Materials Science. 2013; **49**(5):1964-1972

[49] Li X, Yang W, Li H, Wang Y, Bubakir MM, Ding Y, et al. Water filtration properties of novel composite membranes combining solution electrospinning and needleless melt electrospinning methods. Journal of Applied Polymer Science. 2015;**132**(10)

[50] Jiang G, Zhang S, Qin X. Effect of processing parameters on free surface electrospinning from a stepped pyramid stage. Journal of Industrial Textiles. 2016;**45**(4):483-494

[51] Kostakova E, Meszaros L, Gregr J. Composite nanofibers produced by modified needleless electrospinning. Materials Letters. 2009;**63**(28):2419-2422

[52] Cengiz F, Dao TA, Jirsak O. Influence of solution properties on the roller electrospinning of poly(vinyl alcohol). Polymer Engineering & Science. 2010;**50**(5):936-943

[53] Wang X et al. Needleless electrospinning of uniform nanofibers using spiral coil spinnerets. Journal of Nanomaterials. 2012;**2012**:1-9

[54] Liu Z, Ang KKJ, He J. Needle-disk electrospinning inspired by natural point discharge. Journal of Materials Science. 2017;**52**(4):1823-1830

[55] Ali U et al. Needleless electrospinning using sprocket wheel disk spinneret. Journal of Materials Science. 2017;**52**(12):7567-7577

[56] Forward KM, Rutledge GC. Free surface electrospinning from a wire electrode. Chemical Engineering Journal. 2012;**183**:492-503

[57] Moon S, Gil M, Lee KJ. Syringeless electrospinning toward versatile fabrication of nanofiber web. Scientific Reports. 2017;**7**:41424