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Electrospinning of Polymer Nanofibers and their Applications–A Review

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1. ELECTROSPINNING IN THE WORLD OF NANO

In the history of science no other field has attracted so much attention from so many researchers all over the world as the field of nanotechnology. Again, this topic has attracted a large number of researchers from a different spectrum of fields like physics, chemistry, material science, agriculture, biology, including every field of engineering and medicine. Nanotechnology has indeed transcended the man made "boundaries" among the different branches of science and has emerged as an interdisciplinary field in every sense of the term. However, nanotechnology research invariably demands very high investments in terms of infrastructure and instruments such as clean room, SEM, AFM, etc., in order to enable researchers to prepare and observe such nanometer sized objects and features. This makes this area inaccessible and prohibitively expensive for modest laboratories in the world. However, since the field is of interest to so many people involved in such diverse fields, there is every possibility for them all to come together and establish collectively such nanotechnology laboratories by pooling all their resources. This also fosters in addition the interdisciplinary research. In addition it will also foster interdisciplinary research. Many universities and research establishments have also taken the cue and started nanotechnology initiatives to build such common infrastructures for researchers across the departments and even universities to work and benefit together.

There are a number of ways of producing such nano clusters and features from conventional Silicon wafer technology to chemical schemes such as self assembly, etc. Among several such possibilities, 'Electrospinning', is a "top to down" approach of polymer nanofiber preparation. This is one of the simplest techniques to prepare nanometer diameter fibers of any polymer. If the number of papers and patents filed is a good indicator of the intense activity in any area of research then Electrospinning is a very active field indeed with growing popularity among researchers around the world. In fact more people are venturing into this field as can be observed from the numbers in the two graphs shown below. Fig. 1(a) shows papers published and 1(b) that of patents awarded from the year 2000 until now. It is also perhaps interesting to observe the number of papers published in different key branches of science and engineering which is shown in Fig. 2(a) while Fig. 2(b) shows the country-wide distribution of the contributions. USA and China are leading in this area of research with major contributions and Korea is not far behind. The graph also shows clearly the application area which is attracting more and more researchers.

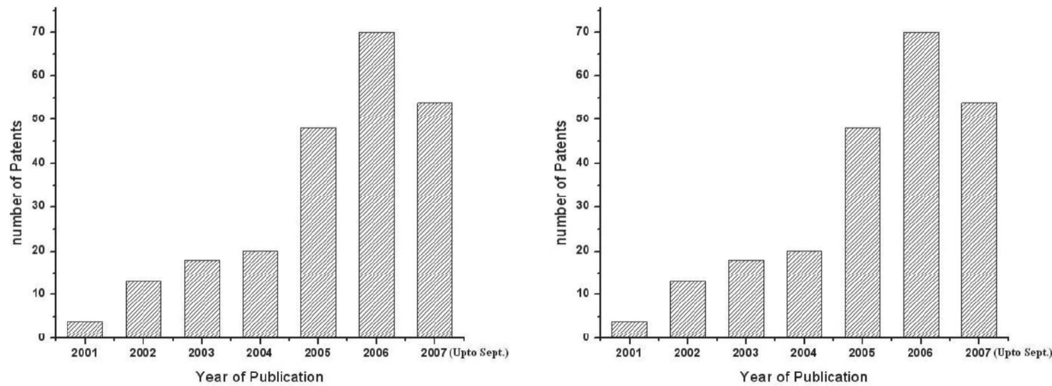


Figure 1: Shows the number of (a) papers published and (b) patents awarded, during the years 2000 to 2007 (upto Septemebr 2007) in Electrospinning.

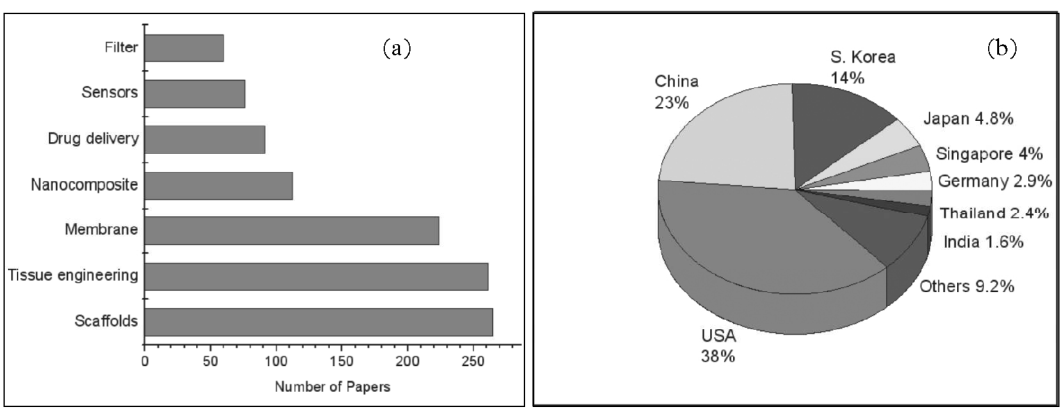
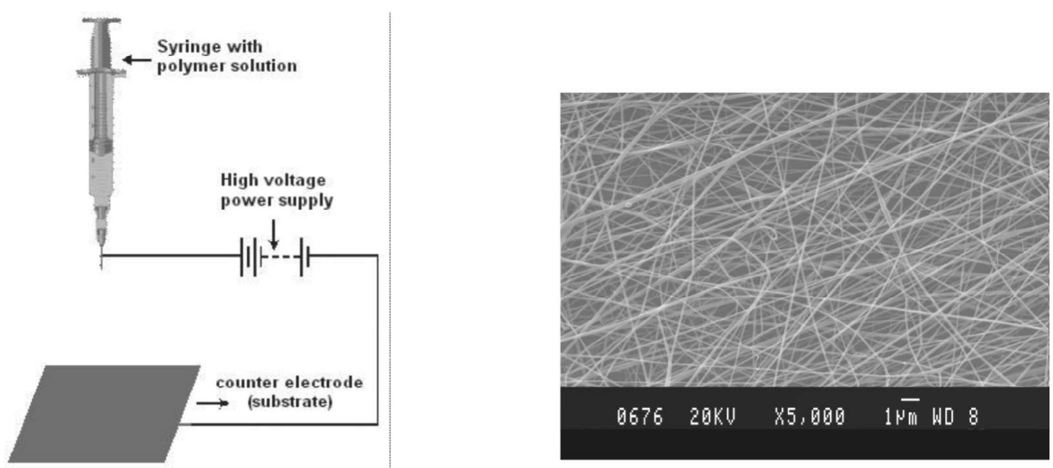


Figure 2: (a) shows the area-wise and (b) the country-wise distribution of papers published in the area of Electrospinning.

2. ELECTROSPINNING

2.1 What is Electrospinning?

Electrospinning [1,2] is a simple and versatile method to produce polymer nanofibers by accelerating a charged polymer jet in a very high electric field. The diameter of the fibers are in the range of 10μm to 10 nm, which is typically 1-3 orders less than that obtained by the conventional spinning process [3]. The electrospinning process in laboratory scale is discussed here followed by theoretical explanations of the process. A schematic diagram of a typical electrospinning setup is shown in Fig. 3. The main components of the electrospinning process can be classified as (i) syringe (or pipette), (ii) high voltage power supply and (iii) counter electrode or substrate. Polymer in solution (or melt) form is loaded in the syringe and is connected to the positive terminal (it also can be negative terminal) of the high voltage power supply. For continuous production of nanofibers, the solution should be pushed at a constant flow rate. Generally, a syringe pump serves this purpose. In the electrospinning process a high voltage is used to create an electrically charged jet of polymer solution or melt. One electrode is connected to the spinning solution/melt and the other attached to the collector. In most cases, the collector is simply grounded, as indicated in Fig. 3. The electric field is concentrated at the tip of the needle that contains a pendant droplet of the solution held by its surface tension. Accordingly, charges are induced on the surface of the drop. Mutual charge repulsion and the tendency of the surface charges to move towards the counter electrode, result in an electrostatic force against surface tension. As the intensity of the electric field is increased, the hemispherical surface of the fluid at the tip of the capillary tube elongates to form an inverted cone known as the Taylor cone [4, 5]. On increasing the electric field further, a critical value is reached when the repulsive electrostatic forces overcome the surface tension forces and a fine jet of charged polymer solution is ejected from the tip of the cone. This jet is further subjected to elongation process and instabilities, which results in the jet becoming very long and thin as they move towards the counter electrode. The polymer strands now start moving away from each other due to mutual repulsion and ultimately collect on the counter electrode as a random coil of nanofibers. Once the jet comes into the atmosphere, the low boiling point solvent evaporates, leaving behind only the charged polymer strands.



(a) (b)

Figure 3: (a) Schematic diagram of electrospinning setup and (b) Typical electrospun fibers.

2.2 A Brief History

The fundamental idea of electrospinning dates back to more than 60 years. During 1934 to 1944, Formhals obtained a series of patents, describing an experimental setup for the production of polymer filaments using an electrostatic force [6-10]. A polymer solution, such as cellulose acetate, was introduced into the electric field. The polymer filaments were formed, from the solution, between two electrodes bearing electrical charges of opposite polarity. One of the electrodes was placed into the solution and the other onto a collector. Once ejected out of a metal spinneret with a small hole, the charged solution jets evaporated to become fibers which were collected on the collector. The potential differences and the fiber characteristics depended on the properties of the spinning solution, such as polymer molecular weight and viscosity. When the distance between the spinneret and the collecting device was short, spun fibers tended to stick to the collecting device as well as to each other, due to incomplete solvent evaporation. In 1952, Vonnegut and Neubauer produced uniform droplets of about 0.1 mm. in diameter by applying potentials of 5-10 kV AC or DC to liquids taken in small capillaries [11]. In 1955, Drozin investigated the dispersibility of a series of liquids at high electric potentials and they found that large electrostatic pressure plays a predominant part in the process of dispersion and is a function of dielectric constant and radius of curvature of the liquid in the capillary [12]. He used a setup similar to the one by Vonnegut and Neubauer. After Forhmals in 1966 Simons filed a patent on electrospinning. He patented an apparatus for the production of non-woven fabrics of ultra thin fibers forming different patterns by using electrostatic field [13]. In 1971, Baumgarten spun fibers by electrostatic means with diameters measuring less than 1 μm. He studied the effect of electric field, electrical conductivity, jet length of solution viscosity, surrounding gas, flow rate and geometry on the diameter of the fiber. The present electrospinning process is almost similar to that described by Baumgarten [14].

Until 1993, this technique had been known as electrostatic spinning, and there were only a few publications dealing with its use in the fabrication of thin fibers. In early 1990s, several research groups (in particular, the Reneker group at the University of Akron) revived interest in this technique by demonstrating the fabrication of thin fibers from a broad range of organic polymers [1, 2]. The term "electrospinning" is coined at that time and is now widely used in literature. It has triggered a lot of experimental and theoretical studies related to electrospinning.

2.3 Advantages and Challenges

Nanofibers have very attractive features over other types of materials. They are almost one dimensional and have large aspect ratio and large surface area to volume ratio. Though there are other schemes by which such nano fibers can be made, for example, by template synthesis, self-assembly, etc., electrospinning is a very simple technique requiring very minimum resources in terms of laboratory facilities. It does not require any sophisticated clean rooms, special atmospheres, etc. One can obtain them under normal room temperature. Even if the polymer does not dissolve in any known solvent, still fibers can be obtained from melts. Thus there is almost no polymer literally which can not be electrospun. It is even possible to obtain ceramics such as TiO_2 and $BaTiO_3$ can also be formed into fibers by a clever scheme. One can have these compounds in the form of nano powder for example, and disperse them in any standard polymer like polystyrene or PMMA through ultrasonic agitation, etc. After thorough mixing one can form fibers by electrospinning. Evaporate the polymer in an oven at temperatures above the melting point of the polymer and what you would be left with will be nano meter diameter ceramics or metal nano particles which were dispersed in the polymer solution while electrospinning.

Though the general scheme to obtain nano fibers is simple, there are a few challenges. The process is dependent on several parameters, processing parameters like, electric potential, flow rate, concentration, distance between the capillary and collecting screen, motion the target screen and solution parameters like viscosity, conductivity and surface tension, ambient parameters like temperature and air velocity in the chamber and the system parameters like molecular weight of the polymer all affect the diameter of the fibers formed. Hence there is a distribution of diameter in the fibers formed. Further the fibers are formed in a random fashion and hence aligning them becomes difficult when the process itself is dependent on so many parameters.

2.4 Reviews on Electrospinning

There have been a number of reviews which have appeared in the scientific journals, some of them are comprehensive and some are written on specific aspects of Electrospinning. A book also has been published titled "An Introduction to Electrospinning and Nanofibers" [15]. We give below a brief view of a few of the reviews that have appeared in the recent past. The list is in no way exhaustive.

A review addressing the current state of nanofibrous filter media was discussed by Barhate *et al.* [16]. Improving filtering media in terms of lower energy consumption, longer life, high filtration capacity and easier maintenance are discussed. The use of such fibrous membranes in filtration of blood, water, air, beverages, gases, chemicals, oils, diesel and petrol, etc. are discussed. A review by Michael Goldberg *et al.* [17] on application of electrospinning in drug delivery and tissue engineering compares both traditional and electrospun scaffolds. The limitations of current drug delivery systems and the possible use of nano-scale drug-delivery systems are covered in their review. Another review on drug delivery and tissue engineering was written by Chew *et al.* [18]. The interaction of cells with extracellular matrix and their use in nanomedicine is discussed in their review. Applications of electrospun scaffolds with oriented nanofibers and other assemblies were covered in the two reviews by Wee-Eong Teo *et al.* [19] and Rajesh Vasita *et al.* [20].

Polymer nanofibers/nanotubes, ceramic nanofibers/nanotubes and metal nanofibers have been fabricated using electrospinning directly or through post-spinning processes. Electrospinning apparatus should be modified accordingly to have application on such diverse processes. The electrospinning apparatus and the production of different nanofibrous assemblies are discussed in the review by W E Teo [21]. Ceramic nanofibers with a solid, porous or hollow structure can be produced by combining sol gel process with electrospinning. An overview of the production of such nanofibers and their applications were discussed in the article by Dan Li *et al.* [22].

Electrospinning of functional polymer nanofibers was discussed in a review by J. Zeng *et al.* [23]. Mohammad Munim Hussain *et al.* [24] briefs the application of functional nanofibers in advanced areas like chemical process industries, chemical protective clothing, biomaterials, drug delivery, tissue engineering etc. The current spinning methodology for designing nanostructured scaffolds using the electrospinning technique is discussed by Ramalingam Murugan *et al.* [25]. In a review S Ramakrishna *et al.* [26], discusses about the use of electrospinning in some of the applications which have global impacts such as energy storage, health care, biotechnology, environmental engineering, defense and security. There are different companies which manufacture nanofibers and mats in bulk using electrospinning technique. Chung [27] wrote a review on electrospinning from an industrial point of view.

The application of nanofibers in biomedicine and biotechnology is discussed by J. Venugopal *et al.* [28]. In their review they cover some of the applications like multifunctional membranes, scaffolds used in tissue engineering, wound dressing, drug delivery, artificial organs, vascular grafts, protective shields in specialty fabrics and filter media for submicron particles in the separation industry.

A general review on electrospinning was written by Thandavamoorthy Subbiah *et al* [29]. Fundamental understanding of electrospinning process and the recent developments in electrospinning as well as some of their application are covered in their review. Nano composites and nano ceramics obtained using electrospinning are the topic of the review by Zheng-Ming Huang [30] and Chronakis[31]. One dimensional (1D) nanostructures containing hetero-junctions between different materials, finds useful applications in electronics, photonics, catalysis, sensing etc. A review by Mieszawska *et al.* [32] covers different methods to create such junctions.

2.5 Fiber Alignment

Many of the simple applications in filtering and in biomedical fields we need not look for good alignment of the fibers. However, when it comes to devices and sensors if the fibers can be formed in a targeted way with the possibility of precise positioning it would be useful. Various approaches have been taken to obtain aligned electrospun fibers. These include: spinning onto a rotating drum, spinning onto the sharp edge of a thin rotating wheel, introducing an auxiliary electrode or electrical field, rapidly oscillating a grounded frame within the jet, and using a metal frame as the collector. With these approaches, various degrees of alignment of the electrospun fibers can be achieved. When fibers are electrospun onto a solid collector, their diameters are generally observed to increase with an increase in solution concentration. Bead-like structures are sometimes observed on electrospun fibers and these have been shown to decrease in size or disappear with an increase in solution concentrations.

Researchers tried to produce aligned polymer fibers by using a rotating drum collector setup. Mathews *et al.* [33] used a rotating mandrel (Fig. 4) to study the effect of motion of collector in electrospinning. They prepared collagen fibers and the degree of alignment they reported was average. Kameoka *et al.* [34] used a scanning tip instead of a syringe and a rotating counter electrode to get aligned polymer fibers. They dipped a silicon scanning tip into polymer solution and a drop of polymer solution was formed when the tip taken out. The polymer drop attached to the silicon tip served as the source of polymer solution and the fiber alignment was obtained by using a rotating counter electrode. Their setup is shown in Fig. 5.

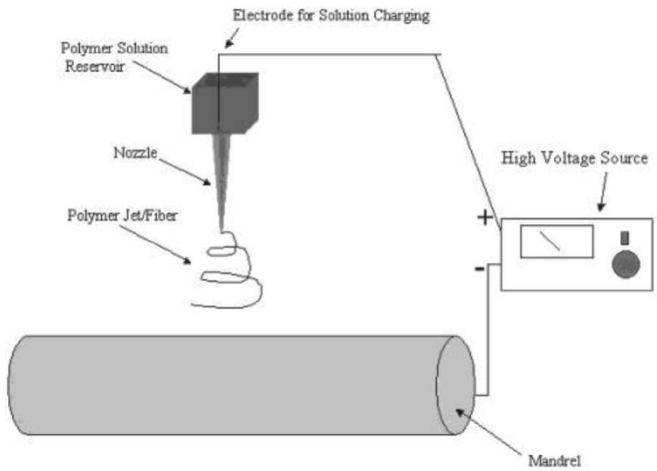


Figure 4: Rotating Mandrel setup [33].

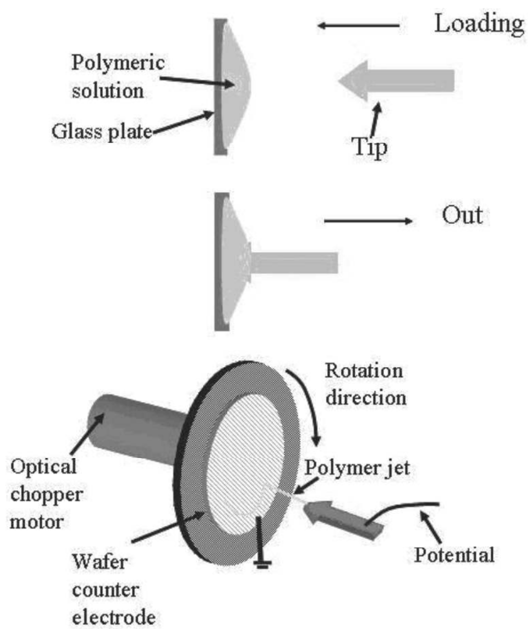


Figure 5: Scanning tip method [34].

Sundaray *et al.* [35] used a sharp tip as electrode instead of a planar or cylindrical electrode as shown in Fig. 6. They inserted a sharp metal tip inside a nonmetallic hollow cylindrical drum. The fibers are collected on flexible polymer sheet wound over the drum. Polystyrene fibers having very good alignment was produced using the setup and criss-cross pattern was also prepared. The effect of rotation speed on alignment was studied and the matching speed of the mandrel was found out. Above the matching speed fibers are found to be broken at several places. An array of sharp blades was used as electrodes (Fig. 7) by Teo *et al* [36]. A rotating drum just above the array of blades collects the fibers formed. Another configuration of electrode in the form of a rotating disk with sharp edge was put forward by Theron *et al* [37] (Fig. 8). The nanofibers collected on the wheel's edge were assembled in a parallel array. Katta *et al* [38] tried to align polymer fibers suing a wire drum (Fig. 9) as the collector.

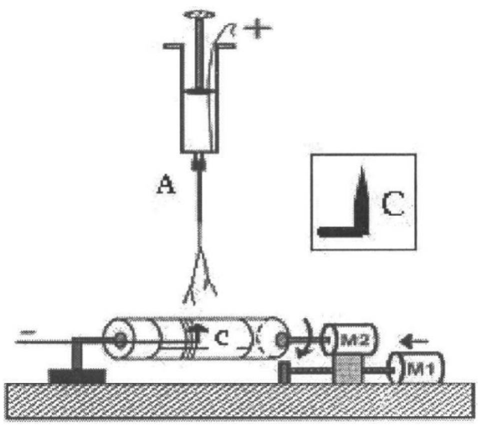


Figure 6: Sharp metal tip collector [35].

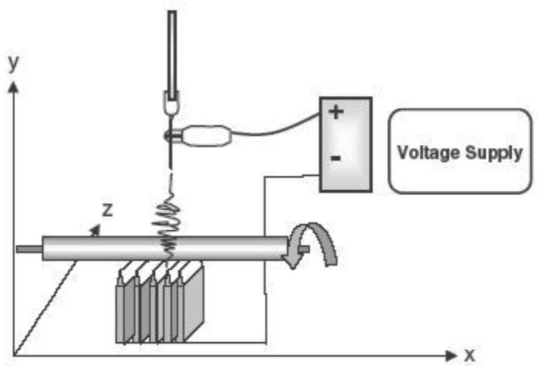


Figure 7: Array of Blades collector [36].

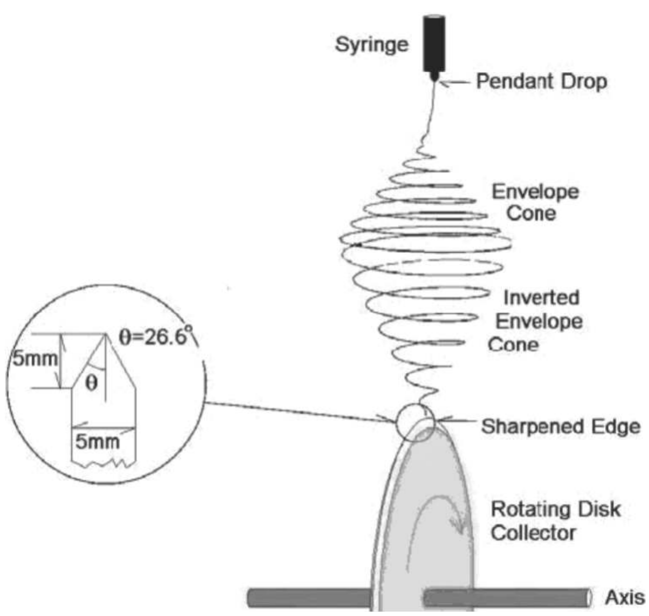


Figure 8: Disk collector [37].

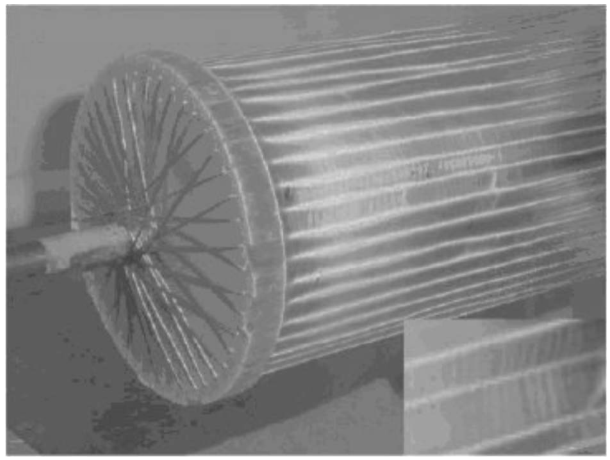


Figure 9: Wire drum collector [38].

Ceramic hollow nanofibers were prepared by Li *et al.* [39] using coaxial electrospinning (Fig. 10). They were able to control the wall thickness by adjusting some of the experimental parameters. They proposed the use of these hollow ceramic fibers in nano fluidic devices or optical waveguides. A pair of conducting strips separated by a gap was used by Li *et al.* [40] to get aligned fibers (Fig. 11). In their method the fibers are aligned in one direction due to the mutual repulsion of the fibers since they are charged and hence resembles like self assembly. In the next section a brief discussion on the different modifications of electrospinning scheme are discussed.

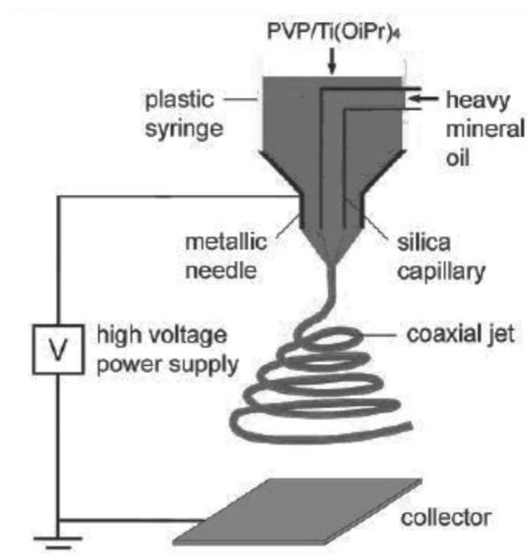


Figure 10: Coaxial electrospinning [39].

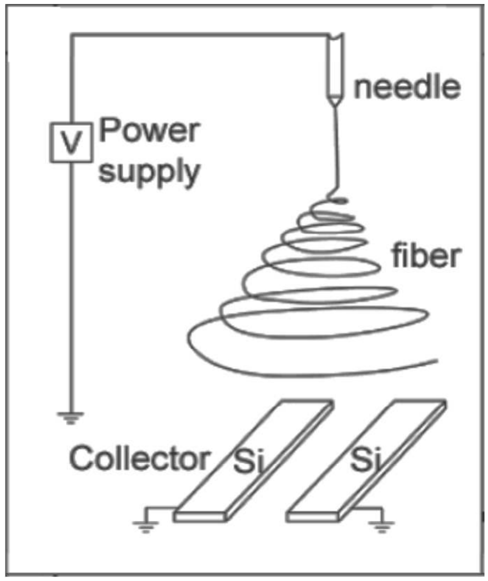


Figure 11: Metal collector with a gap [40].

2.6 Variations of Electrospinning

If the fibers are to be used on a microchip to make chemical sensors, or in other applications such as tissue engineering, we have to control where they go. In chemical sensing, the challenge is design complex inorganic circuits along with an organic material, which is much more difficult to produce and control at the nanoscale. AC voltage instead of DC was used in electrospinning that allowed Tepper's team to control and manipulate the polymer fibers into aligned arrays [41].

Polymer fiber interconnects are produced between microscale features on substrate using only electrostatic forces. In one scheme, electric field driven directed growth of fibers is achieved between microscale droplets of a concentrated polymer solution deposited on a substrate. After depositing the droplets, the droplets on or near the positive electrode become positively charged and the droplets on or near the negative electrode become negatively charged. Fibers form between the positively and negatively charged droplets due to electrostatic forces (Fig. 12). The conical structures appear to be analogous to the characteristic Taylor cones formed in an electrospinning process and the process is interpreted as a microscale version of electrospinning.

In another scheme, the electric-field process to make nanofibers in a direct, continuous and controllable manner was reported. The technique, known as near-field electrospinning [42], offers the possibility of producing nanofibers with organized patterns (Fig. 13) that can be used for such applications as wound dressings, filtrations and bio-scaffolds.

Recently, an atomic force microscope (AFM) based voltage-assisted electrospinning technique (ANES) was reported [43]. Single fiber of polyethylene oxide (PEO) polymer with nanometer scale diameters were formed on substrate via simultaneous preparation

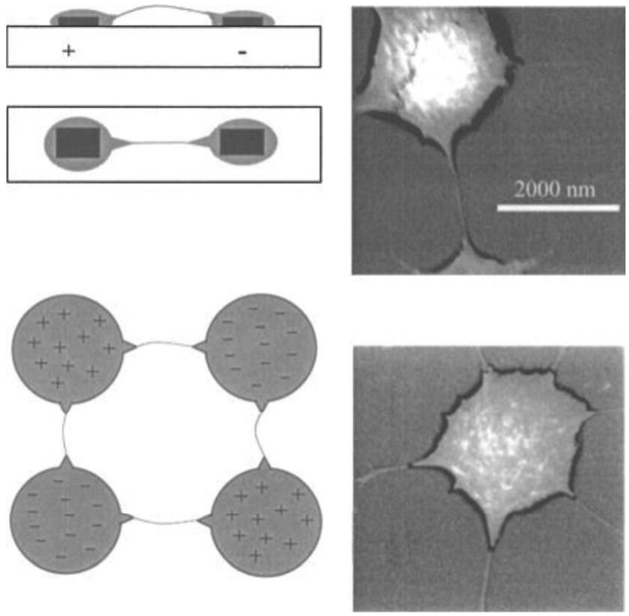


Figure 12: Electric field driven directed growth of fibers is achieved between microscale droplets of a concentrated polymer solution deposited on a substrate [41].

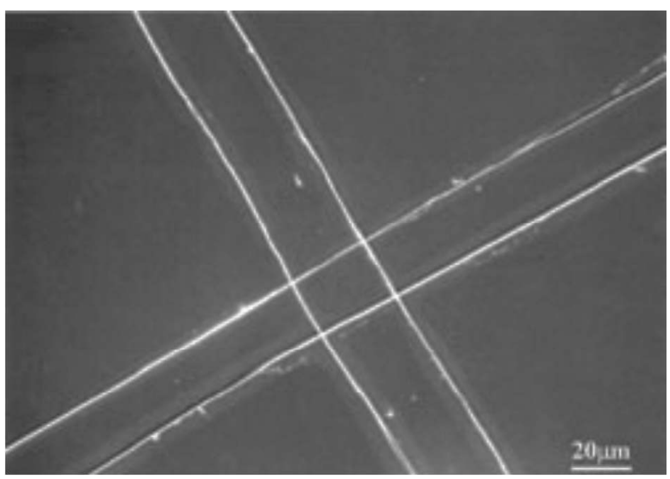


Figure 13: These orderly rows of nanofibers were created using the new near-field electrospinning process [42].

and deposition (Fig. 14). The results demonstrate the feasibility of this method for assembling nanofibers at predetermined positions. Using this ANES scheme nanometer fibers are created from a viscous polymer solution by applying an electric field to a droplet of the solution coated on an AFM tip in a controllable fashion.

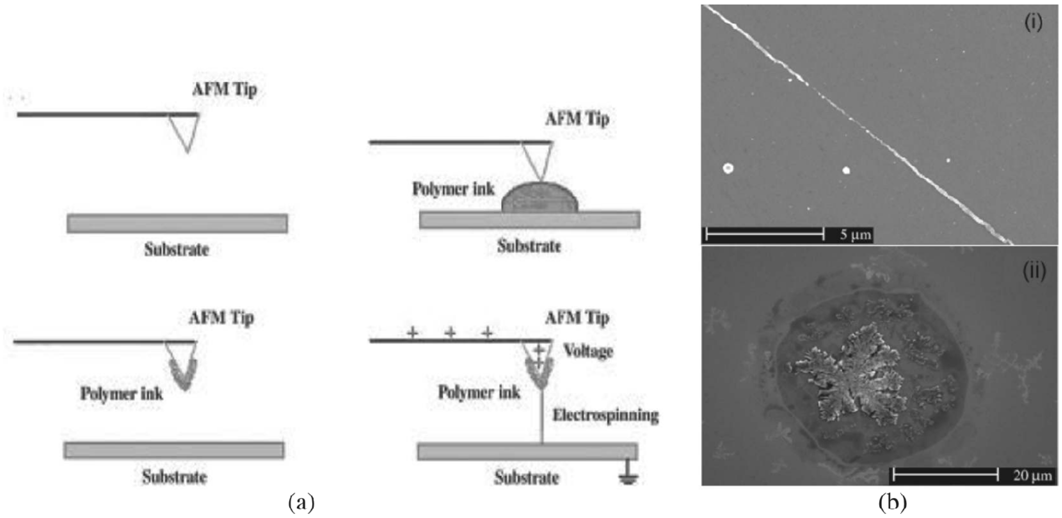


Figure 14: (a) Schematic illustration of atomic force microscope assisted nanoelectrospinning (ANES). (b) SEM images of fiber and relic prepared via ANES using different parameters: (i) a spinning voltage of 8 V and a spinning distance of 10 ìm; (ii) a spinning voltage of 8 V and a spinning distance of 15 ìm [43].

2.7 Modeling of Electrospinning

Although this method of nanofiber fabrication appears very simple, the process is very complicated. It can be described as the interaction of several physically unstable processes. This complexity is not surprising, considering that a liquid strand (solution or melt) undergoes complex structure-forming processes even in absence of an electric field; the strand is subjected to the so called Rayleigh instability. However several researchers attempted to explain theoretically the electrospinning process.

Generally the process can be decomposed into five operational components, namely, charging the fluid, formation of the Taylor cone, thinning of the steady jet, onset and growth of jet instabilities that give rise to diameter reduction into the submicron regime, and collection of the fibers into useful forms. The modeling of the process typically focuses on two stages. In the first, a polymer jet ejects from the nozzle and is accelerated and stretched smoothly by electrostatic forces. In the second stage, a "bending instability" occurs farther downstream when the jet gets sufficiently thin, and the fiber spirals violently. The theoretical developments of electrospun jets has been studied by Spivak and Dzenis [44], Hohman *et al.* [45-48], Rutledge *et al.* [3], Feng [51,52], Reznik *et al.* [53].,Reneker *et al.*,Theron *et al.*,Yarin *et al.* [49,50,54] and Colman *et al.* [55].

For the steady stretching in stage one, Spivak and Dzenis published a simple model that assumes the electric field to be uniform and constant, unaffected by the charges carried by the jet and considered power law fluid behavior [44]. Hohman *et al* later proposed a slender-body theory for electrospinning that couples jet stretching, charge transport, and the electric field [45,46]. These effects are predicted to play an important role in the jet development. They discussed only about Newtonian fluids. Fridrikh *et al* gave a simple analytical model for the forces that determine jet diameter during electrospinning as a function of surface tension, flow rate, and electric current in the jet [3]. Feng reformulated and expanded the Hohman *et al.* treatment, accounting for viscoelastic polymeric rheological behavior by incorporating the Giesekus constitutive equation into the jet governing equations [51,52]. A different approach has been used by Reneker *et al.*, Theron *et al.* and Yarin *et al.*, who model the jet as a series of charged beads connected by viscoelastic dumbbell elements [49,50,54]. A study on critical length of straight jet in electrospinning was conducted by He *et al.* [57]. Reznik *et al.* studied the shape of liquid droplets under the action of strong electric fields and the emergence of liquid jets from these droplets [53]. Theron *et al.* studied the effect of the external electric fields and mutual electric interaction of multiple charged jets on the path and evolution in electrospinning [54]. Colman *et al.* proposed a theoretical model for the jet using a thin filament approximation and considered for both Newtonian as well as viscoelastic fluid [55]. Their simulation resulted in a good quantitative jet radius profiles for the initial jet development.

The second phase of electrospinning has been the focus of several studies by Reneker *et al.* and Hohman *et al.*, who proposed models to describe the phenomena observed in the region of instability during electrospinning. The enormously increased contour length produces a very large stretch ratio and a nanoscale diameter. Recently Tao Han *et al.* studied various buckling instabilities in electrospinning jet [56]. They reported frequency corresponding to the buckling patterns was of the order of 10^5-10^6 Hz, whereas the frequency of the bending loops was of the order of 10^3 Hz.

3. APPLICATIONS

Polymer nano fibers have excellent characteristics which make them ideal for several applications in a wide range of fields. They have large aspect ratio in terms of ratio of length to diameter and large surface area to volume ratio. Further, polymers in general have excellent thermal and mechanical properties which also make these fibers attractive in a variety of applications.

3.1 Nanocomposite Fibers

Carbon Nano Tubes (CNTs) [58] have very attractive properties but are very few microns only in length. To obtain very long CNTs in millimeters and centimeters is very difficult. If we can prepare well aligned and long CNTs they can be very useful in many device applications in nano electronics. Electrospinning appeared to be very attractive in this type of applications. We can prepare polymer CNT composite in solution and then electrospin it to obtain long aligned nano fibers. Such CNT-polymer composites are also found to be useful in gas sensors. Either we can try such composite fibers themselves for device applications when sufficient conductivities are achieved or obtain the CNT arrays inside the fibers by evaporating the polymer in an oven at elevated temperatures.

However, one big issue is the dispersion of the CNTs inside the polymer solution. There are some advances that have been made on dispersion of CNTs in a polymer matrix, including optimum blending, in situ polymerization and chemical

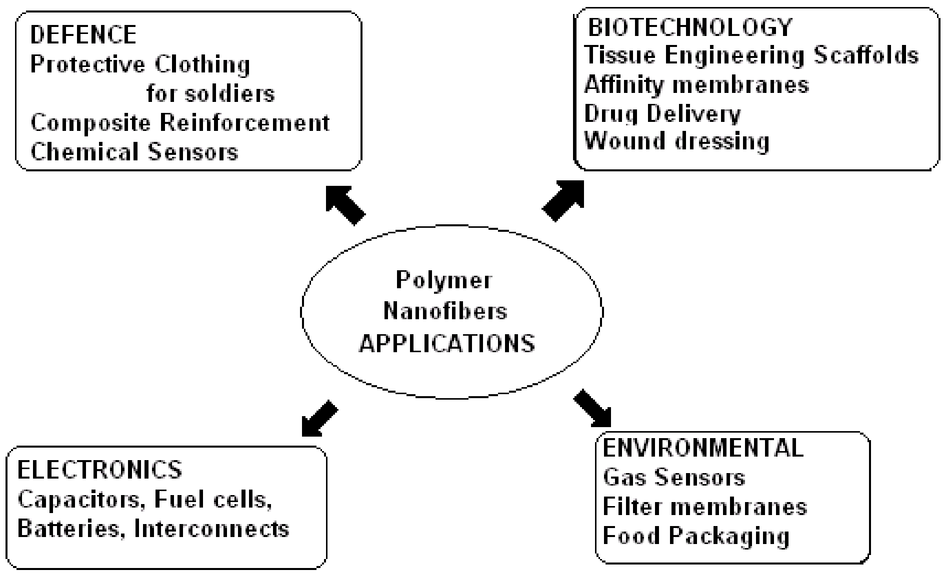


Figure 15: Applications of electrospinning.

functionalization [59-61]. Alignment of CNTs in the matrix can be enhanced by ex-situ techniques, force and magnetic fields, electrospinning and liquid crystalline phase-induced methods. Another interesting scheme is to functionalise the CNTs by treating them with suitable acids and then chemically attach our molecule of interest on to the surface and then disperse them in polymer solution. In addition many studies on mechanical, thermal, electrical, electrochemical, optical and super-hydrophobic properties of CNT-polymer composites are available in scientific literature [62-64].

Till date several reports have been published on such composites with CNTs with different polymers [65-71]. Using the electrospinning method, Chang *et al.* prepared single walled CNT (SWNT)/polyvinylidenefluoride (PVDF) fiber mats and investigated the percolation threshold for the insulator-to-metal transition of the composite mats with different loading of SWNTs [65]. Ko *et al.* have prepared continuous CNT-filled nanofibers (NFs) and observed that they contribute to thermal stability and provide a significant reinforcement effect at less than 3% volume of SWNT [66]. Zussman and co-workers prepared PEO electrospun nanofibers of PEO loaded with multi walled CNT (MWNT) as well as SWNT separately [67, 68]. Haddon and co-authors prepared SWNT-polymer electrospun mats and found that functionalized CNTs enhance better mechanical properties than as prepared CNTs [69]. They reported 104% enhancement in tensile strength for SWNT loaded electrospun compared to pure polymer electrospun mat. Ge *et al.* prepared highly oriented, large area continuous composite nanofiber sheets made from surface-oxidized multiwalled carbon nanotubes (MWNTs) and polyacrylonitrile (PAN) [70]. They reported very good orientation of MWNT inside the nanofiber and good enhancement in mechanical properties. The same group studied the shrinkage of MWNT after carbonization [71]. Ra *et al.* studied the electrical properties of PAN/

MWNT electrospun mat and found anisotropy in electrical conductivity [72]. Ko and co-authors prepared nanocomposite electrospun fibers of Bombay mori silk and single wall carbon nanotubes (SWNT) and reported an enhancement of 460% in Young's modulus due to SWNT loading[73]. Sundaray and co-authors studied the electrical properties of single electrospun fibers of polymer MWNT nanocomposites and reported dramatic improvement in electrical conductivity with low loading of MWNT [74, 75]. Jose *et al.* prepared well aligned nanofibrous nanocomposites of Nylon 6 and surface-modified multiwalled carbon nanotubes (MWNTs) by electrospinning and reported an enhancement in structural and mechanical properties by MWNT incorporation [76]. Wang *et al.* studied the electrical properties of electrospun fibers of MWNT/PVA nanocomposites [77]. Several order improvement of conductivity of nanofiber achieved with CNT loading from their pure counterpart. McCullen *et al.* investigated the electrospun fibers of poly (L-D-lactic acid) (PLA) loaded with multi-walled carbon nanotubes (MWNT) for use of scaffold in tissue engineering. They reported MWNT enhances the electrical conductivity and elastic modulus of the resulting nanofibers [78].

Some of the problems associated with CNT-polymer composites are with regard to the dispersion and behaviour of CNTs in solutions. Alignment in the matrices is another major difficulty (since CNTs are anisotropic, they must be aligned in the composite matrix to achieve the optimal mechanical properties), while bonding to the matrices can also be difficult (carbon nanotubes have inert graphite surfaces). Thus, further studies are needed to overcome critical issues with CNT embedment in nanocomposites during processing and large scale manufacturing.

Pavan Kumar *et al.* Investigated giant negative magnetoresistance (GMR) in nanocomposite aligned fibers using electrospinning. The nanocomposite contains polymethylmethacrylate (PMMA) matrix and the nanoparticles of polymer grafted magnetite (PGM), (PMMA grafted Fe_3O_4). Even for the low magnetic filed (1 Tesla) GMR of about 50% was observed for low loading (5 wt%) of PGM at room temperature [79]. There are few reports to improve the electrical properties of electrospun fibers by using nanocomposites [80, 81].

Integration of nanofibers into nanomatrices requires nanofibers with well-controlled orientation, size, and other target characteristics, as well as reproducibility in locating them in specific positions and orientations. The ability to do so, however, continue to remains a major challenge in the field in spite of the recent advances achieved in terms of Near Field Electrospinning and Atomic force supported electrospinning schemes.

Attention must also be given to organic–inorganic nanofibers by electrospinning; as such materials combine the advantage of nanocomposites and ultra thin nanofibers. Furthermore, as is evident, there is less information available on the mechanical properties of nanofibers and nanofiber composites with or without the use of carbon nanotubes. Research on the mechanical properties of nanofibers and their composites from a variety of polymers is essential for a greater understanding of their contribution and performance. Combining the now well-established field of electronic polymers with the emerging field of nanofibers can potentially develop a new technology. Applying the electrospinning process for obtaining nanofibers of pure electronic polymers (in their semiconducting and metallic regimes) and/or their blends in conventional organic polymers, opens the way for a number of applications. The use of nanofibers in conducting media is of significant interest because of the potentially high range of conductions that can be obtained with significant processing versatility and because of their flexibility and light weight. Conductive nanofibrous assemblies can provide the fundamental building blocks for the construction of nanostructures. Producing smart nanostructures that possess electrical, electronic, magnetic, optical properties, mechanical and sensing properties (mass, strain and pressure sensing) and demonstrate processability as a result of embedded nanofibers remains a major challenge. It is worth mentioning that other functional molecules, biomolecules or nanoparticles could also be easily incorporated into the electrospinning solutions to generate a combination of nanofiber functionalities.

3.2 Filter

Nonwoven mat obtained from electrospinning show great promise in filtering applications. The average pore size obtained can be controlled by electrospinning random coils of fibers for a longer period on the substrate. Polyacrylonitrile (PAN) fibers with mean diameters in 270–400 nm range were prepared by electrospinning for use as a filter media [82]. Compared to commercial filters made of polyolefin and glass, the fibers of electrospun filters were more uniform in diameter. The performance of electrospun filters was evaluated by measuring the penetration of monodisperse NaCl nanoparticles (below 80 nm in size) through the filters. It was found that electrospun filters could be made having nanoparticle penetration values comparable to commercial filters but with substantially less filter mass. The penetration of nanoparticles through the electrospun filter media could be reduced by increasing the filter thickness, by controlling the collection time during the process.

Nanoparticle collection by electrostatic forces was found to be negligible for electrospun filters. Filter quality factors and single fiber collection efficiencies were found to be independent of filter thickness for electrospun filters, and the penetration of nanoparticles through electrospun filters was in better agreement with theoretical predictions than was the measured penetration through a commercial filter. Charged, uncharged, and charge neutralized particles all had the same penetration through electrospun filters, which implies that electrostatic collection was minimal. Overall, electrospinning allows for advanced fibrous materials production with controlled, uniform fiber size which allows for the production of low nanoparticle penetration, low mass filters [83]. This shows that electrospinning is a promising technology for the production of high performance nanoparticle filters.

3.3 Bio Applications

Functional nanofibrous scaffolds produced by electrospinning have great potential in many biomedical applications, such as tissue engineering, wound dressing, enzyme immobilization and drug (gene) delivery. For a specific successful application, the chemical, physical and biological properties of electrospun scaffolds should be adjusted to match the environment by using a combination of multi-component compositions and fabrication techniques where electrospinning has often become a pivotal tool. The property of the nanofibrous scaffold can be further improved with innovative development in electrospinning processes, such as two-component electrospinning and in-situ mixing electrospinning. Post modifications of electrospun membranes are effective means to bestow the electrospun scaffolds properties of controlled anisotropy and porosity.

Challenge in tissue engineering is to produce scaffold which should mimic the extra cellular matrix for cell adhesion, proliferation and differentiation. The key factors of tissue engineering are to create a three-dimensional scaffold with suitable degradation rate to meet the requirements of new tissue growth; to supply interconnected pores for cell–cell and cell–matrix communication; to bring cells together to form a tissue; to regulate cell phenotype and to acquire normal tissue structure and function [84-86]. Electrospinning is a simple technique which can be used to produce fibrous scaffolds of many different polymers (biodegradable, biocompatible and bio polymers) and the technique is proven to be suitable for tissue engineering applications. Electrospinning has been used for muscle tissue engineering, bone tissue engineering, nerve tissue engineering, vascular tissue engineering, cartilage, tendon and ligament tissue engineering.

Non woven electrospun nanofiber has desirable properties of large surface-to-volume ratio, high porosity, and large interstitial space making it an ideal material for biological applications. Electrospun nanofibers have found potential use in a wide range of health care applications. Numerous research groups have focused in the past to adapt nanofibers as scaffolds for tissue engineering, vascular grafts [87-92], drug delivery [93-96], medical implant devices, medical diagnostics and instrumentation and dressing material for burns and wounds [97-99]. Nanofibers are also seen as potential protective fabric material against pathogens in hospital environment. They also find a role in cosmetic and dental applications [26]. The renewed interest in electrospinning in recent times can be attributed to its applications in biomedical engineering.

Nanofiber scaffold is ideal for tissue engineering as these fibers can be designed and shaped to bestow the requisite mechanical properties to bring about cell growth, proliferation, differentiation. Further there is a huge scope to deliver growth factors, drugs through these scaffolds to enhance regeneration of tissues [26].

Research groups have derived nanofibers having 45% collagen, 15% elastin, and 40% synthetic polymer which mimic the ratio of collagen and elastin in native blood vessels. Such electrospun scaffolds are nontoxic, stable in an *in vitro* culture environment, and possess controlled mechanical properties that mimic the architecture of native blood vessels [100]. Chitosan nanofiber scaffolds have been used to fill in anatomical defects in cranium with encouraging results. Collagen-modified nanofibers when used for neural stem cells culture have shown modification of collagen enhances the attachment and viability of the neural stem cells [99].

For tissue engineering and wound dressing, electrospun polymer nanofibers serve as tissue scaffolds which enhance cell growth and proliferation. By chemically attracting ligands on to membranes formed with electrospun polymer fiber surface, one can separate the targeted biomolecule. This type of applications with affinity membranes can improve the efficiency of separation significantly as the surface area of the nanofibers is very large. These nanofibrous membranes also help in filtering moisture and dust from unclean air and thereby improving the air quality. These features are useful in food packaging applications to improve shelf-life of packed food and beverages.

Drug delivery is one of the applications of electrospun fibers. The required drug is mixed with a carrier polymer solution and the fibers are electrospun. This drug incorporated polymer is administered into the patients body, the drug gets released at a steady rate into the body. Several such experiments were conducted to study the drug delivery mechanism with respect to time [93, 101]. Collagen coating on electrospun nanofibers of poly(l-lactic acid)-*co*-poly(ε-caprolactone) [P(LLA-CL)] copolymer improved viability and attachment of endothelial cells [102, 103].

4. CONCLUSION

Electrospinning of polymer fibers has become one of the very simple, interesting and useful technique having control over a wide range of application areas. There are still many challenges such as patterning and targeting specific locations at the nano levels on a given substrate. New techniques are being developed to achieve this. However, there are many application areas where such alignment and patterning are not crucial. For example, in filtering, bio-medical applications and in sensors one does not need such facility. Hence it is believed that the field will continue to grow attracting best minds to contribute significantly in developing technologically rewarding discoveries in the future.

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