Review: Electro Spinning Technique and Factors Affecting Electro Spun Nano Fibers and Some Applications

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Abstract— Electrospun nanofibers in recent times have found numerous applications in various fields of everyday life. These nanofibers can be synthesized in a number of ways like self-assembly, phase preparation etc. but here we will be focusing on nanofibers synthesized using electrospinning technique. In this review, we look at the electrospinning setup in some detail beginning right from the history of electrospinning machine. We discuss the working principal and the factors which affect the electrospun fibers synthesized suing this technique. Finally, we present some state of the art applications of electrospun nanofibers like in bone-tissue engineering, environmental pollution, skin grafting and biomedical scaffolds.

Key words: Electro spinning, Nano Fibers, Nanotechnology, Scaffolds

I. INTRODUCTION

Among the three techniques available namely Self Assembly, Catalytic Based [1], Phase Separation, Template Based [2] and Electro spinning for the manufacture of nano fibers, electro spinning is the most used process. Electrostatic fiber spinning also called as “Electro spinning” is a simple, adaptable technique for generating nano fibers from rich variation of materials including polymers, composites and ceramics. Electro spinning combines the operating characteristics of both electro spraying and conventional solution dry spinning. The process of electro spinning does not stand in need of coagulation chemistry or high temperature in order to manufacture solid fibers from the solution. Thus, large compound molecules can be used for the synthesize of nano fibers. A quintessential setup of electro spinning comprises of three main components i.e.: (a) a high voltage power supply, (b) a capillary tube with a pipette or needle of small diameter and (c) a metal screen. A high voltage power supply (5-30 kV) is used to generate an electrically charged jet of polymer solution or melt out of the pipette or needle. This high voltage supplier is connected to the needle. Before reaching the collector screen which is kept at a distance of 5-20 cm from the needle tip, the solution evaporates or solidifies. The small fibers thus synthesized are collected. One electrode is placed into the spinning solution/melt and other is connected to the collector. Many a times the collector is just grounded. The correlation of solution’s properties, the applied voltage and tip to collector distance are distinct for each solution. In others words, the polymeric solution glides through the needle creating a drop at the tip of the needle. As the voltage is increased, the electric force disfigures the shape of the droplet until a critical voltage is reached. Further the electric forces are overcome by the viscoelastic forces in the fluid and the jet takes the form of a Taylor cone. Finally the discharged polymer solution jet withstands in-stability and elongation process allowing the jet to become very long and thin. Simultaneously the solvent evaporates leaving behind charged polymer fibers.

II. BRIEF HISTORY OF ELECTRO SPINNING

The history of any explicit technology is usually troublesome to tease out from the overall progress of science and civilization. In 1600, the first record of electricity attraction of a liquid was perceived by William Gilbert [3]. Extremely nitrated polysaccharide was made by Christian Friedrich Schonbein in 1846. Later in 1887, a paper on nano fiber production was written and presented by Charles Ver-non Boys [4]. Then in 1900, John Francis Cooley [5] filed the primary ever patent on electro spinning followed by W. J. Morton in July, 1902 [6]. In 1914, John Zeleny brought out the behavior of fluid droplets at the top of metal capillaries [7]. His work drove towards mathematically modelling the behavior of fluids under electrical forces. Within the years from 1931 to 1944, Anton Formhals printed at least twenty two patents on the novel technique of electro spinning [8].

Electro spun fibers generated into filter materials were additionally developed in 1938 by N. D. Rozenblum and Petryanov-Sokolov [9]. Furthermore, between 1964 and 1969 Sir Geoffrey Ingram Taylor marked the beginning of theory of electro spinning by mathematically modelling the form of the (Taylor) cone shaped by the fluid drop under the impact of an electrical field. Since 1995, the amount of publications concerning electro spinning has been increasing exponentially each year. As mentioned earlier electro spinning was initial proprietary within the USA in 1902, the method was seldom in use till the 90’s. With engrossment within the field of nano science and nano engineering, researchers took keen interest in nano fiber production via electro spinning. Fig. 1 offers a pictorial depiction of around two hundred universities and research institutes that deal in the study of synthesis and production of nano fibers. Fig. 2 is concerning the quickly growing number of patents printed within the field of electro spinning from its method to application. Start-ups like eSpin Technologies, Nano Technics, and KATO are some of the businesses that deal with studies to reap the distinctive benefits offered by electro spinning, whereas firms like Donaldson Company and Freudenberg are utilizing electro spun fibers in their air filtration products for the last twenty years.

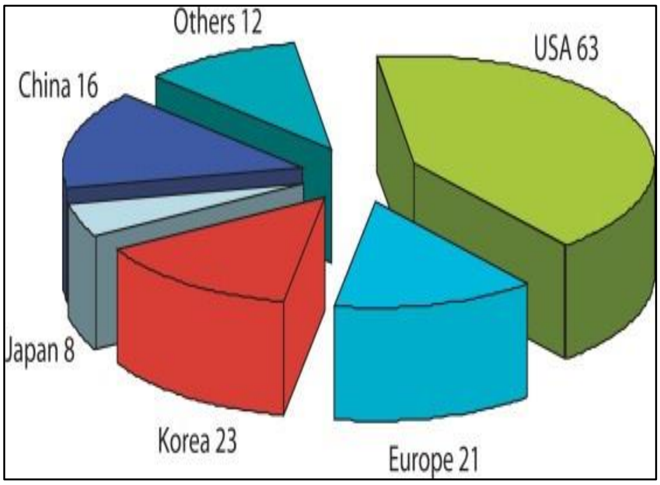

Fig. 1: Electro spinning work in different universities

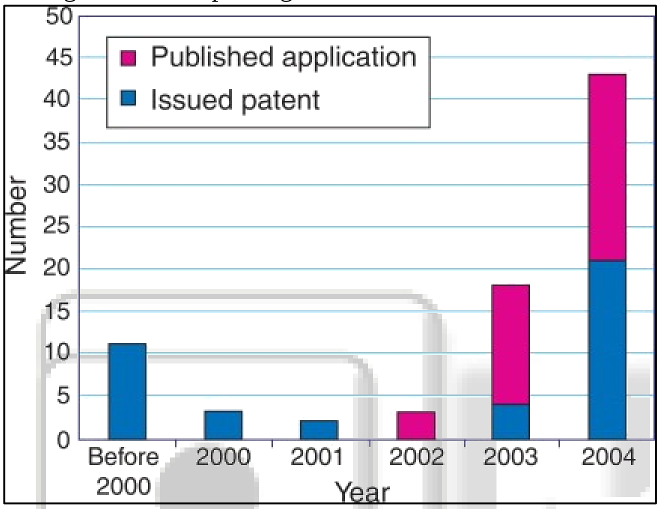

Fig. 2: Patents filed and patents applied (U.S)

III. WORKING PRINCIPLE

A very basic nano fiber production method is called electro spinning and it is known from the beginning of the 20th century. The typical setup of electro spinning technique is shown in Fig. 3. The fundamental components of this process include a high voltage power supply, a collector drum and injection pump. The needle is said to be the positive electrode and the collector is the negatively charged electrode. A polymeric solution in filled in the syringe and put into the injection pump. This pump controls the flow rate of the polymeric solution. The distance from the tip of the needle to the collector drum can be kept anywhere between 5-20 cm depending on the type of fibers required to be produced. When a drop of polymer ejects out from the needle and the required voltage is applied to the drop, it becomes charged and the electrostatic repulsion counteracts the surface tension. Thus, the stretching of the drop takes place. When a critical point is reached, the liquid erupts from the surface. This eruption is known as Taylor Cone as depicted in Fig. 4 [10, 11].

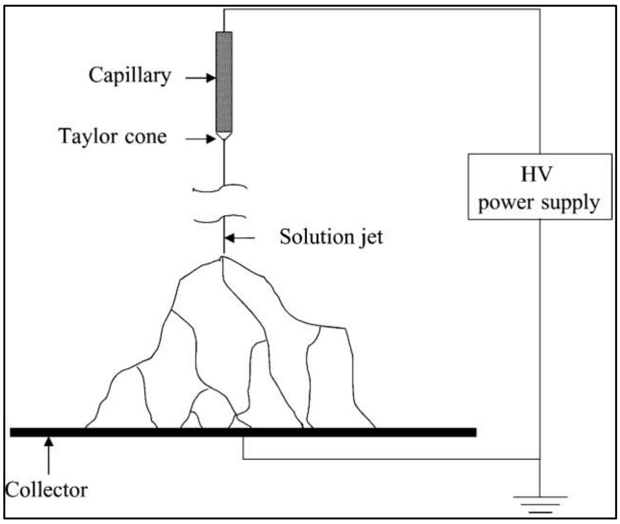

Fig. 3: Process of electro Spinning

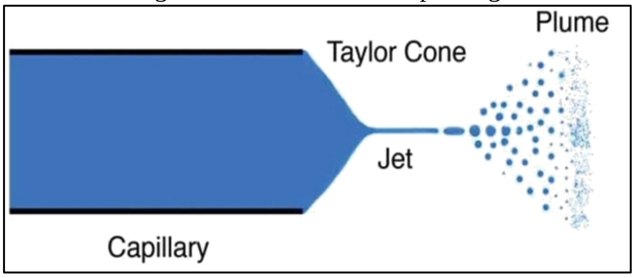

Fig. 4: Taylor cone

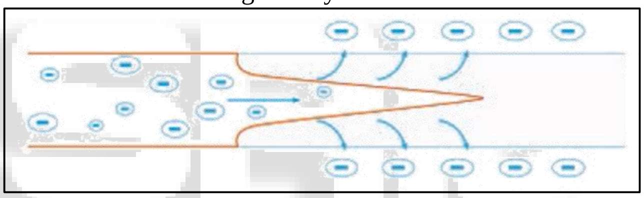

Fig. 5: Discharge of charge as polymer jet dries

Further as the solution jet travels towards the collector, it dries (see Fig. 5) and the mode of current flow changes from ohmic to convective because the charge migrates to the surface of fiber The process of whipping is thus caused by electrostatic repulsion initiated at tiny bends within the fiber, till it's finally deposited on the collector as shown in Fig. 6. The elongation and dilution of the fiber ensuing from this bending instability ends up in the formation of uniform fibers with nanometer-scale diameters.

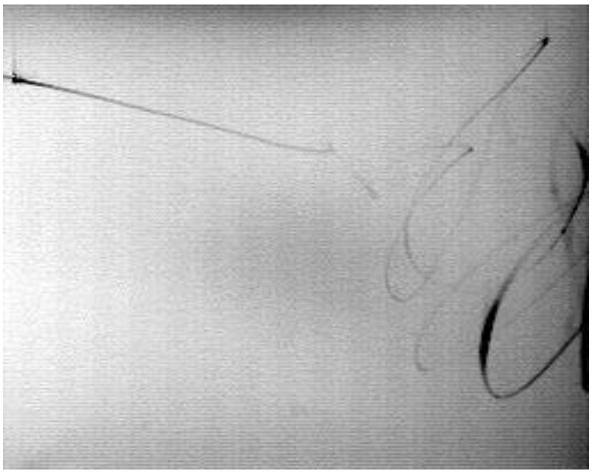

Fig. 6: Whipping

IV. Factors Influencing the Electro Spinning Process

A. *Solution Properties*

1) Concentration

The concentration of the polymer impacts the electro spinning process in different ways and these are discussed as follows:

- When the concentration of the polymer is low, electro spraying takes place instead of electro spinning because the solution becomes less viscous and thus increases the surface tension.
- When the concentration of the polymer is slightly high, the solution becomes sufficiently viscous leading to fibers and beads formation.
- When the concentration is suitable, very smooth nature of nano fibers is achieved.
- If the concentration of the polymer is very high in solution, micro-sized ribbons are formed. Fig. 7 gives the Scanning Electron Microscope images of nano fibers according to concentration differences.

2) Molecular Weight

Molecular weight also determines the nano fiber structure and morphology. Molecular weight depicts the interconnection of the chains of polymer that is nothing but the viscosity. By keeping the concentration of polymeric solution constant, decreasing the molecular weight tends to form beads, whereas increasing the molecular weight gives smooth nano fibers. However, further increasing the molecular weight leads to micro-sized ribbon structure with low concentration of polymer in the solution. Fig. 8 demonstrates nano fiber structures of different molecular weights of PVP. Figure 7: SEM of different concentrations of polymer solution Figure 8: Various different molecular weights of PVP

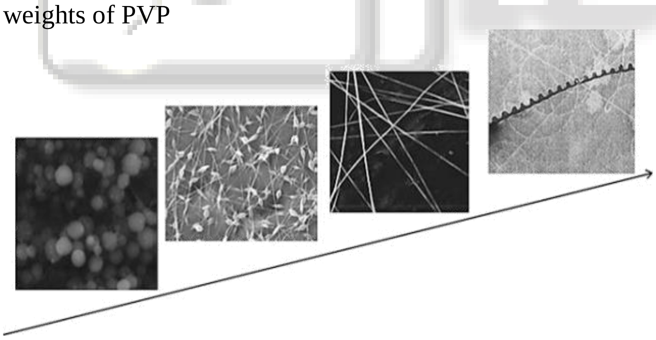

Fig. 7: SEM of different concentrations of polymer solution

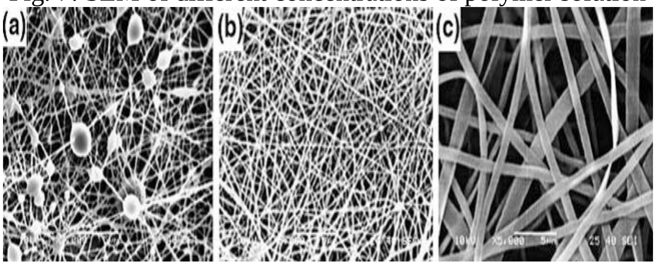

Fig. 8: Various different molecular weights of PVP

3) Viscosity

Viscosity is a vital factor in the process of determining the morphology of the solution. Very low viscous solution yields to discontinuous fibers and highly viscous leads to hard polymeric solution.

This becomes difficult as the solution is not easily ejected out of the tip of the needle. Thus, suitable viscosity is a matter of concern for electro spinning. The concentration of the polymer, molecular weight and viscosity are interlinked to one another. These parameters differ for each type of solution being used. When the viscosity is very low the dominant factor is the surface tension and thus beads are formed. Only when the solution is of ideal viscosity, nanofibers can be obtained by electrospinning technique.

4) Surface Tension

Another important factor in deciding the nanofiber morphological structure is that of surface tension. Effect of surface tension on the morphology of nanofiber products with PVP as the polymer and different solvents such ethanol, MC etc. have reported that surface tension is different for different solvents. Furthermore, surface tension can be reduced and therefore beads formed can be made into smooth nanofibers. Keeping rest of the conditions constant, surface tension helps to determine the lower and the high boundaries of the process of electrospinning.

5) Conductivity

The types of polymer and the solvent type help in determining the conductivity of the solution. Natural polymers are less likely to be conductive as they are polyelectrolyte in nature. This increases the charge on the jet and more tension is created in the electric field. This results in poor formation of nanofibers. At times, ionic salts are added to tune the conductivity. This also helps in controlling the fiber diameter.

B. *Processing Parameters*

1) Voltage

The voltage being applied during the process of electro spinning plays a pivotal role. Reports on this reveal different results, such that, higher voltage applied leads to thick nano fiber formation as well as narrow nano fiber formation. Thus, the change in voltage does affect the fiber diameter and morphology of nano fiber.

2) Flow Rate

Flow rate of the polymeric solution must be as low as possible. This allows the solution to be polarized. Higher flow rate leads to formation of beads instead of smooth fibers.

3) Collectors

Collector is considered as the negative electrode during the nano fiber production by electro spinning. Aluminium foil is wrapped onto the collector for the collection of nano fibers. However, other substrates are also used instead of aluminium foil such as wire mesh, liquid bath etc. Fig. 9 depicts the various types of collectors.

4) Distance Between the Tip of Syringe and Collector (H)

Less the distance, less is the time for the jet to solidify before reaching the collector drum. Higher the distance, more are the chances of beads formation.

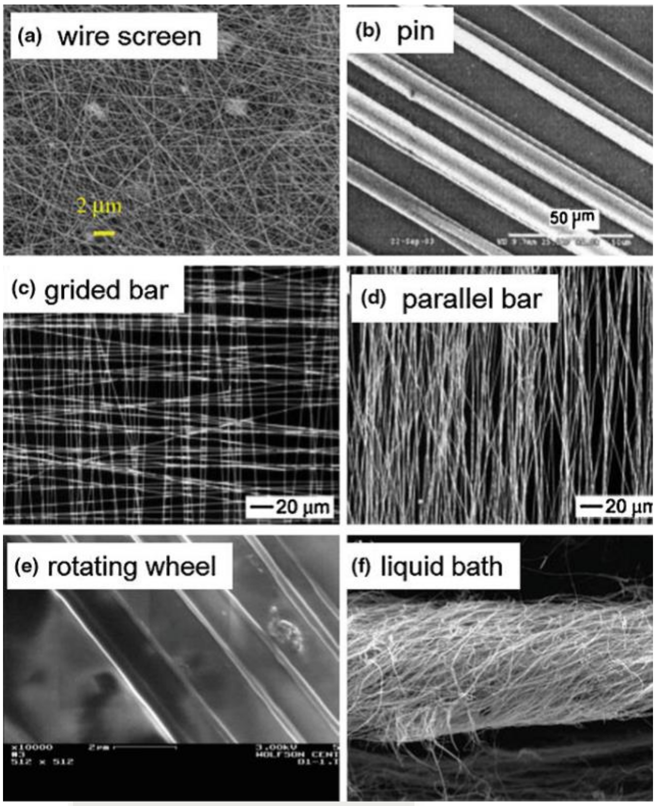

Fig. 9: Types of collectors

C. Environmental Conditions

Ambient parameters such as temperature and humidity has affect on fiber diameter including the morphology. High temperature gives thinner fibers. As far as humidity is concerned, low humidity increases the solvent evaporation rate whereas high humidity gives thick nano fibers.

V. Applications of Electro spun Nano fibers

Due to their small diameter and very high surface area along with the properties imported from the polymers of which they are made, nanofibers have a huge number of applications in various fields like environment protection and biomedical field [12, 13]. A basic schematic of these applications is demonstrated in Fig. 10. Below we list some of these applications in brief.

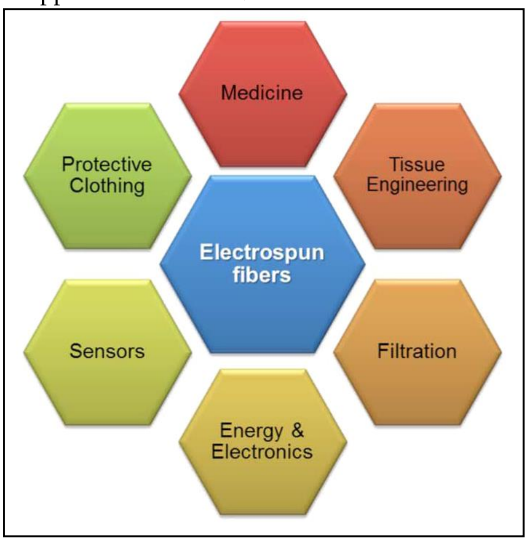

Fig. 10: Applications of Nano Fibers

A. Filtration

It is sometimes very important to remove soli particles from any other media like gas or liquid phase substances. This can be carried out by filtration. Macro sized particles are filtered by sieving whereas very fine particles are filters by various phenomena like browning motion, electrostatic attraction, interpretation etc. Filtration find a huge number of applications in the field of medical, automobile, household, defence and other day to day chores. Electrospun fibers demonstrate characteristics which are ideal for filtration. It has been reported that electrospun nanofibers filtration capabilities surpassed even the filtration potential of HEPA filter whose filtration efficiency is 99.97%. PVA, Polystyrene are some of the materials used for the fabrication of nano-fibers for filtration.

B. Water Purification

Water pollution is a serious problem our world is facing today and needs to be catered as soon and as efficiently as possible. Water contains ions which are positively charged as impurities and these can be detrimental to human health and pose great risk. This ion however has been found to be removed by affinity towards certain functional groups by physical or chemical ways. Electrospun nanofibrous materials have shown great potential towards this goal. Their inherent property of being functionalized while being electrospun, their high surface area and very high porosity guarantee that such ions are trapped once these nanofibers are used as filters. Examples include keratin/silk nanofibers for collecting Cu(II) metal ions and amidoxime-modified PAN nanofibers for trapping in Cu(II) as well as Pb(II) impurities.

C. Fuel Cells

Fuel cells are electrochemical devices which use metal catalyst for converting hydrogen fuels and hydrogen rich fuels into electric current charge.
There are different types of fuel cells such as:

- Proton exchange material fuel cells
- Direct methanol fuel cells
- Alkaline fuel cells
- Solid Oxide fuel cells

Electro spun materials are being used in fuel cells instead of Platinum nanoparticles due to its high cost. Platinum nanoparticles also face limited commercialization. Thus, there was a need of economically suitable replacement in the form of electro spun materials which are made as an alternative for catalyst and have properties like high catalytic efficiency and high durability.

D. Drug Delivery

Drug delivery is the process by which medication is administrated to the patient at a controlled rate for optimum delivery, prevention against drug toxicity and to minimize any side effects. In this system, a carrier material is used to load the drug and this is then detached from the carrier whenever delivery of the drug is required. Electro spun fibers due to their hydrophilic and highly porous character have proved to be excellent drug carriers. They have very high specific surface area which guarantees higher controlled release rate than bulk films. All three different drugs i.e. water soluble, water insoluble and water sparingly soluble along with macromolecules like bioactive proteins and DNA [14] have been tested on biodegradable polymers and have demonstrated excellent drug delivery potential depending on nano fiber morphology i.e. hydrophobic or hydrophilic character.

E. Wound Healing

When we get injured, our body starts a complex biochemical process of several reactions taking place to heal the wound. Injuries which are shallow and small in size can be healed very quickly, but the larger and deeper ones require considerable amount of time. When such a recovery takes place, we do not want foreign bodies to attack the already injured site and thus we provide a wound dressing.

However, the wound dressing much ensure that for proper recovery of the wound, it has the property of absorbing the fluids discharged from the wound, permeability of oxygen and moisture, prohibiting the entry of microorganisms from attacking the affected site and enhance the wound healing process. All these properties are possessed by electrospun fibers which due to their highly optimally sized pores are able to provide these features along with even including the desired medications in these pores for faster recovery. Hence electrospun nanofibers are an excellent choice for forming dressings for wound healing. Polyurethane (PU), PCL, PVA, PLGA/Collagen are some of the materials which have been found to be the suitable candidates for wound healing application.

F. Tissue Engineering

Tissue engineering which consists of artificial tissue growth for replacement or repair of the damaged organs is one field which has turned into reality thanks to the scaffolds made of nano fibers. The procedure consists of growing a tissue in lab by supporting the cell culturing on an artificial scaffold/ matrix made of nano fibers. When this tissue fully grows into the organ to be replace it is then replaced in the body with damaged organ. Being highly porous and biodegradable, this artificial scaffold then degrades in the body to be excreted away. Thus, its basic functioning is to give proper shape and size to the artificial organ being grown.

On similar grounds blood vessels are ultra-thin with great mechanical properties and come in different sizes. If these need to be replaced, similar properties are expected of nano fibrous materials, luckily which they possess if fabricated accordingly. The design if made bilayered of the nano fibers, proved to be an excellent choice for blood vessel replacement and cell culturing. This bilayered nanofibrous artificial blood vessel consists of a still outer oriented layer and a randomly oriented inner layer. The materials used for fabrication can be poly (lactic acid) (PLA), poly (ester-urethane) urea etc. Similarly, it has been found that the scaffolds made of poly (capro lactone) (PCL), when treated with mesemchymal stem cells in the presence of extracellular matrix and collagen (type I) were able to form bone like appearance demonstrating the possibility of these nano fibers in bone tissue engineering. These scaffolds showed significant improvement in their functioning when blended with materials like nanoparticles of calcium carbonate, gelatin or hydroxapatite. The property of wettability is utilized for the growth of artificial muscle growth as it promotes cell adhesion. When collagen is introduced in this arrangement, it enhances the tensile strength and elasticity of the fiber. Polystyrene nano fibers when treated along with the argon plasma, increases the wettability many fold thus promoting cell adhesion. Other important aspect of tissue engineering is artificial skin generation. Skin is the largest tissue of our body, protecting us from the intruding foreign bodies and regulating body temperature by water retention. Many scaffolds like PCL Collagen, PVA-Chitosan etc. have shown adhesion for fibroblasts which are essential for skin regeneration. Furthermore, materials like polyethylene glycol (PEG) having a very low molecular weight, when blended with PLLA have demonstrated to increase the hydrophilic character of the scaffold increasing cell adhesion. Talking about PLLA, it has also been found that these nano fibers can also find application in neural tissue repair. Apart from these efforts are underway to grow artificial heart, urinary tract, ligament and cartilage via similar technique of cell culturing and proliferation on nano fibrous scaffolds.

VI. Conclusion

This review article thus makes an attempt to have a basic idea about the process of electro spinning along with its historical perspective. The process parameters of the spinning process have huge impact on the resulting nano fibers. Depending upon how the setup is made and how the components are placed tells us the nature of nano fibers being synthesized. Also, as the nano fibers are being manufactured there are few factors that are to be considered which affects the fiber morphology, properties and mainly the diameter. Thus, a solution with proper viscosity along with the high molecular weight helps manufacture smooth nano fibers. In addition more the distance of tip to collector, less is the flow rate keeping the voltage constant and depending upon the polymeric solution, the fiber diameter is altered. Further, applications of these electro spun nano fibers were discussed including scaffolds for bone tissue engineering, skin grafting and wound healing and also water purification and other filtration techniques.

References

[1] Kenneth Bk Teo, Charanjeet Singh, Manish Chhowalla, And William I Milne. Catalytic Synthesis Of Carbon Nanotubes And Nanofibers. Encyclopaedia Of Nanoscience And Nanotechnology, 10(1), 2003.

[2] G Che, Bb Lakshmi, Cr Martin, Er Fisher, And Rodney S Ruoff. Chemical Vapour Deposition Based Synthesis Of Carbon Nanotubes And Nanofibers Using A Template Method. Chemistry Of Materials, 10(1):260–267, 1998.

[3] William Gilbert And Edward Wright. De Magnete, Magneticisque Corporibus, Et De Magno Magnete Tellure: Physiologia Noua, Plurimis & Argumentis, & Experimentis Demonstrata. Excudebat Short, 1967.

[4] Charles Vernon Boys. Lvii. On The Production, Properties, And Some Suggested Uses Of The Finest Threads. The London, Edinburgh, And Dublin Philosophical Magazine And Journal Of Science, 23(145):489–499, 1887.7

[5] Jf Cooley. Improved Methods Of And Apparatus For Electrically Separating The Relatively Volatile Liquid

Component From The Component Of Relatively Fixed Substances Of Composite Fluids. Patent Gb, 6385, 1900.

[6] Wj Morton. Method Of Dispersing Fluids. Us Patent, 705:691, 1902.

[7] John Zeleny. The Electrical Discharge From Liquid Points, And A Hydrostatic Method Of Measuring The Electric Intensity At Their Surfaces. Physical Review, 3(2):69, 1914.

[8] Formhals Anton. Process And Apparatus For Preparing Artificial Threads, October 2 1934. Us Patent 1,975,504.

[9] As Colleagues. On The 100th Anniversary Of The Birth Of Iv Petryanov-Sokolov. Izvestiiarussian Academy Of Sciences Atmospheric And Oceanic Physics C/C Of Izvestiia-Rossiiskaia Akademiia Nauk Fizika Atmosfery I Okeana, 43(3):395, 2007.

[10] Jayesh Doshi And Darrell H Reneker. Electro spinning Process And Applications Of Electrospun Fibers. In Industry Applications Society Annual Meeting, 1993., Conference Record Of The 1993 Ieee, Pages 1698–1703. Ieee, 1993.

[11] Hao Fong And Darrell H Reneker. Electro spinning And The Formation Of Nano fibers, Volume Chapter, 2001.

[12] Hongfei Jia, Guangyu Zhu, Bradley Vugrinovich, Woraphon Kataphinan, Darrell H Reneker, And Ping Wang. Enzyme-Carrying Polymeric Nano fibers Prepared Via Electro spinning For Use As Unique Biocatalysts. Biotechnology Progress, 18(5):1027–1032, 2002.

[13] Thurston E Herricks, Sae-Hoon Kim, Jungbae Kim, Dan Li, Ja Hun Kwak, Jay W Grate, Seong H Kim, And Younan Xia. Direct Fabrication Of Enzyme-Carrying Polymer Nano fibers By Electro spinning. Journal Of Materials Chemistry, 15(31):3241–3245, 2005.

[14] Xdhr Fang And Dh Reneker. Dna Fibers By Electro spinning. Journal Of Macromolecular Science, Part B: Physics, 36(2):169–173, 1997.

