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Overview of Nano-Fiber Fabrication via Electro-Spinning Tailored for Energy Storage Systems

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Abstract. The ultra-fine fibers arising from electrospinning have two significant properties, such as a large surface to volume ratio and a structure that is relatively free from defects at a molecular level. A high surface to volume ratio makes electro-spun materials suitable for undertaking activities that require a higher physical contact, including providing a site for a chemical reaction as well as the filtration of small-sized physical materials. The fibers provide sufficient storage space and also play a critical role in converting the stored energy into electrical currents by easing the transfer of electrons. However, electrospinning possess various limitations, including difficulties in preparing inorganic nanofibers and limited quantity or variety of polymers used in the process. In this analytical study, the nano-fiber bundles' fabrication process with electrospinning and correlation between extrinsic electrospinning parameters and relative abundance of different resulted fiber morphologies tailored for energy storage systems is examined.

1. Review on Electrospinning and Electrostatic Phenomenon

In the early 1930s, Formhals employed electrospinning fabrication method as a fiber spinning technique. In 1934, the invention was patented, titled as" process and apparatus for preparing artificial threads" which developed spinning techniques. However, some practical issues such as fiber drying and collection had remained until he initiated his first patent overcoming spinning difficulties at the time. A movable thread was applied to collect the threads in a stretched condition. In his patent, he reported the spinning of cellulose acetate fibers utilizing acetone as the solvent [1, 2].

Electrostatic phenomena arise from the ability of electrons to move with relative ease in various materials. Electrostatics comprises of two general classes including conduction and induction. Induction refers to a temporary state where electrons in a substance are either attracted to the repelled by the nearby charged object [3]. Conduction, on the other hand, occurs when a charged object comes into actual contact with a neutral object. The excess electrons move from a charged object to a neutral object; thus, when the objects are separated, the objects acquire the same charge [4]. Electrostatic charges exert forces calculated using Coulomb's law F= k Q1.Q2/d^2 between opposite charges causing water droplet deformation [5]. In general, electrospinning refers to the production of fibers by means of electric current to

draw charged threads of polymer solutions. The fibers produced using this process usually has a thickness of hundreds of nanometers. The electrospinning process shares the characteristics of conventional dry spinning as well as electro-spraying of fiber [6]. The process is highly suitable for the production of complex and large molecules as the process does not involve the use of chemistry coagulation or the application of the high temperatures [7–12].

2. Overview of Nano-fiber Bundles Fabrication Methods and Electro-spinning

Nanofibers refer to fibers that have a diameter of less than 1000nm; they can be developed using various processing techniques [7,8]. So far the nano-fiber making techniques include direct drawing [13–15], magneto-spinning [16], extrusion [17, 18], melt-blowing [19], hard templating [20], soft-templating [21], self-assembly [21, 22], lithography [23, 24], centrifuge spinning [25, 26], hydrothermal/solvothermal [27], ball milling [28], chemical vapor deposition [29, 30], and electrospinning [31–34]. Among thereof fabrication methods, electrospinning outperforms due to its many advantages such as controllable fiber diameter (from tens of nanometer to a few microns), covering fabrication of wide range of materials (natural and synthetic polymers, metals, ceramics, composites, sol-gels), versatile fiber morphologies (porous, dense, core-sheath, hollow, spiral, side-by-side, nanoparticles, nanorods, nanowires, nanosheets, and nanobelts), and capable of large scale production [7–11].

Nano-fibers formation stems from the electrostatic force along with the spinning force resulting in the continuous splitting of polymer droplets. Nanofibers deposit on the metal collector plate, layer upon layer, thus resulting in the formation of a nanofibrous mat [35–37]. The extrinsic parameters of the electrospinning process significantly impact the nanofiber structural morphology. Extrinsic parameter comprises of the working distance, viscosity, conductivity, polymer solution, humidity, temperature, as well as the applied voltage. To attain a uniform nanofiber mat, it is crucial to optimize the extrinsic parameters. When the nano-fibrous mat is uniform, it results in the formation of the bead-containing fibrous structure and continuous fibrous structure (nanofiber yarns). Nanofiber yarns are defined as entangled continuous fiber bundles possessing two intrinsic features: continuous length and interlocked twisted structure [38].

The correlation between extrinsic electrospinning parameters and relative abundance of different fiber morphologies leads to the formation of different nanofiber bundles forms [39]. In general, nanofiber bundles can be categorized as the following [40] (See Figure 1):

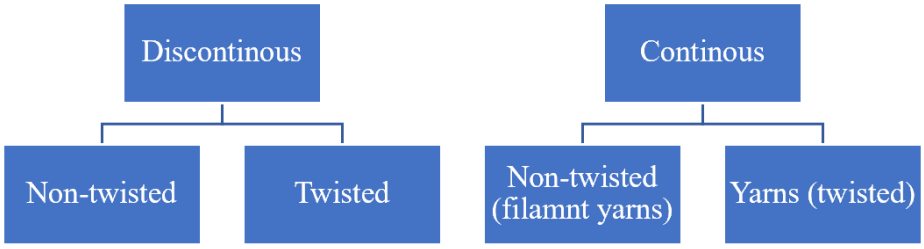


Figure 1: Nanofiber bundle categories.

3. Electrospinning Categories

Nanofibers production by means of electrospinning technique may occur in two ways needle-less and needle-based. Needle-based electrospinning constitutes starting with a polymer solution in

a tightly closed reservoir as these limits as well as prevents solvent evaporation. The needle-based system is essential as it allows for the processing of a wide range of materials, including highly volatile solvents [41]. Needle-based electrospinning has the following advantages process flexibility where it has the capacity to process various structures such as multi-axial and core-shell fibers. The distinction between the two fibers enables the incorporation of Active Pharmaceutical Ingredients (API) to be incorporated in the fiber. Another advantage is that the needle-based method has tightly controlled flow rate, minimizes solution waste, and has a limited number of jets [42]. The Numerous advantages have made the needle-based method immensely popular.

On the other hand, needle-less electrospinning allows for the large-scale production of materials. A Starting polymer solution inside an open vessel is utilized to generate nanofibers using a rotating or stationary platform [43]. However, the needle-less electrospinning method cannot carry out versatile fiber production. Also various process parameter cannot be controlled, including the flow rate [44].

4. Electrospinning Process and Principles

Electrospinning refers to a process used to develop a nonwoven fabric that is impermeable using submicron fiber when a liquid jet that is a millimeter in diameter is pushed through a nozzle that has an electric field. In general, the fiber formation process in electrospinning can be observed and classified into three different stages: Deformation of the prolate droplet (Talyor cone) and jet initiation, whipping or bending instability, and fiber deposition. The general setup for electrospinning is depicted in Figure 2. The electrostatic charging at the tip of the nozzle is crucial to the formation of a Taylor cone where a single jet of fluid ejects [36]. The acceleration and thinning of the jet in the electric field and radial charge repulsion causes the primary jet to split into multiple filaments; this is referred to as "Splaying." The size of the resultant fibers depends on the number of the subsidiary jets formed. Under normal conditions, the fluid jet whipping in electrospinning is immensely fast as this condition is essential for the production of nanofibers [45]. In general, the fiber formation process in electrospinning can be observed and

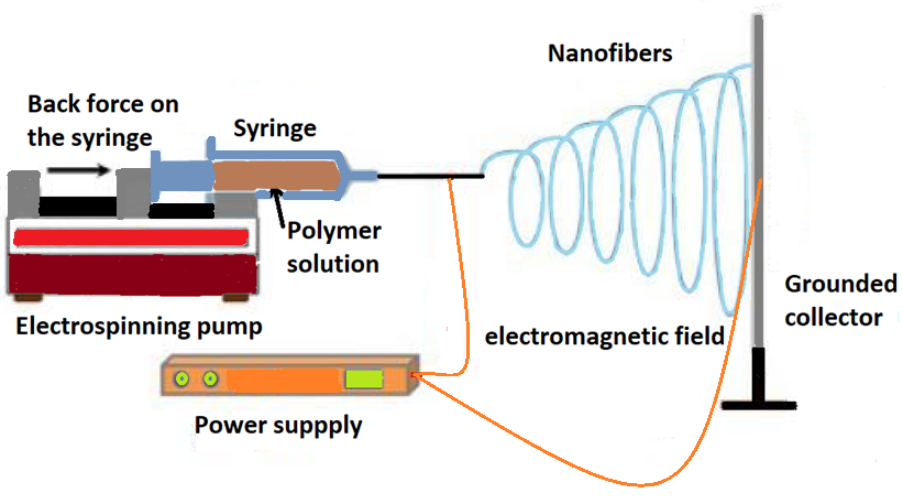


Figure 2: General electrospinning setup.

classified into three different stages: Deformation of the prolate droplet (Taylor cone) and jet

initiation, whipping or bending instability, and fiber deposition.

4.1. Taylor Cone

In 1964, Geoffrey Taylor in initially described the cone. Taylor's primary interest was in determining how water droplets behave within strong electric fields, for instance, thunderstorms. Exposing a small volume of a liquid that is electrically conductive to electric field results in shape distortion due to surface tension. Increase in voltage increases the impact of the electric field, as the electric field exerts a magnitude force on the droplet similar to the surface tension results in the formation of a cone shape. On reaching a given threshold voltage, the rounded tip invert then releases a jet of liquid. The cone-jet commences the start of the electro-spraying process achieved at a voltage higher than the threshold. The Taylor cone refers to the theoretical limit of a cone-jet when the electro-spraying process commences. For a perfect cone to be achieved there needs to be a semi-vertical angle of 49.3 degrees, the cone surface needs to be equipotential, and the cone ought to exist in a steady-state equilibrium [46]. Taylor cone formation is an essential part of the electrospinning process. Symmetrical vortices arising within the Taylor cone is likely to increase the velocity of the solution. Beads that occur in cone-jet results in the formation of beaded nanofiber [47].

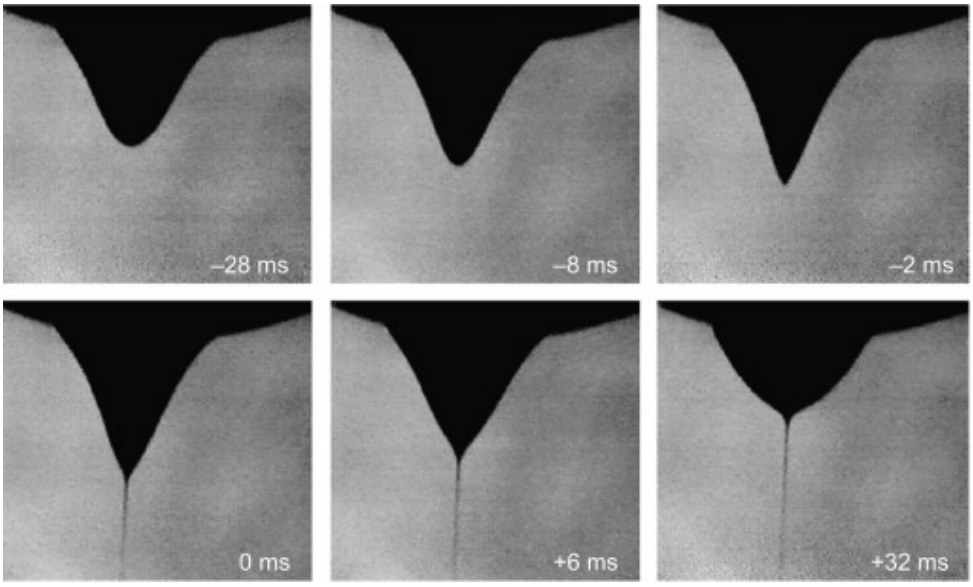


Figure 3: Deformations of the prolate droplet and Taylor cone by increasing the electric field captured in different timings and ultimately, the formation of the jet [37].

In Figure 3, the formation of a Taylor cone captured in different timings can be observed.

4.2. Whipping and Jet Instability

A strong electric field is likely to deform a liquid of finite electric conductivity form a conical shape arising from the balance between the surface tension and electric stresses. Conversely, close to the apex of the cone the structure is unstable and the thin jet structure replaces the associated singularity. The electrospray arises from the imposed flow rate of the liquid of the cone-jet structure that has stability within certain applied voltage values — the arising from the cone-jet structure breaking into spherical droplets due to axisymmetric instabilities. However, a lateral instability causes the jet to bend of its axis arising from electrostatic repulsion between

the straight and the bent parts of the jet. In the instance that the whipping instability growth rate is larger than the one associated with a jet breakup; thus, the jet off-axis movement becomes a significant aspect of its evolution [48].

Replacing a liquid with a polymer solution where the solvent evaporates prior to a drop breakup taking place results in polymer fiber formation. The existence of lateral instability within the electrospinning application results in the formation of thinner fibers as the bending continues to stretch and along with thinning the jet. However, in most experiments carried out, the whipping is noticeably chaotic, thus making it difficult to have an in-depth understanding of its properties and structure [7, 8, 48].

4.3. Fiber Deposition

Nano-fibers formation emanates from the electrostatic force accompanied by the spinning mechanical force resulting in the continuous splitting of polymer droplets. Nanofibers deposit on the metal collector plate, layer upon layer, thus resulting in the formation of a nanofibrous mat [35–37].

5. Solution-based Electrospinning and Related Effective Parameters

Solution-based electrospinning needs a solvent to solubilize a given polymer. Consequently, identifying the correct solvent plays a vital role in attaining a homogeneous polymer solution. The solution parameter is lucrative in determining a suitable solvent for a given polymer. Solubility parameter takes into consideration the various molecular interactions in a given mole of material including such as polar interaction, dispersion forces, as well as specific interaction, including hydrogen bonding [49]. Cohesive energy is given as

$$E = \Delta H - RT \tag{1}$$

Where: ΔH is Latent heat of vaporization, T is Absolute temperature, and R is Universal gas constant.

Later, Charles M. Hansen extended the Hildebrand solubility theory to Hansen Solubility Parameters (HSP) 21, which estimates the relative miscibility of polar and hydrogen bonding systems as [50]:

$$\delta_i{}^2 = \delta_d{}^2 + \delta_p{}^2 + \delta_h{}^2 \tag{2}$$

where: δ_i is Hansen solubility parameter, δ_d is Dispersive component, δ_p is the polarity, and δ_h is the hydrogen bonding. A suitable solvent for a particular polymer ought to have a solubility parameter close to that of the polymer. Therefore, calculating the Hansen solubility parameter where the polymer-solvent ought to have a small value of Ra [51].

$$Ra^2 = 4(\delta_{d1} - \delta_{d2})^2 + (\delta_{p1} - \delta_{p2})^2 + (\delta_{h1} - \delta_{h2})^2 \tag{3}$$

Additionally, a suitable solvent ought to have a relative energy difference (RED) of less than one. And RED = Ra/Ro Where Ro refers to the radius of a sphere [51]. where:
RED < 1 the molecules are similar and dissolve, RED $= 1$ the molecules partially dissolve, and RED > 1 the molecules do not dissolve.

Nanofibers fabrication could be affected by many factors which lead to different morphologies such as uniform or ordered pattern structure with a round cross-section, beads-on-string structures, or individual beads. These crucial factors such as polymer type, polymer molecular weight, polymer distribution, polymer concentration [52, 53], solution conductivity, solution surface tension, solution viscosity, and solvent properties. Solvent properties contain boiling point, volatility, and dielectric properties [54]. Operating factors are another key parameter in final fiber morphology, which including applied voltage, collecting distance, the flow rate

of the polymer solution [55]. Last but not least, external conditions or ambient conditions for intense humidity, ambient temperature, and addition flow are also effective parameters on electrospinning [7, 8, 33, 56].

5.1. Concentration

The electrospinning process depends on polymer concentration as the most crucial factor. Such that changing in polymer concentration leads to a change in solution viscosity. As the polymer concentration increases, the viscosity increases first at a steady rate and thereafter at a much higher rate [57]. The solution viscosity is extremely governed by intermolecular interactions between polymer-polymer, polymer-solvent, and solvent-solvent within the polymer solution. Electrospinning a dilute polymer solution is analogous to an electro-spraying process. On the other hand, the polymer intermolecular distance within the solution is so considerable that the interaction is considered to be very weak. Therefore, the viscoelastic force in the polymer jet is minute to form a uniform fibrous structure. In this process, the jet splits into separate charged sections as the voltage is applied. Gradually theses charged sections turn into droplets or individual beads as a result of high surface tension caused by solvent evaporation while spinning. Similarly, an increase in the polymer concentration leads to higher viscoelastic force and more difficult for the jet to be split. In lieu of breaking the like-charged sections, electrostatic repulsion within the solution elongates the links between charged sections, consequently forming thinner filaments. Relatively thicker sections stretch thinner although to the links between charged sections. As the solvent evaporates while spinning, due to the surface tension, filaments tend to take the shape of beads-on-string morphology. Accordingly, a further increase in the polymer concentration, brings about uniform elongation of and formation of the jet, resulting in homogeneous fiber morphology [7, 8, 57, 58].

critical concentration (c*) is defined to distinguish whether predominant intermolecular interaction will happen or not leading to a chain entanglement [59]. In this regard, the following formula has been utilized to describe solution entanglement. The following formula calculates the ratio of polymer molecular weight to the solution entanglement molecular weight [60, 61]:

$$(n_e)_{solution} = \frac{M_W}{(M_e)_{solution}} = \frac{\phi M_W}{M_e} \tag{4}$$

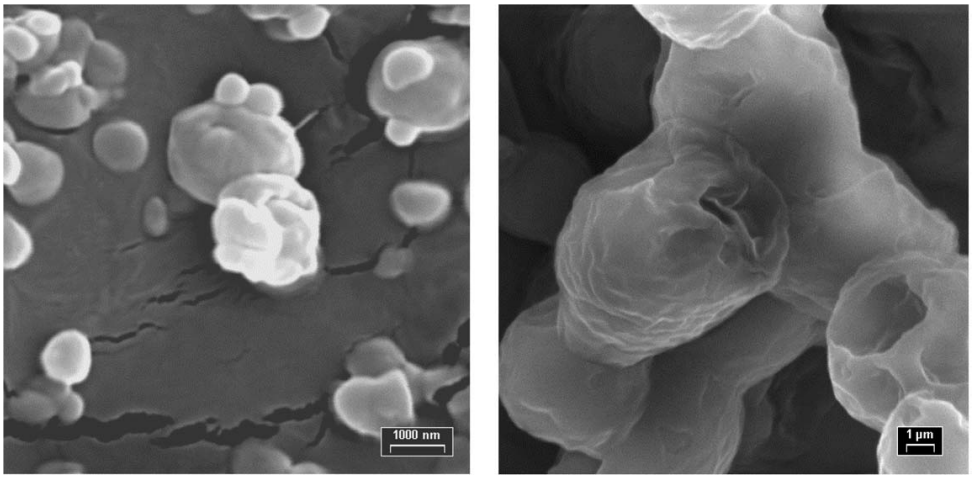
where: M_e is entanglement molecular weight, M_W is polymer weight average molecular weight, and ϕ is polymer volume fraction.
if $(n_e)_{solution} < 2$: polymer chains do not entangle and individual beads structure is formed.
if $2 < (n_e)_{solution} < 3.5$: insufficient polymer chain entanglement and beads-on-string structure is resulted.
if $(n_e)_{solution} > 3.5$: sufficient polymer chain entanglement and beads-on-string structure is shaped.

In general, throughout electrospinning, the solution viscosity can be increased by using a concentrate polymer solution or increasing the weight of the molecular polymer. For instance, polylactide solution doped with polyethylene oxide that has a high molecular weight increases viscosity of the polymer solutions [62]. Increased viscosity improves the jet stability allowing for the construction of multi-filament yarn, individual fiber, and aligned unidirectionally across a large area or enabling the individual filaments the develop an ordered pattern. Introducing a fiber-forming agent resulted in the formation of an elongated stable jet suitable for the collecting arrays of aligned fibers [63]. Research has shown that using the polymers with a higher molecular weight and increasing viscosity by increasing the concentration of the electrospinning solution results in a stable jet [56].

5.2. Solvent

Selecting a proper solvent plays a prominent role in the electrospinning process. Since solution's conductivity, viscosity and surface tension are affected by a handful of solvent's characteristics including solvent's conductivity, boiling point, vapor pressure, polarity, dipole moment, dielectric constant, etc.

Solvent volatility ought to match up with the jet's traveling time, i.e., solvents with low volatility result in wet web structure in the end. In the same manner, rapid evaporation of highly volatile solvents is accompanied with cooled down and frozen filament surface leading to a porous surface on the web structure [64] (see Figure 4).



(a) (b)

Figure 4: (a) solid beads vs.(b) porous beads produced by electrospinning [64].

Electro-spinnability of a solution can be enhanced by doping a solution using salt, using a solvent that has a high dielectric constant and higher conductivity as this increases the spinning jet charge density. However, these same factors result in a shortened length jet that ought to be avoided if one has an objective of attaining acquitting a stable jet with a greater length. Doping polyethylene oxide with salt illustrates higher conductivity minimizing the length of the stable jet. However, the chloroform system the critical conductivity between the bending instability and the long stable jet is estimated to be as low as 0.6 $\mu S/cm$ [65].

5.3. Voltage and Electric Field

Conventionally, in the electrospinning process, an increase in the voltage leads to an increase in the length of a stable jet. The elevation in length stems from a larger tangential electric field from starting from the needle tip as well as lower static charge density to stabilize the electrospinning jet. However, the conventional effect does not cater to all solutions. The inconsistency may be due to a variety of factors such as dielectric property and conductivity of the solution. These factors have more influence on jet stability [66].

The bending and stretching stability of the jet are affected by applied voltage in the sense that uniform patterned web could result at higher voltages in some cases. However, the applied voltage is not the only principal element, and other elements such as flow rate and jet traveling speed, and density have to be compromised at the same time [67].

Typically, the electrospinning process uses direct-current (DC) voltage; however, alternating-current (AC) has been reported in a few papers which are not considered as safe as DC voltage, particularly in high voltage circumstances [68–70]. The reason for taking advantage of AC could be witnesses when highly aligned fibers are sought. In this sense, highly aligned web structure is collected on a rotating mandrel when the AC power source is applied [71].

5.4. Flow Rate

The solution flow rate has to be reached at a minimum certain point at which the spinning jet can compensate for the solution evaporation rate in order to maintain the continuous flow of the fibers [72]. If the flow rate is higher than needed, the solution will accrue at the tip of the needle resulting in a formation of large droplets hindering the formation of normal Taylor cone, and ultimately solution dripping off the tip. Sometimes also blockage of the needle or nozzle happens, which is due to the rapid evaporation of the solvent, causing solidification of the droplet inside the needle or nozzle [73, 74].

5.5. Collecting Distance

The collecting distance is proportional to the electric field intensity in the sense that solution traveling time can be affected directly. In some circumstances, less collecting distances can be helpful meaning that stronger electrostatic force is applied to the jet consequently shorter time for the jet to travel. A stronger electrostatic force can be either efficacious due to the effective stretching of the jet hence the formation of finer fibers on the collector. However, shorter distance may cause reverse effects, i.e., incomplete solvent evaporation, thereafter formation of wet fiber webs. Similarly, increasing the distance can lead to a weaker electric field and dripping of the jet in the half-way towards the collector [8, 55, 72, 73].

5.6. Polarity

The electrospinning process with high voltage electrode applied to the nozzle causes more strong and concentrated electric field on the nozzle such that when the jet travels the distance from the high charged needle to the collector, it experiences a reducing electrostatic force. This facilitates the chaotic whipping instability, which brings about a large fiber deposition area. Contrary, a higher voltage applied to the collector leads to a more intense electric field near to the collector, i.e., it strengthens the jet movement toward the collector. This suppresses the whipping movement [7].

5.7. Humidity

Electro-spun fiber morphology is influenced by ambient humidity, i.e., interaction between jet solution and moisture. Humidity can affect fiber diameter by means of modifying the solvent evaporation rate. The average diameter of nanofibers decreases with humidity increase. At relatively high humidity environments, beaded fibers start to form. Conversely, at relatively lower humidity level, the evaporation rate of the solvent could be high due to a difference in pressure between vapor and ambient air inside the electrospinning chamber. As a result, fibers happen to solidify thereafter producing coarse fibers as compared to fibers generated in relatively higher humidity levels [75].

Humidity also affects the surface structure in such a way that, in fast evaporation circumstances caused by low humidity, porous fibers start to form. This could be explained by the fact that evaporation takes heat energy out of the jet surface, resulting in a reduction on surface temperature to a level that can initiate tiny ice formation on the filament surface. These tiny ices are preserved until the deposited fibers on the surface of collector exchanges heat with the ambient air and reaches the ambient condition [76].

5.8. Temperature

Temperature is considered to be in a close relationship with polymer properties affecting crystallinity and molecular chain orientations [7]. According to Yang et al., the surface tension and the viscosity of the electrospinning solution decreases with increasing the ambient temperature. However, an extra increase in temperature causes rapid evaporation of the solvent, which can disrupt the electrospinning process. Therefore, a balanced temperature point shall be found in order to gain the most desired fiber quality [75, 77].

6. Common Polymers in Electrospinning

Polymers used in electrospinning can be natural, synthetic, or copolymer depending on the needs of the manufacturers as well as the availability of the materials. Examples of natural polymers include collagen, chitosan, and fibrinogen [8]. Natural polymers have some advantages over synthetic polymers due to their immunogenicity and biocompatibility. Natural polymers such as collagen and gelatin can provide solutions used in the electrospinning process. In circumstances where synthetic fibers are readily available, natural fibers may not suffice. Some of the synthetic polymers include polyvinyl alcohol (PVA), Polyvinylpyrrolidone (PVP), polylactide (PLA), polyglycolide (PGA), poly-D-lactide (PLDA), and polylactide-co-glycolide (PLGA) [57]. Combining either natural or synthetic fibers or combining several synthetic fibers can produce copolymers [59].

The aim is to develop polymers that can withstand various limitations, including heat and degradation. Copolymers are usually developed to overcome the limitations of a given natural or synthetic polymer [60]. For example, adding poly (glycolide) can minimize the stiffness or rigidity of poly (ethylene-co-vinyl alcohol) (PEVA) [61]. Most copolymers provide a variety of features needed by manufacturers to develop suitable nanofibers.

7. Applications of Electrospinning and its Role in Energy Storage Systems

Electro-spun fiber size may exist within the nanoscale while the fibers may have the nanoscale surface texture that results in various modes of interaction in comparison with the macroscale materials. The ultra-fine fibers arising from electrospinning have two significant properties, such as a large surface to volume ratio and a structure that is relatively free from defects at a molecular level. A high surface to volume ratio makes electro-spun materials suitable for undertaking activities that require a higher physical contact, including providing a site for a chemical reaction as well as the filtration of small-sized physical materials. Also, minimal defects at a molecular level allow electro-spun fibers to attain maximum strength, thus can attain high mechanical performance for composite materials [78].

There are various applications of electro-spun fiber can act as filters; for instance, the Lycopodium moss spores have a diameter of 60 micrometers, thus can only be captured by an electro-spun polyvinyl alcohol fiber. Nanofibers webs may act as an efficient filtering medium as the nanofibers have small London-Van Der Waals forces that are crucial for adhesion among the fiber that captures materials. Nanofibers in textile manufacturing provide an opportunity of developing seamless non-woven garments that may have a variety of functions including environmental, flame, and chemical protection. Electrospinning can combine various coatings and fibers in order to develop three-dimensional shapes, for instance, clothing that consists of different layers of polymers [79].

Medical application of nanofibers involves tissue engineering where electro-spun scaffold may be penetrated with cells that treat or replace biological targets [80]. Also, wound dressing using nanofibers have an excellent capability to separate the wound from microbial infections [81]. Electrospinning is essential in the development of medical textile materials or diverse fibrous treatment delivery system comprising of transdermal patches and implants. Electrospinning can ensure the establishment of a continuous manufacturing system within the pharmaceutical industry. Synthesized liquids can be turned into a tablet using electrospinning [82].

Electrospinning is a feasible process that can be suitable for the manufacture of elongated composite materials within a stipulated timeframe. The process has the potential to produce fibers in sufficient quantities within a reasonable period. Research has illustrated that electrospinning is the most cost-effective way to manufacture the various medical fibers such as medical implants, scaffolds, wound dress for artificial human tissues. Scaffolds function similarly like an extracellular matrix found in natural tissues [83]. Biodegradable fibers are used as an extracellular matrix and may be coated with collages in order to promote cell attachment. The

last application of electro-spun fibers is that they act as catalysts, where they act as a surface where enzymes are immobilized. The enzyme can be vital in breaking down toxic chemicals from the environment [84]. The role of electrospinning is to produce fibers used in energy conversion and storage. The electrospinning process produces fibers with diameters ranging from nanometers to micrometers [85]. The fibers provide sufficient storage space and also plays a critical role in converting the stored energy into electrical currents. A general spinning setup consists of a high voltage power supply, a grounded collector, and a syringe with a metallic needle [86].

In most cases, the supply of the voltage is either a melt or a solution. As the heating continues, a pendant droplet forms beneath the syringe. The pendant droplet is subjected to electrostatic repulsion to turn it into a cone-shaped material known as Taylor cone. As the electrostatic propulsion continues, the conical droplet discharges polymer solution at the tip of the needle [87]. The interaction between the electric field and surface tension eventually forces the solvent to evaporate, leaving behind a long, thin filament which solidifies into a uniform fiber. Electrospinning began in the 1930s, and experts have used it in the development of fibers used in storing and conversion of energy inside the lithium-ion batteries [88]. Many adjustments have been made to the process to make it less energy consuming and more productive.

Some of the advantages of electrospinning include flexible temperatures, short production cycle, and little pressure. Besides, nanofibers synthesized from the hydrothermal method have a lower aspect ratio, which is critical in the transfer of energy [89]. In other words, fibers made from electrospinning are likely to provide more efficient energy transfer compared to other methods such as electro-spun NWs [90]. However, electrospinning also has various limitations, including difficulties in preparing inorganic nanofibers and limited quantity or variety of polymers used in the process. Limited variety of polymers restricts manufacturers to the use of available materials which may not reach the desired energy capacities [91]. Besides, the performance of nanofibers made from the inorganic materials is likely to decline after calcination. Manufacturers are also silent about the aging process which renders many batteries inefficient. The aging process drains the energy capacity of various cells and reduces the performance of lithium-ion batteries. According to Zhang, Tan, Kong, Xiao, and Fu (2015), much research is ongoing to determine the cause of aging and develop appropriate measures [92].

8. Conclusion

The ultra-fine fibers arising from electrospinning have two significant properties, such as a large surface to volume ratio and a structure that is relatively free from defects at a molecular level. A high surface to volume ratio makes electro-spun materials suitable for undertaking activities that require a higher physical contact, including providing a site for a chemical reaction as well as the filtration of small-sized physical materials. Also, minimal defects at a molecular level allow electro-spun fibers to attain maximum strength, thus can attain high mechanical performance for composite materials.

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