

# Electrospun Polymer Nanofibers

Subjects: [Polymer Science](#)

Contributor: Abdulhamid Al-Abduljabbar , Irfan Farooq

Electrospun polymer nanofibers constitute one of the most important nanomaterials with diverse applications. Nanofibers are classified as fibers with a ratio of length to thickness in the order of one thousand, or nanomaterials that have at least one dimension of 100 nm or less. A nanofiber with a diameter of  $\sim 100$  nm can have a specific surface area up to 1000 m<sup>2</sup>/g. Nanofibers can be produced by selecting the proper combination of polymers and additives, and using appropriate production techniques based on several essential characteristics that impact criteria of the intended particular application area. Electrospinning of polymer nanofibers is a widely used for investigation of their properties for uses in quite diverse applications. Attractive properties of electrospun nanofibers include the extremely high specific surface area, high porosity (typically 90%), light weight, controllable pore size, flexibility in surface functionalities, large permeability, excellent mechanical properties, high aspect ratio, and length up to many centimeters. Due to their exceptional characteristics, electrospun polymer nanofibers are used in many applications, which include biomedical technology, such as tissue engineering, wound healing and dressing, and drug delivery systems. In addition they have diverse uses in sensors and biosensors applications, air filtration, defense applications, energy devices and protective textiles.

polymer nanofibers

electrospinning

polymer processing

mechanical properties

biomedical application

energy storage separation

## 1. Polymers Used in Electrospinning

The most prominent characteristic of electrospinning is its ability to process a huge variety of polymers to generate nanofibers for a variety of applications. Polymers can be categorized into synthetic, natural, or mixed polymers. Each category will be discussed in this section, with special significance placed on the electrospinning process.

### 1.1. Natural and Synthetic Polymers

Generally, electrospun nanofibers made of natural polymers replicate the physicochemical properties of the extracellular matrix. Natural polymers are composed of lipids, proteins, nucleic acids, and polysaccharides and so on. In the medical field, natural polymers showed superior biocompatibility and decreased immunogenicity in contrast to synthetic polymers. Natural polymers have an inherent affinity of closeness to cells because they have a unique protein arrangement, as in glycine and aspartic acid, which makes them a strong candidate for tissue engineering technology. Tissue scaffolds based on natural polymer function better in clinical settings. Nevertheless, synthetic polymers are more advantageous than natural ones due to their superior mechanical properties, such as strength and viscoelasticity, and higher rate of degradation. In medical applications, synthetic polymers such as

polylactide, polyglycolide, and poly (E-caprolactone) are frequently utilized as hydrophobic biodegradable polyesters [1].

## 1.2. Composite Polymers/Copolymers

It was demonstrated that the advantages of natural and synthetic polymers can be combined through using both of them in the electrospinning process. For example, various studies were conducted on combinations of polycaprolactone coated with gelatin, silk/polyethylene oxide blend, hyaluronan and polycaprolactone, polycaprolactone–polylactic coated with collagen, starch/polycaprolactone blend, chitosan–polyethylene oxide, poly-L-lactic acid or poly(lactic-co-glycolic acid), or a mixture of natural polymers such as collagen and chondroitin sulphate, collagen and chitosan, collagen and elastin, and gelatin with PHBV [2][3][4]. Copolymers can also be used in electrospinning to alter cellular affinity, morphology, mechanical characteristics, and various physical properties. For instance, the spinning blend of an ethylene-co-vinyl alcohol nanofibrous mat was strengthened by incorporation of glycolide. The effective compromise between decomposition speed and hydrophilicity was shown by a three-block copolymer made of polylactic acid, p-dioxanone, and polyethylene glycol.

## 2. Electrospinning Process Parameters

During the electrospinning process, the polymer solution is converted into nanofibers, which is influenced by various factors [5][6]:

- Parameters related to the solution, such as polymer molecular weight, polymer concentration, surface tension, conductivity, solvent volatility, and viscosity.
- Parameters related to processing such field strength, flow rate, tip-to-collector separation, applied voltage, placement and design of the needle tip, composition and geometry of the collector, and take-up velocity of the collector.
- Properties related to environmental factors including temperature, humidity, and pressure.

Changes in any parameter among these sets will definitely change the evolution of the electrospinning process and, thus, will change the characteristics of the resulting nanofibers. Therefore, it is important to investigate these parameters within their containing sets and assess respective effects on the process. In the following, these factors will be discussed.

### 2.1. Parameters Related to the Polymer Solution

Among the different variables affecting the outcome of the electrospinning process, the characteristics of the polymer solution have the main effect on the development polymer nanofibers with a broad range of sizes and morphologies. This can be categorized in the following.

### 2.1.1. Concentration of the Polymer

For chain entanglement to take place, the polymer concentration should be at the optimum level: neither too low, nor too high. To produce continuous fibers, viscosity and surface tension have a prominent role for selecting the concentration of polymer. In the electrospinning process, the polymer solution with a low concentration affects the surface tension, which leads to synthesize beads instead of fibers [7]. Additionally, when the polymer solution is highly concentrated, it gets stuck at the capillary tip due to high viscosity.

### 2.1.2. The Solvent

Choosing an appropriate solvent to prepare the polymer solution is an essential step in its spinnability. The selected solvent is to have the right properties, such as appropriate evaporation rate, boiling point, and vapor pressure. In case of a binary solvent, molecular interactions, in terms of attraction or repulsion, entirely depend on solvent variety. As the polymer jet travels from the tip to the collector, solvent evaporation and phase separation take place simultaneously prior to the deposition of solid polymer fibers. This process is substantially influenced by the solvent evaporation rate [8]. The solvent vaporization rate is significantly influenced by the solvent vapor pressure [9]. Results confirm that physical characteristics of the polymer depend upon the selection of solvent. Natural solvents are expensive and also harmful to the environment. Thus, prior to application, extra washing or purification is required [10]. Morphology of fibers is also influenced by the rate of evaporation of the solvent. Rapid evaporation may cause the generation of flat fibers as opposed to the more typical round ones. Flat fibers actually develop when a little solvent is entrapped among fibers, causing the fiber to flatten out as the solvent evaporates [11]. The selection of solvent influences fiber diameter.

The choice of a good solvent and preparation of a suitable solvent system for the desired polymer are necessary for the generation of electrospun polymer nanofibers. Solubility parameters are combined to aid in the search for the desired solvent system. In literature, ternary solubility diagrams, also known as Teas graphs, are widely used for the selection of solvent systems.

### 2.1.3. Electrical Conductivity

In the electrospinning technique, the electrical conductivity of polymer melts or solution is an important factor. The type of polymer utilized, the solvent employed, and the presence of ionizable salts all influence in determining the conductivity of a polymer solution [10]. In comparison, conductive solutions have a higher charge density than less conducting solutions. Therefore, in the presence of an electric field, a high conductive fiber jet experiences higher tensile force when compared to a less conductive one. It was discovered that during spinning, raising the electrical conductivity of the solution causes a sizable decline in the diameter of nanofiber. By contrast, with low conductivity, the electric field is unable to provide enough jet elongation to generate uniform fibers, leading to the appearance of beads. In comparison to synthetic polymers, natural polymers such as gelatin, that are polyelectrolytes by nature, have less ability to form fibers. Ions undergo additional stress during the electrospinning process when they are exposed to an electric field, as their carrying charge capacity is increased. Salt addition results in thinner, more uniform fibers, and it also reduces the development of beads [8][9]. This phenomenon is caused by a rise in charge

density, which enables the jet polymer to be subjected to greater elongation and dielectric stresses, leading to the formation of thinner fibers [2].

#### 2.1.4. Viscosity

Most of the research indicates that viscosity is a prominent factor in analyzing diameter and morphology of the fibers. Enhancing the viscosity by molecular weight or by an increase in the polymer's concentration increases the production of polymer fibers with a larger diameter, while the probability of bead generation is reduced, and fibers are more uniform in appearance. It was demonstrated that at very low viscosities, due to the deficiency of chain entanglement, there is no formation of any continuous fiber, and the fiber jet breaks into droplets. On the other hand, when a polymer solution has very high viscosity, it is difficult to shoot a jet from the solution, because the polymer flow stops at the needle's tip. Viscosity of the solution is significantly correlated to the concentration of polymer. In electrospinning, each polymer has an optimal viscosity which has significant influence on morphology of the resulting polymer nanofiber.

#### 2.1.5. Molecular Weight

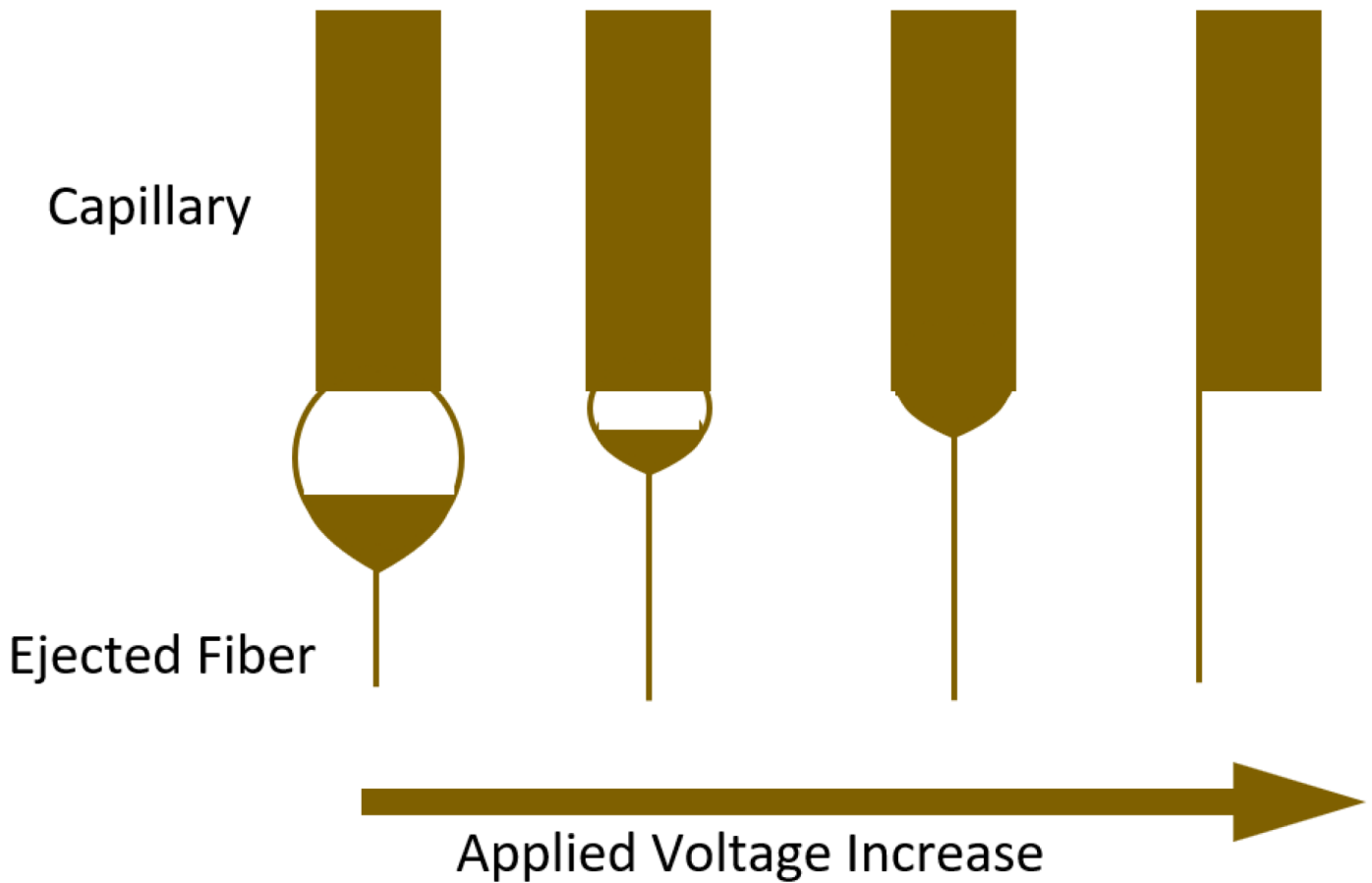
Polymer molecular weight is another vital parameter related to the solution which influences the morphology of the polymer nanofiber. The rheological properties, such as viscosity and surface tension, conductivity, and dielectric strength, are significantly influenced by molecular weight [12]. Therefore, large molecular weight polymers are typically employed to manufacture fibers because they offer the appropriate viscosity. Furthermore, Casper et al. discovered that raising the polymer's molecular weight causes variations in the fiber's morphology, such as reduction in the number of beads and irregular form, while also enlarging pore size. As a result, it became possible to create a mesh with more consistent biophysical properties [2][13]. Low molecular weight solutions typically result in beads rather than fibers. In other words, electro-spraying rather than electrospinning occurs in solutions having less molecular weight. However, the increasing molecular weight causes the fibers' average diameter to increase [10]. In the electrospinning process, chain entanglement plays a significant role, for example, when high molecular weight poly-L-lactic acid is utilized in spite of the low polymer concentration. It has been investigated that chain entanglement is more significant than high molecular weight when it comes to manufacturing uniform nanofibers.

## 2.2. Parameters Related Electrospinning Equipment

### 2.2.1. Applied Voltage

The influence of voltage on the size and morphology of electrospun polymer nanofibers has been subjected to significant controversy. It has been suggested that thicker fibers are produced by higher voltage, due to many exiting polymers. Others, however, have asserted that thinner fibers are produced as voltage increases because electrostatic repulsion forces are applied to the polymer jet. However, in the majority of situations, the rapid solvent evaporation and lower fiber diameter are caused by the higher enforced electric forces in the jet. Therefore, at high voltages, there is more chance of bead production. According to Larrondo and Manley, the diameter of the fiber is reduced approximately to half when the applied electric field is doubled. Deitzel et al. examined polyethylene

oxide/water and observed that by enhancing voltage, the shape of the surface is altered where the Taylor cone and jet fiber formed, as shown in **Figure 1** [3] [8].



**Figure 1.** Influence voltage on the Taylor cone creation. At low voltage, a pendant droplet (white) is produced at the capillary tip while a Taylor cone (dark blue) is produced at the pendant droplet tip. By enhancing voltage, a Taylor cone is produced at the capillary tip, and then further voltage results in the ejection of the fiber jet through the capillary.

### 2.2.2. Feed Rate

Polymer solution delivery speed and jet intensity are influenced by polymer flow rate within a syringe, which influences the diameter and morphology of fibers. Electric field intensity, gravity, and pumping pressure all have an impact on how quickly the polymer solution flows during the electrospinning process. Increasing the polymer solution feed rate resulted in a rise in fiber diameter, while a slower flow rate can be used to create thinner fibers. The slower feed rate is preferable, as the solvent has adequate time to evaporate. Larger flow rates, however, result in the development of beaded fibers because the solvent does not have enough time to evaporate before approaching to collector plate. Zuo et al. reported similar outcomes as well [1][9]. Porosity and shape of fibers are also influenced by the flow rate. Megelski et al. examined the influence of flow rate on the structure of electrospun fibers of polystyrene and tetrahydrofuran: both pore size and fiber diameter increased by enhancing flow rate. At a

high flow rate, fibers were unable to completely dry before reaching the collector, which causes the considerable bead flaws [2]. Additionally, incomplete drying of fibers produced flat or ribbon-like fibers, as opposed to fibers having a round cross section [8].

### 2.2.3. Distance between Tip and Collector

The distance between spinneret and collector affects morphology and fiber diameter, as well. For fibers to have sufficient time to dry before they reach the collector, there must be an optimum distance. If not, beads are produced at either too near or too far a distance. Distance can determine whether electrospray or electrospinning will ultimately occur. Additionally, it is noted that increasing distance results in more round fibers while decreasing it produces more flat ones [14]. Doshi and Renker observed that fiber diameter decreases with increasing distance from the Taylor cone. Additionally, Jaeger et al. investigated how the diameter of electrospun fibers made from polymer solutions of polyethylene oxide/water changed with distance from the Taylor cone. According to one study, increasing the spacing from 1 to 3.5 cm resulted in a reduction of nearly two-folds in fiber diameter, from 19  $\mu\text{m}$  to 9  $\mu\text{m}$  [3]. Short distances will result in flat or quasi-ribbon fiber and a beaded structure regardless of concentration of the polymer solution [2]. This is related to the polymer fiber not being adequately dried before entering the collector [8]. Consideration of the optimum distance is also influenced by a lot of parameters, including the nature of the solvent. Therefore, for high volatile solvents, short distances were employed, whereas for low volatility solvents, such as water, larger distances are needed for sufficient evaporation. For fibers to have adequate time to dry before approaching the collector and producing uniform, bead-free fibers, a minimum distance of 8 to 15 cm is required [10].

## 2.3. Parameters Related to Environment

The quality of electrospun nanofibers is significantly influenced by environmental conditions, including temperature, air flow velocity, and humidity, in addition to electrospinning equipment and substrate parameters. Although electrospinning normally proceeds at room temperature, increasing the temperature from 25  $^{\circ}\text{C}$  to 60  $^{\circ}\text{C}$  results in smaller fiber diameters, which lowers viscosity. Temperature and viscosity have an inverse relationship [7]. It was shown that by enhancing humidity, tiny spherical pores begin to develop on the surface, and further raising the humidity will cause pores to gradually connect to each other. Extremely low humidity also presents a challenge, since the rate of solvent evaporation will increase and the solvent will dry out more quickly. However, greater humidity can result in the discharge of an electrospun solution. A larger fiber diameter is attained due to air flow above the injection needle that will cause an increase in the rate of evaporation through convection [2][9][13].

# 3. Properties of Polymer Nanofibers

## 3.1. Mechanical Properties

Advanced nanomaterials and microstructural components are integrated with the electrospun nanofibers for the vast variety of applications in biomedical, textile, airborne, reinforcing elements in composite materials, filter media,

structure, nano-sensors and so on. During their service lives, they are frequently exposed to stress and strain from the surroundings. The utilization of polymer nanofibers in such wide applications will be discussed. Such wide applications require that EPNF possesses the right mechanical properties for the desired functions. The mechanical behavior of the nanofibers includes the overall deformation under static and dynamic responses, friction, and contacts in polymer nanofibrous networks [15][16]. To determine the mechanical behavior of the EPNF structure, it is essential to examine characteristics of a single electrospun nanofiber. Generally, electrospun nanofibers are too thin and fragile, thus, during electrospinning process, they are accumulated on a nonwoven bundle. Therefore, determining the mechanical behavior of a single electrospun nanofiber is a challenging process that requires overcoming many obstacles using a sophisticated set of instruments. Among these instruments are the following [15][17][18][19][20]:

- A manipulation system that precisely isolates, aligns, and grasps a single nanofiber on a frame without slipping or damaging.
- A proper monitoring system to verify that nanofibers are not harmed by characterization tools such as scanning electron microscopes or transmission electron microscopes.
- A sensitive force transducer having a range of nano- to micro-Newton range (n/μN range) resolution that can measure applied force in the n/μN range.
- An actuator that is capable to load nanofibers until fracture, with high resolution (load unit: μN).

There were numerous attempts to investigate the mechanical behavior of electrospun nanofibers based on tensile tests on nanofibrous mats utilizing the universal testing machine [21][22]. The tension test entirely depends on nanofiber diameters, alignment, and entanglements inside nanofibrous mats. Therefore, this technique cannot be considered appropriate [23][24]. In order to address this problem, numerous alternative methods for the mechanical characterization of continuous nanofibers were presented [15]. Atomic force microscopy (AFM), which includes both force and distance sensors and can be operated in air, liquids, and vacuum, has become one of the generic characterization tools. However, AFM is just the primary tool for other measurement methods. Most of these methods rely on fibers' tensile, bending, stretching, nanoindentation, and shear modulation frequency [15][25][26][27].

## 3.2. Chemical Properties

Fourier-transform infrared spectroscopy, nuclear magnetic resonance, circular dichroism, differential scanning calorimetry, X-ray scattering, and X-ray diffraction are commonly used to characterize the chemical composition of nanofibers. The vibrational spectroscopic technique is used for molecule structure analysis. This approach assists in determining chemical reactions between ingredients of polymers in case of polymer blends [11]. Raman spectroscopy is utilized to examine the structural characteristics of carbonaceous polymers. This was used by Sadrjahani et al. to assess the molecular orientation of electrospun polyacrylonitrile nanofibers [28]. A chain alignment parameter of 0.25 was calculated for nanofibers which accumulated at a 59.5 m/min take-up velocity. Surface chemical characteristics of polymer nanofibers can be analyzed by making use of their hydrophilicity. The

latter is calculated by water contact angle, and it is examined by attenuated total reflectance Fourier transform infrared and X-ray photoelectron spectroscopy. Element detection by X-ray photoelectron spectroscopy is possible up to depth of 100 Å [29]. This technique is used to check the shell within core-shell structure of electrospun nanofibers, not to form a blend or react chemically with core [30]. Supramolecular structures, which are referred to as macromolecular configurations in polymer nanofibers, can be examined by small angle X-ray scattering, wide angle X-ray diffraction and differential scanning calorimetry [31]. The crystalline phase and crystal type are identified by wide angle X-ray diffraction, while small angle X-ray scattering is used to examine the lamellar structure of semicrystalline polymers. Other equipment is not used commonly due to complications in interpreting its pattern.

### 3.3. Thermal Properties

Thermal characterizations of electrospun nanofibers, such as melting and crystallization processes, can be determined by differential scanning calorimetry. To carry out this procedure, electrospun mats weighing around 10 mg are placed in a sealed aluminum pan. To preserve ambient pressure and promote evaporation of leftover solvents, pan covers are equipped with holes. Then, the specimens' temperature is raised from 30 °C to 300 °C while maintaining a heating rate of usually 10 °C/min and a steady flow of dry nitrogen. The following equation determines the percent crystallinity ( $\chi_c$ ) [32]:

$$\chi_c (\%) = \frac{\Delta H_f - \Delta H_c}{\Delta H^{\circ}_f} \times 100$$

where the enthalpy of crystallization,  $\Delta H_c$ , and the melting enthalpy,  $\Delta H_f$ , are acquired from differential scanning calorimetry traces, and the heat of fusion  $\Delta H^{\circ}_f$  is a thermal property of a perfectly crystalline substance [32][33]. In comparison to neat polymer, crystallinity of nylon-6,6 electrospun nanofiber is high, which could be a result of shear stress applied on the polymer jet during the electrospinning process [34]. Peresin et al. made a similar observation and noted that electrospinning significantly increased the degree of crystallinity of polyvinyl alcohol and raised 2 °C in melting temperature. These results are attributed to the orientation and improved crystallization of polymer chains in individual polyvinyl alcohol fibers which undergo extreme shear stress during electrospinning process [35].

### 3.4. Electrical Properties

To analyze the electrical properties of nonwoven mats and single fibers, electrodes are pre-patterned on a substratum or vaporized on top of electrospun polymer materials [36]. To measure electrical conductivity readings from current voltage curves, generally four-point probe [37] or two-point probe [38] measurements are utilized. When using a four-point probe, a material of unknown resistance is contacted by four evenly spaced probes. Measurements based on this technique assume a thin film instead of a porous fiber network. As a result, measured conductivity measurements can be lower than the actual measurement for bulk films. Another source of uncertainty for electrical conductivity is the pins' depth (height) of penetration into fiber mats [39]. Penetration of pins into a polymer fiber mat could be the cause of uncertainty in determining the electrical conductivity.



Utilizing interdigitated electrodes to measure electrospun nanofibers electrical conductivity is an alternative approach [40]. According to Zhang and Rutledge, electrical contact can be established by applying hot pressure of nanofibers on electrodes [41]. Contact resistance is calculated by determining overall fiber resistance on interdigitated electrodes having varying finger spacing and with the help of extrapolating resistance value at zero spacing. It is observed that conductivities of fibers increased exponentially by weight fraction of doped polyaniline in fibers; the value for completely doped electrospun fiber was  $50 \pm 30$  S/cm and increased to  $130 \pm 40$  S/cm on further solid state drawing [41].

Electrospinning of electrically conductive polymers primarily focuses on polyaniline and its blends. Extremely conductive electrospun polyaniline fiber doped in sulfuric acid is produced by a blend of polyaniline and various conventional polymers such as polystyrene, polyacrylonitrile, polyethylene oxide and so on. [42].

### 3.5. Optical Properties

Nagata et al. conducted a lot of optical characterization techniques utilizing a luminescence spectrofluorometer and ultraviolet visible spectrophotometers to study optical characteristics of poly (2-methoxy- 5-(2-ethylhexyloxy)-1,4-phenylenevinylene) electrospun nanofibers [43]. A remarkable red shift was detected at all concentrations of MEH-PPV electrospun nanofibers in comparison to thin film. Photoluminescence readings validated the red shift by raising polymer concentration. Babel et al. observed the electrospun nanofiber's optical properties of conjugated polymer blends utilizing ultraviolet visible spectrophotometers, near-infrared spectroscopy, and photoluminescence spectroscopy [44]. Their finding shows that conjugated polymers' binary blend has an adjustable composition based on optical characteristics that can be exploited in field-effect transistors. Balderas et al. observed analogous absorption of red shift electrospun fibers generated from a blend of poly(9-vinylcarbazole) and MEH-PPV [45].

## 4. Applications

### 4.1. Biomedical Applications

One of the most significant applications of polymer nanofibers is in the biomedical sector, particularly in the domains of medication delivery and tissue engineering. Given that biological molecules and nanoscale fibers have similar sizes, the latter are poised to perform well in simulating biological environments and natural extracellular matrices. Nanofibrous meshes exhibit enhanced biological activities, such as increased cell adhesion, differentiation, and proliferation, due to high porosity, large surface area to volume ratio, and interconnectivity of porous matrices comparable to macromolecular ones. Additionally, it is also conceivable for biological molecules to load for nutrients and wastes to exchange through pores [10][46]. The two main research directions in this field are explored below.

#### 4.1.1. Tissue Engineering

Electrospun polymer nanofibers utilized as scaffolds in tissue engineering have attracted much attention. Due to comparable fibrous structure of nanofibrous made of biodegradable polymers with natural extracellular matrices,

they operate so as to support cell proliferation, adhesion, and differentiation. As such, they possess great potential as scaffolds for tissue regeneration [\[47\]](#)[\[48\]](#). Collagen, keratin, elastin fibers and so on. obtained from extracellular matrix are the most often employed materials in this endeavor because they are inherently fibrous in nature and easily transformed into fibrous scaffolds.

#### **4.1.2. Wound Healing and Dressing**

In wound rehabilitation pursuit, the large porosity of electrospun fibers may provide additional structural space for accommodation of transplanted cells, promote cell migration and proliferation, and increase oxygen exchange and waste outflow. The tiny pore size of nanofibrous scaffolds can prevent dehydration and wound infection throughout the healing process. Additionally, tunable mechanical properties of electrospun nanofibers can maintain mechanical consistency between tissue engineering grafts and parent tissue and prevent the wound from wrinkling or shrinkage during implantation. A variety of synthetic biodegradable polymers such as polyglycolic acid, polylactic acid, polycaprolactone, and copolymers are generally used for skin tissue engineering because of their advantageous mechanical and biodegradable characteristics.

#### **4.1.3. Drug Delivery Systems**

Various drug delivery systems such as polymer micelles, liposomes, and nanofibers are studied to diminish the toxicity of dosage and increase therapeutic efficacy [\[49\]](#)[\[50\]](#)[\[51\]](#)[\[52\]](#). There is a potential for electrospun nanofibers to provide significant benefit due to flexibility in selection of materials and medications, encapsulation efficiency, and delivery of therapeutic agents, among others, which makes them appealing candidates in drug delivery, particularly for topical chemotherapy after surgery and in wound casing materials [\[53\]](#). Electrospun nanofibers are utilized in precise and localized drug delivery systems thanks to their main advantages of large surface to volume ratios and well-interlinked, open porous structure. Numerous attempts have been undertaken to integrate bioactive compounds after electrospinning them, either chemically or physically, into the scaffolds. Techniques such as blending, co-axial electrospinning, and surface modification are utilized to load drugs into nanofibers.

### **4.2. Sensors and Biosensors**

Significant advancements have been achieved in the manufacturing of extremely biological and chemical sensitive sensors in response to increasing demands for high-precision reliable detections in different and evolving applications in medicine and sophisticated manufacturing for targeted industries. Electrospun polymer nanofibers provide a fertile source of utilization in sensing applications. An optical sensor that was developed by the electrospinning of fluorescent polymer nanofibers showed three-time improved sensitivity magnitude as compared to film sensors for detection of mercury ions and nitro and ferric compounds. Conductive electrospun polymer nanofibers such as polyaniline nanowires are strong candidates for sensing applications due to their outstanding electrical characteristics [\[54\]](#)[\[55\]](#)[\[56\]](#).

### **4.3. Air Filtration**

Various studies have suggested that electrospun nanofibers have the ability to capture such volatile organic compounds in air. Electrospun polymer nanofiber membranes have shown faster adsorption and desorption of volatile organic compounds compared to conventional activated carbon. The performance of filter membranes is significantly influenced by the structural properties of electrospun fibrous membranes. Fiber diameter and distribution, pore size distribution, surface area, basis, and density constitute the determining factors for filtering process effectiveness. Polymer nanofibers with smaller diameter will have a more accessible surface area, which will reduce pressure drop. Therefore, selecting an optimal electrospun nanofiber diameter is essential to maximizing filtration performance.

#### 4.4. Defense Applications

Polymer nanofibers are considered as exceptional membrane materials for the defense industry in smart textiles for the detection of biological and chemical warfare agents with high sensitivity. Their high sensitivity to biological and chemical pollutants at concentrations of parts per billion make them attractive candidates for sensing interfaces for warfare agents. Studies were conducted to incorporate nanoparticles into an electrospun nanofiber to enhance their properties for effective utilization in smart textiles. In electrospinning polymers such as polyamide, polypropylene, polyvinyl alcohol and so on, their composites are utilized.

#### 4.5. Energy Devices

It was reported that nanofibers perform better than typical materials in devices for energy storage, harvesting, and conversion, offering good alternative materials for use in energy devices such as lithium-ion batteries, nanogenerators, and solar cells [57]. Nanofibers used in solar cells have shown high photoelectric conversion efficiency due to separation, efficient charge transmission, and high light absorption mainly due to a large specific surface area and high porosity. The large ratio of surface area to volume in nanofibers enhances formation of the nonwoven structure, which improves conductivity and gives rise to possible utilization of NF in batteries and fuel cells as a separation medium. Nanofiber-based electrodes in solar cells have shown high cycling stability and specific capacity.

---

## References

1. Kai, D.; Liow, S.S.; Loh, X.J. Biodegradable polymers for electrospinning: Towards biomedical applications. *Mater. Sci. Eng. C* 2014, 45, 659–670.
2. Ashammakhi, N.; Wimpenny, I.; Nikkola, L.; Yang, Y. Electrospinning: Methods and development of biodegradable nanofibres for drug release. *J. Biomed. Nanotechnol.* 2009, 5, 19.
3. Sill, T.J.; Von Recum, H.A. Electrospinning: Applications in drug delivery and tissue engineering. *Biomaterials* 2008, 29, 1989–2006.

4. Stojanovska, E.; Canbay, E.; Pampal, E.S.; Calisir, M.D.; Agma, O.; Polat, Y.; Simsek, R.; Gundogdu, N.S.; Akgul, Y.; Kilic, A. A review on non-electro nanofibre spinning techniques. *RSC Adv.* 2016, 6, 83783–83801.
5. Kulkarni, A.; Bambole, V.; Mahanwar, P. Electrospinning of polymers, their modeling and applications. *Polym. Plastics Technol. Eng.* 2010, 49, 427–441.
6. Doshi, J.; Reneker, D.H. Electrospinning process and applications of electrospun fibers. *J. Electrostat.* 1995, 35, 151–160.
7. Bae, H.-S.; Haider, A.; Selim, K.; Kang, D.-Y.; Kim, E.-J.; Kang, I.-K. Fabrication of highly porous PMMA electrospun fibers and their application in the removal of phenol and iodine. *J. Polym. Res.* 2013, 20, 1–7.
8. Haider, A.H.; Kang, S. A Comprehensive Review Summarizing the Effect of Electrospinning Parameters and Potential Applications of Nanofibers in Biomedical and Biotechnology. *Arab. J. Chem.* 2015, 10, 24.
9. Bhardwaj, N.; Kundu, S.C. Electrospinning: A fascinating fiber fabrication technique. *Biotechnol. Adv.* 2010, 28, 325–347.
10. Ingavle, G.C.; Leach, J.K. Advancements in electrospinning of polymeric nanofibrous scaffolds for tissue engineering. *Tiss. Eng. Part B Rev.* 2014, 20, 277–293.
11. Baji, A.; Mai, Y.-W.; Wong, S.-C.; Abtahi, M.; Chen, P. Electrospinning of polymer nanofibers: Effects on oriented morphology, structures and tensile properties. *Compos. Sci. Technol.* 2010, 70, 703–718.
12. Zafar, M.; Najeeb, S.; Khurshid, Z.; Vazirzadeh, M.; Zohaib, S.; Najeeb, B.; Sefat, F. Potential of electrospun nanofibers for biomedical and dental applications. *Materials* 2016, 9, 73.
13. Nagam Hanumantharao, S.; Rao, S. Multi-functional electrospun nanofibers from polymer blends for scaffold tissue engineering. *Fibers* 2019, 7, 66.
14. Jayaraman, K.; Kotaki, M.; Zhang, Y.; Mo, X.; Ramakrishna, S. Recent advances in polymer nanofibers. *J. Nanosci. Nanotechnol.* 2004, 4, 52–65.
15. Tan, E.; Lim, C. Mechanical characterization of nanofibers—A review. *Compos. Sci. Technol.* 2006, 66, 1102–1111.
16. Bazbouz, M.B.; Stylios, G.K. The tensile properties of electrospun nylon 6 single nanofibers Part B Polymer physics. *J. Polymer Science Part Polym. Phys.* 2010, 48, 1719–1731.
17. Zhou, X.; Ding, C.; Cheng, C.; Liu, S.; Duan, G.; Xu, W.; Liu, K.; Hou, H. Mechanical and thermal properties of electrospun polyimide/rGO composite nanofibers via in-situ polymerization and in-situ thermal conversion. *Eur. Polymer J.* 2020, 141, 110083.

18. Hang, F.; Lu, D.; Bailey, R.J.; Jimenez-Palomar, I.; Stachewicz, U.; Cortes-Ballesteros, B.; Davies, M.; Zech, M.; Bödefeld, C.; Barber, A.H. In situ tensile testing of nanofibers by combining atomic force microscopy and scanning electron microscopy. *Nanotechnology* 2011, 22, 365708.
19. Gu, S.Y.; Wu, Q.L.; Ren, J.; Vancso, G.J. Mechanical properties of a single electrospun fiber and its structures. *Macromolecul. Rapid Commun.* 2005, 26, 716–720.
20. Yang, L.; Fitie, C.F.; Van Der Werf, K.O.; Bennink, M.L.; Dijkstra, P.J.; Feijen, J. Mechanical properties of single electrospun collagen type I fibers. *Biomaterials* 2008, 29, 955–962.
21. Lee, K.; Kim, H.; Khil, M.; Ra, Y.; Lee, D. Characterization of nano-structured poly ( $\epsilon$ -caprolactone) nonwoven mats via electrospinning. *Polymer* 2003, 44, 1287–1294.
22. Hansen, L.M.; Smith, D.J.; Reneker, D.H.; Kataphinan, W. Water absorption and mechanical properties of electrospun structured hydrogels. *J. Appl. Polym. Sci.* 2005, 95, 427–434.
23. Wei, X.; Xia, Z.; Wong, S.-C.; Baji, A. Modelling of mechanical properties of electrospun nanofibre network. *Int. J. ExpeR. Comput. Biomechan.* 2009, 1, 45–57.
24. Domaschke, S.; Zündel, M.; Mazza, E.; Ehret, A.E. A 3D computational model of electrospun networks and its application to inform a reduced modelling approach. *Int. J. Solids Struct.* 2019, 158, 76–89.
25. Dong, Y. *Nanostructures: Properties, Production Methods and Applications*; Nova Science Publishers, Inc.: New York, NY, USA, 2013.
26. Uslu, E.; Gavgali, M.; Erdal, M.O.; Yazman, Ş.; Gemi, L. Determination of mechanical properties of polymer matrix composites reinforced with electrospinning N66, PAN, PVA and PVC nanofibers: A comparative study. *Materials Today Commun.* 2021, 26, 101939.
27. Duan, G.; Liu, S.; Hou, H. Synthesis of polyacrylonitrile and mechanical properties of its electrospun nanofibers. *e-Polymers* 2018, 18, 569–573.
28. Sadrjahani, M.; Hoseini, S.; Mottaghitalab, V.; Haghi, A. Development and characterization of highly oriented pan nanofiber. *Braz. J. Chem. Eng.* 2010, 27, 583–589.
29. Ratner, B.; Chilkoti, A.; Castner, D. Contemporary methods for characterizing complex biomaterial surfaces. In *Biologically Modified Polymeric Biomaterial Surfaces*; Springer: Dordrecht, The Netherlands, 1992; pp. 25–36.
30. Zhang, Y.; Huang, Z.-M.; Xu, X.; Lim, C.T.; Ramakrishna, S. Preparation of core– shell structured PCL-r-gelatin bi-component nanofibers by coaxial electrospinning. *Chem. Mater.* 2004, 16, 3406–3409.
31. Li, H.; Ke, Y.; Hu, Y. Polymer nanofibers prepared by template melt extrusion. *J. Appl. Polym. Sci.* 2006, 99, 1018–1023.

32. Unser, A.M.; Xie, Y. Electrospinning of nanofibers. *The Nanobiotechnology Handbook*; CRC Press: Boca Raton, FL, USA, 2012; pp. 293–320.
33. Ma, P.X.; Zhang, R. Synthetic nano-scale fibrous extracellular matrix. *J. Biomed. Mater. Res. Off. J. Soc. Biomater. Japan. Soc. Biomater. Aust. Soc. Biomater.* 1999, 46, 60–72.
34. Kim, S.H.; Nam, Y.S.; Lee, T.S.; Park, W.H. Silk fibroin nanofiber. Electrospinning, properties, and structure. *Polym. J.* 2003, 35, 185–190.
35. Peresin, M.S.; Habibi, Y.; Zoppe, J.O.; Pawlak, J.J.; Rojas, O.J. Nanofiber composites of polyvinyl alcohol and cellulose nanocrystals: Manufacture and characterization. *Biomacromolecules* 2010, 11, 674–681.
36. Luzio, A.; Canesi, E.V.; Bertarelli, C.; Caironi, M. Electrospun polymer fibers for electronic applications. *Materials* 2014, 7, 906–947.
37. Srivastava, Y.; Marquez, M.; Thorsen, T. Multijet electrospinning of conducting nanofibers from microfluidic manifolds. *J. Appl. Polym. Sci.* 2007, 106, 3171–3178.
38. Prabhakaran, M.P.; Ghasemi-Mobarakeh, L.; Jin, G.; Ramakrishna, S. Electrospun conducting polymer nanofibers and electrical stimulation of nerve stem cells. *J. Biosci. Bioeng.* 2011, 112, 501–507.
39. Nune, M.; Kumaraswamy, P.; Maheswari Krishnan, U.; Sethuraman, S. Self-assembling peptide nanofibrous scaffolds for tissue engineering: Novel approaches and strategies for effective functional regeneration. *Curr. Protein Peptide Sci.* 2013, 14, 70–84.
40. Zhang, Y.; Rutledge, G.C. Electrical conductivity of electrospun polyaniline and polyaniline-blend fibers and mats. *Macromolecules* 2012, 45, 4238–4246.
41. McCullen, S.D.; Stevens, D.R.; Roberts, W.A.; Ojha, S.S.; Clarke, L.I.; Gorga, R.E. Morphological, electrical, and mechanical characterization of electrospun nanofiber mats containing multiwalled carbon nanotubes. *Macromolecules* 2007, 40, 997–1003.
42. Chronakis, I.S.; Grapenson, S.; Jakob, A. Conductive polypyrrole nanofibers via electrospinning: Electrical and morphological properties. *Polymer* 2006, 47, 1597–1603.
43. Nagata, S.; Atkinson, G.M.; Pestov, D.; Tepper, G.C.; Mcleskey, J.T. Electrospun polymer-fiber solar cell. *Adv. Mater. Sci. Eng.* 2011, 2013, 1000.
44. Babel, A.; Li, D.; Xia, Y.; Jenekhe, S.A. Electrospun nanofibers of blends of conjugated polymers: Morphology, optical properties, and field-effect transistors. *Macromolecules* 2005, 38, 4705–4711.
45. Balderas, U.; Falcony, C.; Moggio, I.; Arias, E.; Mondragón, M. A photoluminescence study of electrospun fibers of conjugated poly blended with poly (9-vinylcarbazole). *Polymer* 2013, 54, 2062–2066.

46. Oliveira, J.E.; Mattoso, L.H.; Orts, W.J.; Medeiros, E.S. Structural and morphological characterization of micro and nanofibers produced by electrospinning and solution blow spinning: A comparative study. *Adv. Mater. Sci. Eng.* 2013, 2013, 409572.
47. Moon, S.; Farris, R.J. Strong electrospun nanometer-diameter polyacrylonitrile carbon fiber yarns. *Carbon* 2009, 47, 2829–2839.
48. Rahmati, M.; Mills, D.K.; Urbanska, A.M.; Saeb, M.R.; Venugopal, J.R.; Ramakrishna, S.; Mozafari, M. Electrospinning for tissue engineering applications. *Progr. Mater. Sci.* 2021, 117, 100721.
49. Zahmatkeshan, M.; Gheybi, F.; Rezayat, S.M.; Jaafari, M.R. Improved drug delivery and therapeutic efficacy of PEGylated liposomal doxorubicin by targeting anti-HER2 peptide in murine breast tumor model. *Eur. J. Pharm. Sci.* 2016, 86, 125–135.
50. Asyikin binti Abdul Aziz, Z.; Ahmad, A.; Hamidah Mohd-Setapar, S.; Hassan, H.; Lokhat, D.; Amjad Kamal, M. Recent advances in drug delivery of polymeric nano-micelles. *Curr. Drug Metabol.* 2017, 18, 16–29.
51. Luraghi, A.; Peri, F.; Moroni, L. Electrospinning for drug delivery applications: A review. *J. Control. Release* 2021, 334, 463–484.
52. Zelkó, R.; Lamprou, D.A.; Sebe, I. Recent Development Of Electrospinning For Drug Delivery; MDPI: Basel, Switzerland, 2019; Volume 12, p. 5.
53. Hu, X.; Liu, S.; Zhou, G.; Huang, Y.; Xie, Z.; Jing, X. Electrospinning of polymeric nanofibers for drug delivery applications. *J. Control. Release* 2014, 185, 12–21.
54. Aussawasathien, D.; Dong, J.-H.; Dai, L. Electrospun polymer nanofiber sensors. *Synth. Met.* 2005, 154, 37–40.
55. Yilmaz, O.E.; Erdem, R. Evaluating hydrogen detection performance of an electrospun CuZnFe<sub>2</sub>O<sub>4</sub> nanofiber sensor. *Int. J. Hydr. Energy* 2020, 45, 26402–26412.
56. Wang, W.; Huang, H.; Li, Z.; Zhang, H.; Wang, Y.; Zheng, W.; Wang, C. Zinc oxide nanofiber gas sensors via electrospinning. *J. Am. Ceramic Soc.* 2008, 91, 3817–3819.
57. Zahmatkeshan, M.; Adel, M.; Bahrami, S.; Esmaeili, F.; Rezayat, S.M.; Saeedi, Y.; Mehravi, B.; Jameie, S.B.; Ashtari, K. Polymer-based nanofibers: Preparation, fabrication, and applications. In *Handbook of Nanofibers*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 215–261.

---

Retrieved from <https://encyclopedia.pub/entry/history/show/89936>