Effects of operational variables on electrospun fiber characteristics

Kalpana Krishnaraju[1*] and Noohu Abdulla Khan[1]

[1] Department of Pharmacy, Erode College of Pharmacy, Veppampalayam, Erode, Tamil Nadu, India

Corresponding author: Kalpana Krishnaraju

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Abstract

Electrospinning is a versatile technique that uses electrostatic repulsive forces to fabricate fibers ranging from the nano- to microscale. Its ability to produce nanoscale fibers has attracted significant attention, particularly for applications in biomedicine and drug delivery. The method is simple, cost-effective, and adaptable, involving parameters related to the instrument, solution, and ambient conditions. Optimizing these parameters allows precise control over fiber morphology, diameter, porosity, surface area, and topography. Additionally, electrospinning offers a wide range of material selection and parameter flexibility, making it highly suitable for applications such as drug and gene delivery, wound healing, and tissue engineering.

Keywords: Electrospinning, Drug delivery, Parameters, Morphology, Optimization

Introduction

Electrospinning is a versatile technology used to fabricate ultrafine fibers from polymer solutions. The process relies on electrostatic forces, where a high voltage applied to the polymer solution generates fibers in the micro- to nanometer range [1]. Fibers can also be prepared using other methods, including phase separation, self-assembly, template synthesis, and mechanical drawing; however, electrospinning is considered more conventional, cost-effective, and easier to operate than these alternatives [2].

Electrospun fibers have found applications across diverse fields such as filtration, cosmetic masks, military protective clothing, wound dressing [3], drug delivery [4], enzyme immobilization [5], and tissue engineering. By adjusting electrospinning parameters, it is possible to control fiber morphology, porosity, topography, and density [7].

The principle of electrospinning was first introduced by Rayleigh in 1882, and Formhals patented the method for producing small-diameter fibers in 1934 [7]. Subsequent patents by Formhals addressed limitations of the earlier apparatus [8]. Extensive research has explored the influence of various parameters on fiber morphology and properties, enabling tailored fibers for specific applications [6]. Electrospun fibers are characterized by a high surface area-to-volume ratio [9], making them suitable for applications such as anodes in lithium-ion batteries [10], conducting and magnetic materials in micro- and nanodevices [11], and high-performance air filters due to their unique surface properties [12]. Optimizing electrospinning parameters is therefore essential to control fiber structure and functionality for targeted applications.

Process

The basic electrospinning setup comprises three main components: a syringe pump with a needle, a high-voltage power supply, and a collector. The syringe pump holds the polymer solution and dispenses it at a controlled rate through the needle, while the high-voltage supply is connected to the syringe and the collector. Different types of collectors are used to achieve various fiber structures [14].

The process begins by filling the syringe with the polymer solution, with the needle positioned at a specified distance from the collector to allow adequate solvent evaporation. When high voltage is applied, the electrostatic force overcomes the surface tension of the polymer solution, forming a conical shape known as the “Taylor cone.” A continuous jet of fibers is ejected toward the collector, during which the solvent evaporates, depositing dry polymer fibers onto the collector surface [1].

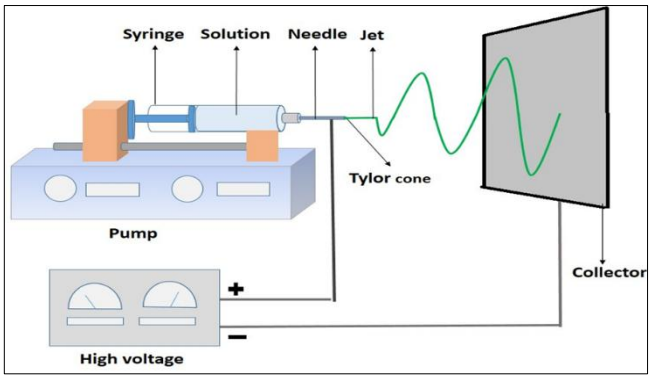

Fig 1: Electrospinning setup

Instrumental parameters

Voltage

The voltage applied to the polymer solution generates electrostatic repulsive forces that enable the solution to overcome surface tension and form fibers. Fiber formation is highly dependent on the applied voltage, as it directly affects the orientation of polymer chains and the crystalline nature of

the fibers. Electrospinning can employ either direct current (DC) or alternating current (AC). DC typically produces a single fiber jet, whereas AC can generate multiple jets from the surface of the polymer solution [15, 16]. The optimal voltage depends on the type of polymer solution used [6]. Increasing the voltage initially decreases fiber diameter; however, excessive voltage can lead to higher polymer ejection rates, producing fibers with larger diameters and bead defects [17].

Flow rate

The flow rate of the polymer solution determines the amount of spinnable material and influences fiber morphology. A higher flow rate increases the production rate but can adversely affect fiber uniformity if not controlled [18]. Maintaining a minimal, appropriate flow rate stabilizes the Taylor cone and ensures uniform fiber formation. At a constant voltage, increasing flow rate generally increases fiber diameter. Excessively high flow rates, however, can result in insufficient solvent evaporation, leading to bead formation, flat, or ribbon-like fibers [19]. De Schoenmaker *et al* reported that increasing flow rate from 2 to 4.5 mL/h increases fiber diameter, whereas further increase beyond 4.5 mL/h destabilizes jets, producing thinner and beaded fibers [18].

Distance

The distance between the needle nozzle and collector is critical for solvent evaporation and uniform fiber deposition. A suitable distance prevents defects such as bead formation, fiber merging, or flattening. Fiber diameter generally decreases and uniformity improves with increasing distance, and the deposition area also expands. However, if the distance is too great, the electric field strength and jet velocity decrease, leading to larger fiber diameters. Conversely, too short a distance may produce beaded fibers. In conventional electrospinning, an optimal distance typically ranges from 10 to 20 cm [19].

Collector type

The choice of collector influences fiber orientation, alignment, and morphology. Metal collectors provide smooth fibers, while grounded solid collectors (e.g., aluminum foil) yield randomly oriented fibers. Patterned fibers can be obtained using guide wire collectors, and rotating collectors generally produce more aligned fibers than stationary ones. Common rotating devices include rotating mandrels, disks, and wire drums, with alignment controlled by rotation speed [20]. For three-dimensional fiber structures, liquid coagulation baths (e.g., water-ethanol mixtures) can be used, allowing fibers to solidify in the bath and subsequently be collected by rollers. Conductive frame collectors also enhance fiber alignment compared to non-conductive frames.

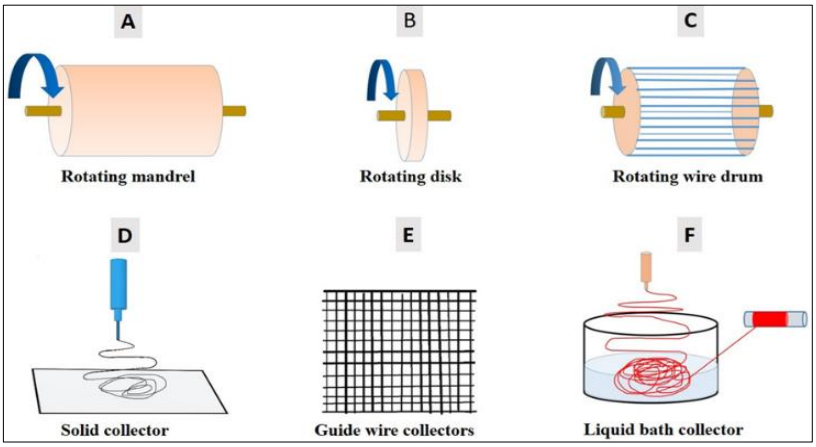

Fig 2: Electrospinning receiving devices (A) Rotating mandrel, (B) Rotating disk, (C) Rotating wire drum, (D) Solid collector, (E) Guide wire collector, (F) Liquid bath collector

Properties of polymer solution

a) Polymer Concentration

The electrospinnability of a polymer solution strongly depends on its polymer concentration. The molecular weight of the polymer influences the solution's rheological and electrical properties. Using polymers of different molecular weights results in fibers of varying diameters [21]. At low polymer concentrations, even under high voltage, continuous fiber formation may not occur, and discrete droplets may eject from the capillary. Increasing polymer concentration enhances chain entanglement and solution viscosity, improving fiber formation. Fiber diameter generally increases with polymer concentration; however, excessively high concentrations may disturb solution flow due to increased viscosity, hampering electrospinning.

b) Viscosity

Viscosity plays a critical role in fiber formation. The polymer's molecular weight, chain length, and solution concentration collectively determine the solution viscosity, which in turn governs fiber morphology. Solutions with low viscosity often produce droplets rather than continuous fibers, while highly viscous solutions require stronger electric fields to maintain stable jet formation. Adjusting viscosity within an optimal range is essential to control fiber diameter and morphology.

Using a mixed-solvent system can further optimize solution viscosity, facilitating efficient fiber production.

c) Surface Tension

Surface tension is the force acting at the interface of the polymer solution per unit length and arises from molecular interactions within the solution. For smooth and continuous fiber formation, the applied electrostatic repulsive force must overcome the solution's surface tension. Increasing polymer concentration reduces surface tension to a favorable range, promoting uniform fiber formation. Surface tension can also be adjusted by modifying solvent composition or adding surfactants. Multi-solvent systems are often used to optimize both surface tension and viscosity simultaneously.

d) Conductivity

Conductivity refers to the solution's ability to carry electric charge and significantly affects electrospinning and fiber morphology. Higher conductivity enhances the tensile forces on the polymer jet, typically resulting in thinner fibers. Natural polymers with polyelectrolytic properties often yield poorer fiber quality compared to synthetic polymers. Conductivity can be modified by adding salts such as sodium phosphate, potassium phosphate, lithium chloride, or ammonium chloride. Semi-conductive or insulating solutions, when combined with appropriate voltage, produce stable fiber jets.

Environmental parameters

a) Temperature

Temperature influences polymer solution properties such as viscosity, conductivity, and solvent evaporation rate. Increasing temperature enhances solvent evaporation, which can create pores in the fibers, while simultaneously reducing viscosity and improving solution conductivity. Proper temperature control optimizes fiber diameter and morphology by regulating these solution properties.

b) Humidity

Ambient humidity affects fiber diameter and porosity. Humidity is inversely related to temperature, as higher temperatures generally reduce ambient moisture. Lower humidity promotes faster solvent evaporation, while higher humidity can lead to thicker fibers due to slower solvent volatilization. Porous fibers are often observed when hydrophobic polymers are electrospun from organic solvents, and the number and size of pores can be tuned by adjusting environmental humidity [22].

c) Air Pressure

Electrospinning is generally conducted at atmospheric pressure; however, variations in air pressure can influence solvent evaporation, fiber diameter, and deposition. Maintaining stable pressure is crucial, as fluctuations can destabilize the polymer jet, affecting fiber consistency and morphology [23].

Table 1: Parameters and their effect on fibers structure

Sr. no.	parameters	Electrospun fibers morphology	
		Lower value	Higher value
1.	Voltage	Fibers of minimum diameter at high voltage	At too high value of voltage, beading occurs
2.	Flow rate	Fibers with smaller diameter	Fibers does not dry before reaching to collector
3.	Distance	Minimum distance required for drying the fibers	Beading in fibers
4.	Polymer concentration/ Viscosity	Beads and junctions in fibers	Fiber diameter increases
5.	Surface tension	Diameter of fiber decreases	Diameter of fiber increases
6.	Conductivity	Affect electrospinning	Uniform bead free fibers
7.	Temperature	diameter size increases	Viscosity decreases and Smaller fibers forms
8.	Humidity	At optimum level thin fibers obtained	Thick fibers obtained

Conclusion

This study reviewed the key parameters that influence the morphology of electrospun fibers. These parameters are closely linked to the components of the electrospinning setup, and instrumental factors and solution properties are often interdependent. For instance, the viscosity of the polymer solution and the applied voltage must be maintained within critical ranges to produce continuous fibers. Similarly, the distance between the needle and the collector must be optimized to ensure complete solvent evaporation and proper fiber deposition, while also interacting with the applied voltage intensity. Polymer concentration affects both solution viscosity and surface tension, which in turn influence fiber formation. Adjustments in these parameters directly impact fiber diameter, porosity, and overall morphology. By carefully controlling these factors, electrospinning allows the fabrication of fibers with tailored structures for diverse applications.

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