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ELECTROSPINNING HYBRID NANOFIBERS: CUTTING-EDGE FABRICATION TECHNIQUES AND REAL-WORLD APPLICATIONS

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ABSTRACT

Electrospinning has emerged as one of the most versatile and widely adopted techniques for producing nanofibers with controlled morphology and tunable properties. Owing to their high surface-area-to-volume ratio, adjustable porosity, and excellent mechanical and physicochemical characteristics, electrospun nanofibers have found extensive applications in bio medicine, including drug delivery, wound healing, tissue engineering, and protective textiles. This article reviews the fundamental principles of electrospinning, highlights various modified electrospinning techniques such as blend, coaxial, emulsion, side-by-side, and multi-needle methods and discusses their roles in enhancing fiber structure and drug release performance. Additionally, the key characterization techniques for assessing nanofiber quality and functionality are summarized, followed by a detailed overview of their diverse applications. The growing significance of electrospun nanofibers underscores their potential in developing advanced therapeutic systems and functional materials for healthcare and industrial uses.

KEYWORDS: Electrospinning; Nanofibers; Hybrid nanofibers; Controlled release; Tissue engineering; Wound healing.

INTRODUCTION

Nanotechnology is a highly promising field with wide applications in healthcare and

biomedicine. At present, there is no universally agreed definition for nanomaterials.[1] Depending on their properties, nanomaterials can be engineered into various forms such as nanoparticles, nanowires, nanotubes, nanofibers, and nanorods.[2] In recent years, nanofibers have attracted considerable attention from researchers across various disciplines. Their distinctive features, such as a high surface area-to-volume ratio, adjustable porosity, and excellent mechanical and physicochemical properties, make them highly suitable for applications demanding extensive surface area.[3] Nanofibers can be fabricated by choosing suitable polymer and additive combinations and employing the right production methods, taking into account key properties that influence their suitability for specific applications.[4] Various methods have been developed to produce polymer nanofibers, including phase separation or inversion, spinneret-based tunable engineered parameter techniques, self-assembly polymerization, template synthesis, hot stretching, and electrospinning.[5]

Electrospinning has emerged as a cost-effective and versatile method for producing continuous nanofibers with tunable properties such as diameter, structure, and alignment.[6] A wide range of materials including natural and synthetic polymers, metals, and composite nanomaterials can be electrospun into fibers tailored for specific uses.[7] Hybrid nanofibers, created by blending polymers or incorporating functional agents like nanoparticles, combine the biocompatibility of natural polymers with the strength and stability of synthetics.[8] This synergy has expanded their role in biomedical applications such as drug delivery, tissue engineering, biosensing, and regenerative medicine, underscoring the importance of advanced fabrication and characterisation strategies in recent research.[9,10]

ELECTROSPINNING

At present, considerable efforts are being directed toward scaling up production and enhancing the properties of nanofibers. Among the various fabrication methods available, electrospinning stands out as a promising approach, allowing the creation of nanofibers from a wide range of materials in diverse fiber structures. In recent years, both academic and industrial sectors have shown great interest in electrospinning due to its straightforward process, broad material compatibility, and cost-effectiveness.[11]

Electrospinning is a straight forward technique compatible with a wide variety of polymers. It can produce long, continuous nanofibers and allows for the fabrication of aligned fibers when

needed. This method enables the reduction of fiber diameters to the nanometer range and offers the potential for large-scale production.[12,13]

Electrospinning is a type of dry spinning method employed to produce continuous nanofibers. In this process, fibers are formed by pulling a polymer melt or solution using electrostatic forces, creating nanofiber networks in a single step. Electrospinning, a term originating from ―electrostatic yarn,‖ is a dry spinning technique that employs electrostatic forces to produce fine fibers ranging from 10–100 µm down to 10–100 nm. This process draws fibers either from a polymer solution or directly from molten polymer.[14] The widespread use of electrospinning across various industries and advanced technology sectors has driven the development of large-scale production infrastructure, making both the equipment and nanofibrous materials commercially accessible. This has made nanofibers available for future clinical use after Food and Drug Administration (FDA) approval.[15]

In 1934, Anton Formhals filed a landmark patent describing the electrospinning process for producing plastic fibers. Between 1934 and 1944, through a series of patents, he detailed the experimental arrangement for generating polymer filaments using electrostatic forces.[16] To produce polymer filaments, a cellulose acetate solution was exposed to an electric field. One electrode was immersed in the solution, while the other was positioned on a collector. The charged jets of solution were ejected through a metal spinneret with a small orifice and solidified into fibers as the solvent evaporated; these fibers were then deposited onto an electrically grounded collector. Later, in 1971, Baumgarten advanced this method by developing equipment capable of electrospinning acrylic fibers with diameters ranging from 0.05 to 1.1 microns.[17]

ELECTROSPINNING PROCESS

Electrospinning is regarded as a technique for producing micro- to nanofibers from polymer solutions by applying a high electric field (in kilovolts) under ambient pressure and room temperature conditions. Typically, electrospinning equipment is designed in either a vertical or horizontal configuration. The electrospinning apparatus primarily consists of three key components: a high-voltage power supply, a syringe or spinneret, and a collector electrode.[18] The high voltage creates electric charges within the polymer solution, causing them to gather on its surface. As these charges repel each other, they eventually overcome the surface tension when a critical electric field is reached, forming what is known as a Taylor cone.

From the tip of this cone, a charged jet emerges and is further stretched by the electric field. As the solvent evaporates, the jet solidifies into fibers.[19]

Typically, fibers are deposited randomly on the collector. However, certain applications demand scaffolds with well-aligned fibers. To achieve this, various methods have been devised to produce organized structures. The simplest technique involves using a rotating mandrel or a wheel-like bobbin collector. However, in some instances, jet bending instabilities can interfere with proper fiber alignment along the rotation axis.[20] Auxiliary electrodes, which adjust the electric field between the needle and the collector, can effectively minimize bending instabilities and enhance fiber alignment.[21]

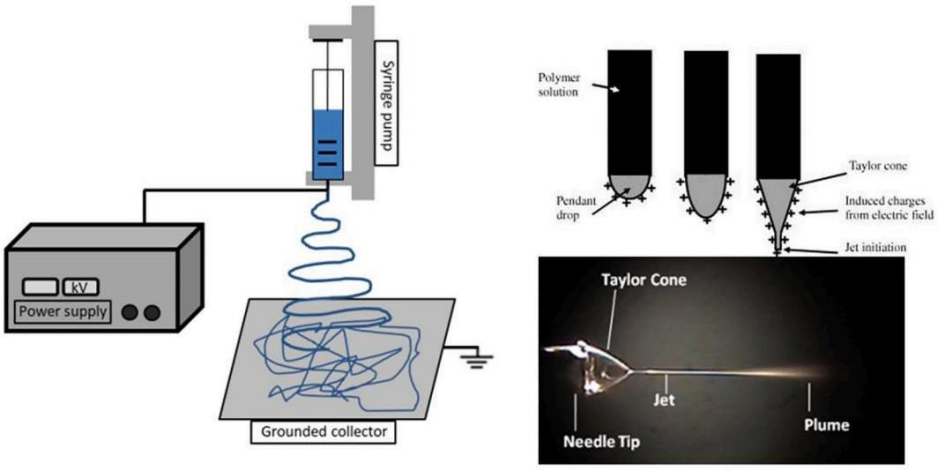

Fig. 1: Illustration of a typical electrospinning setup depicting the development of a Taylor cone.

TYPES OF ELECTROSPINNING

1. BLEND ELECTROSPINNING

Blend electrospinning is regarded as the most straightforward technique, as it involves creating a single electrospinnable solution by mixing different polymers or incorporating functional agents. In this approach, drugs can be loaded directly by dissolving or dispersing them within the polymer blend before the electrospinning process begins. This simple method enables sustained drug release under appropriate conditions. However, the physical and chemical characteristics of the polymers play a critical role in determining how the drug is encapsulated and how it is released, due to interactions between the polymer matrix and the drug molecules. A key factor to consider is the drug's solubility. Poor solubility may cause the drug to migrate to the fiber surface, resulting in an initial burst release. This issue can be addressed by carefully balancing the hydrophilic and hydrophobic nature of both the polymer

and the drug to achieve optimal encapsulation and release behavior.[22,23] However, a common drawback of this technique is that drugs are often released quickly from the nanofibers. This rapid release occurs because the drugs are usually evenly distributed across the fiber surfaces, and the high surface-to-volume ratio of nanofibers further accelerates the release. Nevertheless, the actual release profile is influenced by how well the drug is encapsulated within the polymer matrix and by the level of interaction between the drug and the polymer. To minimize an initial burst release and to achieve a more controlled, sustained release, it is possible to incorporate drug-loaded nanostructures—such as nanoparticles, nanospheres, nanomicelles, or nanotubes—into the polymer solution prior to electrospinning.[24]

2. COXIAL ELECTROSPINNING

To improve the performance of nanofibers, various modifications to electrospinning techniques have been developed over the years. One such advancement is the fabrication of core–sheath nanofibers using coaxial or triaxial electrospinning methods. In this approach, a polymer fiber forms the core while an additional polymer layer serves as the protective or functional outer shell.[25] In this method, the layer-by-layer configuration of nanofibers helps tailor the drug release profile while protecting the drugs embedded in the core from potential damage. The outer shell functions as a physical barrier, enabling sustained release and shielding the drug from degradation caused by direct exposure to the surrounding environment.[26] Interestingly, a single delivery system can achieve two distinct release profiles by loading different drugs into the core and shell layers. Coaxial and triaxial electrospinning are the most widely used methods for producing such hybrid nanofibers. These techniques rely on the simultaneous flow of core and sheath solutions through separate capillaries to fabricate fibers with a layered structure.[27] This approach allows multiple drugs to be loaded into separate layers of the nanofiber, effectively resolving issues related to drug incompatibility.[28] Moreover, core–sheath nanofibers produced using coaxial electrospinning generally offer greater drug loading efficiency than those made by blend electrospinning, while also reducing the risk of an initial burst release. An additional benefit of this method is its capability to fabricate nanofibers from solutions that are otherwise unsuitable for direct electrospinning, giving it an advantage over the blend approach.[29] Therefore, core–shell nanofibers produced through coaxial electrospinning can successfully minimize the initial burst release of drugs and provide a controlled, sustained release profile.[30]

3. EMULSION ELECTROSPINNING

Emulsion electrospinning is regarded as one of the simplest and most effective methods for producing hybrid nanofibers. Numerous researchers have employed this technique to encapsulate various therapeutic agents within nanofibers featuring a core–sheath architecture. Compared to conventional electrospinning methods, emulsion electrospinning offers distinct advantages, such as enabling the incorporation of lipophilic compounds into cost-effective hydrophilic polymers without relying on organic solvents, which is particularly valuable for applications in food and biomedicine where solvent residues must be avoided. The setup for emulsion electrospinning resembles that of blend electrospinning; however, in this case, immiscible phases are spun simultaneously to generate fibers with a core–shell configuration. Initially, the bioactive compounds are emulsified by introducing a surfactant to form a stable water-in-oil emulsion. This emulsion is then combined with the polymer solution to prepare it for electrospinning.[31] As the continuous phase evaporates during the electrospinning process, the viscosity of the solution gradually increases. This developing viscosity gradient promotes the movement of aqueous droplets—containing the bioactive substances—toward the center of the spinning jet. Under the influence of the electric field, these droplets coalesce due to mutual dielectrophoresis, aligning into column-like formations that ultimately produce fibers with a well-defined core–sheath architecture.[32] The parameters such as applied voltage, solution flow rate, and the distance between the spinneret and collector play a crucial role in determining the properties of emulsion-derived hybrid nanofibers.[33] Water-in-oil (W/O) emulsions are particularly advantageous for achieving continuous and sustained drug release while minimising the initial burst effect commonly observed in conventional delivery systems. In this approach, hydrophilic drugs are dissolved in an aqueous phase, whereas hydrophobic polymers are solubilised in organic solvents, allowing effective encapsulation and enhanced protection of the drug within the fiber core. This configuration not only preserves drug bioactivity by shielding it from external factors but also enables differential release rates, with faster release from the shell and a more controlled diffusion from the core through the surrounding matrix. Notably, emulsion electrospinning can produce high-quality core–sheath fibers even from dilute polymer solutions, although stabilising agents like surfactants are often required to maintain emulsion stability and ensure efficient drug encapsulation.[34]

4. SIDE BY SIDE ELECTROSPINNING

The side-by-side electrospinning technique is a two-compartment system designed to produce

Janus nanofibers, which feature two distinct sides with different compositions. Unlike the core–sheath structure, both surfaces of a Janus fiber are directly exposed to the external environment, enabling unique functionalities for advanced applications. In this method, two polymer solutions are fed through separate but adjacent capillaries within a modified spinneret, allowing the formation of fibers with varied widths and interfacial areas by adjusting the spinneret design and electrospinning parameters.[35] Achieving synchronized, stable flows from both chambers under an electric field poses challenges due to the complex interplay between fluid dynamics, electrodynamics, and rheological properties. Additionally, maintaining side-by-side alignment is difficult because both polymer streams are subjected to the same voltage and flow control, which can lead to repulsion and separation of the two phases. Despite these challenges, Janus fibers combine the properties of both polymers within a single structure, enabling a biphasic drug release profile. By incorporating a drug into each side—one with a water-soluble polymer and the other with a water-insoluble polymer—a tailored release can be achieved: rapid release from the soluble side due to polymer erosion and a more sustained release from the insoluble side, making this configuration valuable for applications requiring sequential or controlled delivery.[36,37]

5. MULTI NEEDLE ELECTROSPINNING

Multi-needle electrospinning is a straightforward approach to upscale nanofiber production by simultaneously ejecting the polymer solution through several needles connected to a high-voltage supply. Its simplicity lies in using a common syringe pump to regulate flow, although higher voltages are often needed to sustain the larger solution throughput. Despite its high productivity, this technique faces several technical challenges. The electric field may become unstable, leading to inconsistent fiber diameters. Needle tips can clog, cleaning becomes cumbersome, and electrostatic repulsion between adjacent jets can reduce jet stability and fiber uniformity. For example, systems with more than six nozzles require larger collectors to accommodate expanded deposition areas, and fiber quality may decline without proper control of nozzle spacing and setup design. On the plus side, multi-needle setups support the inclusion of multiple drugs or polymers in a single session, enabling complex or staged release profiles.[38,39]

CHARACTERISATION OF ELECTROSPUN FIBERS

Characterisation of nanofibers is essential to assess their quality during fabrication and to understand how their structural attributes relate to functional performance. Various analytical

techniques are employed to examine different aspects of nanofibers, including their morphology, molecular configuration, and mechanical strength, which collectively define their key properties. The choice of characterisation method often depends on the intended application. For instance, parameters such as air permeability, particle filtration efficiency, and porosity are critical for protective gear like gas masks, whereas properties like electrical conductivity, optical behaviour, and surface reactivity are vital for sensor applications. Many of these evaluation techniques adhere to standards set by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO).[40] Overall, the main characterisation approaches can be grouped into the following categories.

1. MORPHOLOGICAL ANALYSIS[41]

Pore size distribution and overall porosity can be determined using methods such as mercury intrusion porosimetry, liquid extrusion porosimetry, nuclear magnetic resonance, or capillary flow porometry. The fiber diameter and its distribution are typically examined using imaging techniques like Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), and Atomic Force Microscopy (AFM).

2. MECHANICAL CHARACTERISATION[42]

The mechanical strength and flexibility of nanofibers are generally assessed through nano-tensile testing and Dynamic Mechanical Analysis (DMA).

3. STRUCTURAL AND PHASE ANALYSIS[43]

Crystalline structure and phase composition are commonly evaluated using X-ray Diffraction (XRD) techniques.

4. CHEMICAL COMPOSITION AND THERMAL PROPERTIES[44]

Chemical bonds, elemental composition, and thermal stability can be analysed through X-ray Photoelectron Spectroscopy (XPS), Fourier Transform Infrared Spectroscopy (FT-IR), Raman Spectroscopy, Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and Differential Thermal Analysis (DTA).

5. MAGNETIC PROPERTIES[45]

Magnetic behaviour is characterised by measuring M–H hysteresis loops using a Vibrating Sample Magnetometer (VSM) or by analysing B–H hysteresis loops.

6. ELECTRICAL AND DIELECTRIC PROPERTIES[46]

Electrical conductivity and dielectric performance are investigated by evaluating dielectric behaviour and measuring electrical resistivity.

APPLICATIONS OF ELECTROSPUN NANOFIBER[47,48,49,50]

Electrospun nanofibers have garnered significant interest due to their high surface-area-to-volume ratio, tunable porosity, and versatility in material composition. These attributes make them suitable for a broad range of fields.

1. DRUG DELIVERY

Electrospun fibers are widely employed as drug carriers that enable controlled and sustained release. By tailoring fiber structures—such as single, core–shell, or multi-layered forms various active substances including small molecules, proteins, and nucleic acids can be efficiently encapsulated and protected from degradation. Such systems have demonstrated improved local delivery for cancer treatment, wound care, and site-specific therapies, minimizing systemic side effects.

2. WOUND DRESSING AND SKIN REGENERATION

Nanofiber mats mimic the extracellular matrix, supporting cell adhesion and proliferation while ensuring adequate gas exchange and moisture balance at the wound site. Their ability to incorporate antibacterial agents, bioactive peptides, or growth factors enhances healing outcomes and reduces infection risk. Moreover, recent developments integrate sensors into these dressings for real-time monitoring.

3. TISSUE ENGINEERING SCAFFOLDS

Due to their biomimetic structure, electrospun scaffolds serve as effective frameworks for regenerating skin, bone, cartilage, nerve, and vascular tissues. The fibers can be modified with biochemical cues to direct cell behavior, supporting differentiation and tissue integration.

4. CANCER MODELS AND THERAPIES

Beyond drug delivery, nanofiber scaffolds provide three-dimensional platforms for studying tumor biology and drug responses in vitro. Such models better replicate in vivo conditions compared to conventional cell cultures, enabling more accurate preclinical testing.

5. FILTRATION AND ADSORPTION

Nanofiber membranes have been successfully used in air and liquid filtration systems, capturing fine particulate matter and harmful chemicals due to their fine pore structures. They have shown excellent performance in water purification, removing heavy metals and organic pollutants.

6. SENSORS AND PROTECTIVE TEXTILES

Functionalized nanofibers are integrated into sensors to detect gases, metal ions, and biological markers with high sensitivity. They are also applied in smart textiles for protective clothing, where they provide breathability along with chemical or biological hazard resistance.

7. COMPOSITE REINFORCEMENT

In composite materials, electrospun fibers enhance mechanical strength, thermal stability, and wear resistance. Such composites are relevant in aerospace, automotive, and medical implant applications where material performance is critical.

CONCLUSION

In summary, electrospinning represents a powerful and flexible platform for fabricating nanofibers with tailored properties suitable for a broad spectrum of biomedical and industrial applications. Modifications to the basic electrospinning process—such as blend, coaxial, emulsion, side-by-side, and multi-needle techniques—have significantly advanced the ability to control drug loading, release profiles, and fiber architecture. Comprehensive characterization ensures that the resulting nanofibers meet the performance standards required for their intended uses. Electrospun nanofibers have demonstrated remarkable promise in drug delivery, wound management, tissue regeneration, filtration, sensing, and composite reinforcement. Ongoing research and development are expected to further expand their applications and enable scalable production for future clinical and commercial deployment.

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