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Electrospinning - A Potential Bio-Fabrication Method for Developing Various Tissue Engineering Scaffolds

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Abstract: Scaffolds in tissue engineering provide essential support for new tissue growth. Such scaffolds could be fabricated from materials like natural and synthetic polymers with prime properties such as biocompatibility and mechanical strength. Among other developments made, electrospinning has been a significant factor in making intricate scaffolds that imitate the extracellular matrix of tissue. It gives various properties in the fibers for specific applications by the controlled parameter conditions like voltage and flow rate. It is innovations like multi-component fibers and 3D structures that assist in the problem of uniformity and mechanical strength. Electrospinning research still is on the front line in increasing its potential applications in tissue engineering, filtration, and drug delivery. Process parameters optimization is among the strategies deployed to lessen the electrospinning problem of bending instabilities. The modified setups offer fiber production versatility. The setups introduced include far-field electrospinning that provides long, directed nanofibers and near-field electrospinning that gives good fiber deposition. Electromechanical spinning unifies electrical and mechanical aspects to have controlled fiber properties. In the area of applications of electrospun nanofibers, so far, the areas like biomedical, environmental, energy, textile, sensor, agriculture, cosmetic, and food packaging industries come as a real versatile bunch. This potential of the technology in divergent fields is ever-growing, in ongoing research continues to enhance its effectiveness toward tissue engineering solutions.

Keywords: Scaffolds; Electrospinning; Tayler's Cone; Bending instabilities; Application of electrospinning

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1. Introduction

Tissue engineering scaffolds are structures that provide an enabling environment where cells can grow and increase to finally develop into a functional tissue or organ in a three-dimensional way [1]. Therefore, such scaffolds should replicate as closely as possible the natural extracellular matrix within the body tissues to instruct cellular behavior and tissue formation. They can be prepared from a variety of materials, either natural polymers like collagen or fibrin, synthetic polymers such as polycaprolactone or poly(lactic-co-glycolic acid), or a combination [2]. An ideal tissue engineering scaffold should exude biocompatibility and biodegradability, be mechanically strong and porous, and facilitate cell adhesion, proliferation, and differentiation. Besides, the scaffolds should have the proper pore size and interlinked networks to facilitate the diffusion process of the required nutrients and oxygen, removal of waste, and growth of tissues. In addition, scaffolds can be modified to have physicochemical properties that meet specific tissue or organ requirements by modulating composition, structure, and mechanical properties. Such innovations in scaffold design and manufacturing methods, such as 3D printing and electrospinning, have resulted in the realization of more intricate and functional scaffolds for several tissue engineering purposes. Tissue engineering scaffolds are three-dimensional designs for supporting the growth of new tissue. These scaffolds act as a provisional matrix on which the cells attach themselves, start proliferating, and eventually form new tissue that aids in restoring parts of the body that may be damaged [3].

Scaffolds in tissue engineering are designed using various materials [4,5], including natural polymers like collagen and hyaluronic acid, synthetic polymers such as polylactic acid and polycaprolactone, and composite materials that combine the strengths of both. Essential properties of scaffolds include biocompatibility to support cell growth without immune reactions, biodegradability to synchronize with tissue formation without leaving toxic residues, mechanical strength to bear loads until tissue regeneration, and high porosity for cell migration and nutrient exchange. Common fabrication techniques include electrospinning for creating fibrous, porous structures, 3D printing for precise architectural control, freeze-drying to produce porous scaffolds, and solvent casting with particulate leaching to form porous structures [2,6].

Tissue engineering applications span various fields, including bone, cartilage, skin, cardiac, and nerve tissue engineering, each leveraging scaffolds for cell growth, repair, or regeneration [7,8]. Scaffolds also address critical challenges like ensuring vascularization, minimizing immune responses, and achieving functional integration of new tissues with existing ones. Ongoing research focuses on improving scaffold materials, fabrication methods, and strategies for effective tissue integration to enhance the efficacy and applicability of tissue engineering solutions.

2. Electrospinning

Electrospinning is one of the newest and most versatile techniques used in the fields of nanotechnology and materials science. In this process, ultrafine fibers are created by applying an electric field to a polymer solution or melt [9]. The resulting fibers may have diameters in the range between a few nanometers and several micrometers. Main features of the electrospun fibers are a high surface area to volume ratio, porosity, and high aspect ratio. These features make it possible to use electrospun fibers in such areas of technology as tissue engineering, drug delivery, sensors, filtration, protective clothes, and energy storage devices. The electrospinning process has a great deal of tunability, with the possibility of changing parameters such as polymer concentration, solvent type, applied voltage, and the distance between the spinneret and collector to control fiber diameter, alignment, and morphology. Such precision allows the tailoring of fiber properties for a given application. In short, electrospinning represents a new powerful technology that drives innovations in every walk of life, acting as the seat of material innovation for new materials with very unique properties as well as their applications. These will be continued as an important field of development in tissue engineering scaffolds, where much active research is now focused on overcoming current challenges and extending its applications [10–15].

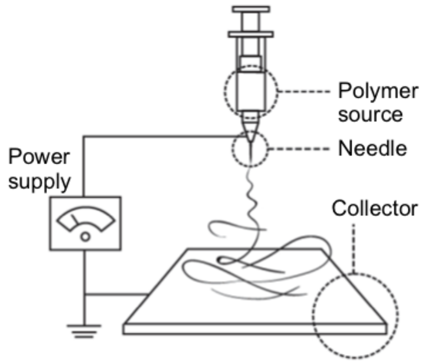

Figure 1. Experimental setup for electrospinning.

2.1. Electrospinning experimental setup

Electrospinning produces nanofibers by applying a high voltage to a polymer solution. The experimental setup normally consists of a few key components:

(1) High voltage power supply: It provides the appropriate voltage needed to generate an electric field between the spinneret and collector.

(2) Spinneret: This may be a needle or nozzle through which the polymer solution is extruded. The nanofiber diameter would depend on the diameter of the spinneret.

(3) Syringe pump: This sets the flow rate of the polymer solution through the spinneret.

(4) Collector: Grounded plate or drum upon which the nanofibers collect.

(5) Polymer solution reservoir: Container to hold polymer solution, feeding into the syringe pump.

(6) Grounded electrode: This collects the charged nanofibers and completes the circuit.

(7) Enclosure: A chamber where one can control temperature and humidity.

Such parameters can be controlled in a very stringent manner given voltage, spinning distance, collector distance, flow rate, and other environmental conditions for tuning the properties of the nanofibers produced for tissue engineering, filtration, and drug delivery [16,17].

2.2. Components of an electrospinning setup

The experimental setup for electrospinning are as follows (**Figure 1**):

(1) High voltage power supply: Supplies the electric field needed to electrospin the polymer solution into fine fibers. Voltages used are normally between 10 kV and 30 kV.

(2) Spinneret: A nozzle or a needle, using which the polymer solution is spun. The diameter of the spinneret affects the diameter of the resulting nanofibers.

(3) Syringe pump: The combination helps regulate the infusion of the polymer solution by the spinneret. It equally leads to uniform and controlled production of fibers.

(4) Collector: This may be a grounded surface, flat plate, or rotary drum on which the nanofibers are collected. The shape and movement of the collector will determine the alignment and morphology of the fibers.

(5) Polymer solution reservoir: These will hold the polymer solution and feed to the syringe pump crucial to the process are the properties and concentration of the solution.

(6) Grounded electrode: It is meant to complete the electric circuit and collect the deposited charged nanofibers.
(7) Enclosure: A chamber that controls environmental conditions such as temperature and humidity, which can have a huge influence on the electrospinning process and the properties of the obtained fibers [18,19].

2.3. Controlling parameters in electrospinning

(1) Voltage: Determines the strength of the electric field and affects the formation of the Taylor cone and the fiber diameter.
(2) Flow rate: Influences the rate at which the polymer solution is extruded, affecting the thickness and uniformity of the fibers.
(3) Spinneret-collector distance: Impacts the stretching and thinning of the fibers as they travel to the collector.
(4) Solution properties: Including viscosity, concentration, and conductivity, which affect the fiber formation and morphology.
(5) Environmental conditions: Temperature and humidity can alter the solvent evaporation rate and the behavior of the polymer solution during electrospinning [20,21].

2.4. Applications of electrospun nanofibers

(1) Tissue engineering: Nanofibers are capable of mimicking the ECM, hence supporting cell attachment, proliferation, and differentiation. They find applications in scaffolds for tissue engineering of bone, skin, nerve, and cardiac tissues.
(2) Filtration: Because nanofibers have high surface areas to volume and very small pore sizes, they can suitably be applied in both air and water filtrations.
(3) Drug delivery: Nanofibers can be loaded with drugs and provide controlled release profiles, hence increasing the efficacy of the drug delivery system.
(4) Wound healing: Electrospun nanofibers have the potential to produce dressings facilitating the healing process by protecting from infections, supporting gas exchange, and absorbing fluids [22–24].

2.5. Advantages of electrospinning

(1) High surface area: Nanofibers have a large surface area, beneficial for applications requiring high interaction with the environment or cells.
(2) Porosity: The interconnected porous structure facilitates cell infiltration and nutrient exchange in tissue engineering.
(3) Versatility: A wide range of polymers can be electrospun, allowing for customization of fiber properties to suit different applications.

2.6. Challenges and innovations

(1) Uniformity and control: It is challenging to achieve homogeneity in fiber diameter and uniform scaffold properties.
(2) Mechanical strength: Electrospun fibers can be too weak for high mechanical strength applications and require reinforcement.
(3) Scale-up: Quality assurance is a continuing challenge in large-scale production.

(4) Multi-component and functionalized fibers: Research studies are focused on the development of composite fibers and the introduction of bioactive molecules to impart functionality.

(5) 3D structures: Developing techniques for the creation of three-dimensional electrospun structures for more complex tissue engineering applications. Refining the process of electrospinning and researching new materials and techniques have been helping researchers move the potential applications of electrospun nanofibers into an increasingly broad spectrum of fields.

2.7. Working principle

(1) Solution preparation: A polymer solution or melt is prepared. The choice of the polymer, solvent, and concentration used is important since they will affect the viscosity, surface tension, and conductivity of the solution.

(2) Solution loading: The polymer solution is loaded into a syringe equipped with a metal needle (spinneret).

(3) High voltage application: A high-voltage power supply is applied to the needle. The voltage between the spinneret and a conducting collector serves to provide an electric field.

(4) Jet formation: The voltage is increased until it reaches a point where electrostatic forces are stronger than the surface tension of the polymer solution, whereby a Taylor cone is formed at the tip of the needle. If the electrostatic force overpowers the surface tension, a charged jet of polymer solution is squirted off from the tip.

(5) Stretching and thinning: The jet is gradually subjected to stretching and thinning as it moves toward the collector. This results in the evaporation of the solvent and the solidification of the polymer fibers.

(6) Deposition: The fibers are deposited on a grounded collector, usually a flat plate, a rotating drum, or other structures that can provide a proper geometry for subsequent fiber alignment and properties [25].

2.8. Experimental setup

(1) Syringe and needle (Spinneret): The polymer solution is held in a syringe connected to a metal needle. The needle serves as the spinneret from which the polymer jet is ejected.

(2) High-voltage power supply: This is used to generate the electric field required for electrospinning. Typical voltages range from 5 to 30 kV.

(3) Pump system: A syringe pump controls the flow rate of the polymer solution. The flow rate needs to be optimized based on the polymer and solvent used.

(4) Collector: The collector is grounded and placed at a certain distance from the needle. The design of the collector can vary:

(5) Flat plate: For randomly oriented fibers.

(6) Rotating drum: For aligned fibers.

(7) Rotating mandrel: For tubular structures.

(8) Environmental control: Some setups include a controlled environment chamber to regulate temperature, humidity, and air flow, as these factors can influence fiber formation and properties.

2.9. Process parameters

Several parameters can be adjusted to control the characteristics of the electrospun fibers:

(1) Solution properties: Concentration, viscosity, surface tension, and conductivity of the polymer solution.

(2) Voltage: The magnitude of the applied voltage affects the jet formation and fiber diameter.

(3) Flow rate: The rate at which the polymer solution is fed to the needle.

(4) Distance between needle and collector: Affects the flight time and, consequently, the fiber formation.

(5) Collector type and speed: Influences fiber alignment and density.

Electrospinning is an advanced process for the fabrication of nanofibers by applying a high tension to a polymer solution. This method produces fine fibers, and these fibers are collected over a grounded surface. The properties of the resultant fibers for a specifically desired application could be easily tailored with the manipulation of the experimental parameters at a fine scale. Electrospinning is the process of creating extremely fine fibers by using an electric field to convey a polymer solution or melt onto a small droplet at the tip of a slender fiber. The general configuration of the electrospinning experiment is done with a syringe pump to control polymer solution liquid delivery, a high voltage power source that creates an electric field, a spinneret to extrude a polymer solution as a jet, a collector to store the fibers, and a grounded plate that closes the electrical circuit. First, the electrospinning polymer solution is injected by a syringe pump and then, under the influence of high voltage supplied from a power source, electrical charges are applied. The electrostatic forces are created by the repulsion of similar charges in the polymer solution, overcoming surface tension, and creating a jet from the solution, elongated and thinned towards the collector. Simultaneously, solvent evaporates and fine fibers are laid on the collector. Some important parameters affecting the electrospinning process include the concentration of the polymer solution, flow rate of the solution, applied voltage, tip-to-collector distance, and environmental conditions. All of these variables are tuned for tailoring the diameter, morphology, and properties of the final electrospun fibers for a plethora of uses in tissue engineering, filtration, and drug delivery.

2.10. Taylor cone in electrospinning process

In the process of electrospinning, nanofibers form through the Taylor cone. A high voltage is applied to a polymer solution or melt in this process. As the charged material jet travels toward the collector, the repulsion of like charges stretches it, making it increasingly thin in radius. The Taylor cone is a pointed projecting shape that forms at the jet tip when electrostatic forces overcome the surface tension of the polymer solution. The cone-shaped formation is named after Sir Geoffrey Ingram Taylor, who studied the behavior of electrified droplets in the early 1960s. The Taylor cone's formation is rather important since it determines the stability and morphology of nanofibers resulting from it. A stable cone shape in the process produces uniform and well-defined nanofibers, whereas if it is unstable, beads-on-a-string morphology or irregular fibers will form. That is to say, generally, the Taylor cone in the process of electrospinning acts as a very crucial factor that impinges on the quality and properties of the nanofibers produced and becomes an important focus of research and optimization in electrospinning technology [26–29].

2.11. Bending instabilities in electrospinning

Bending instabilities are widespread in this technique for manufacturing nanofibers. The instabilities occur when a charged jet is extruded from the spinneret tip with a polymer solution, getting bent as a result of various mechanisms: these range from the field intensity, the solution viscosity, and the flow rate. The jet, in its trajectory toward the collector, can be affected by whipping, buckling, or meandering motions, making the morphologies produced irregular. Bending instabilities are very important regarding both controlling and understanding electrospinning in order to produce uniform and nanofibers with high quality. Various researchers have provided suggestions to overcome the bending instabilities, such as optimal choice of processing parameters, reducing the dielectric constant, coaxial spinnerets, use of additives in the polymer solution, and introduction of secondary electric fields in guiding the jet. By minimization of such instabilities in bending, the mechanical properties, porosity, as well as functionality of electrospinning nanofibers (for a wide array of applications including tissue engineering, filtration, and drug delivery) are hoped to be improved. In general, overcoming the bending instabilities found in the electrospinning pack is needed both for the advancement of the technology in general and to properly unleash the potential capability of materials based on nanofibers for its multiple applications [30,31].

2.12. Controlling parameters in electrospinning

One of the versatile techniques used in producing nanofibers is electrospinning, where electric fields are applied to a polymer solution. In this process, different parameters must be controlled to produce fibers with desired properties. Some of the most important parameters are polymer concentration, solution viscosity, applied voltage, flow rate, the distance between the needle tip and collector, and finally the environmental conditions like temperature and humidity. The polymer concentration can be varied to impact fiber diameter and morphology. Usually, larger diameters are the result of higher polymer concentrations. This then changes the viscosity of the solution affects the alignment of the fibers and, indirectly, their mechanical properties. The applied voltage influences the extent of stretching and thinning of the polymer jet that changes the fiber diameter. The flow rate affects the productivity and morphology of the fibers, higher flow rates give finer fibers. The distance between the needle tip and the collector should be optimized for controlling the fiber alignment and collection efficiency. Environmental conditions impact the drying and solidification of fibers, hence finally affecting the characteristics of the fibers. Those variables can be changed systemically by researchers or engineers to further fine-tune the features of the electrospun fibers to exhibit some desired properties relevant to applications related to biomedicine, filtration, or tissue engineering [32–34].

2.13. Modified electrospinning setups

Electrospinning is one of the most versatile techniques developed for the production of nanofibers from different materials. There may be some variations or enhancements in the modified electrospinning experimental setup compared to the traditional one for achieving a specific objective or improvement in the process. Some common modifications/enhancements are

(1) Needle configuration

   (a) Multi-needle setup: This configuration uses multiple needles to increase the production rate of nanofibers;

   (b) Coaxial electrospinning: A technique where there is a needle within a needle for generating core-shell fibers that enable the encapsulation of materials therein.

(2) Collector design rotating drum collector

   Using this collector, the fibers are oriented in one direction, which may become very useful in applications that require oriented nanofibers.

(3) Solution delivery system syringe pumps

   They are used to control with high accuracy the flow rate of the polymer solution. Pressurized systems can enhance the uniformity in fiber diameters by providing consistent solution flow.

(4) Environmental control

Humidity and temperature control can influence the evaporation rate of solvents and the morphology of fibers.

(5) Enclosed chambers

This may reduce contamination and permit more stringent control of environmental factors.

(6) Electric field mods

(a) Variable voltage: Voltage adjustment controls fiber diameter and morphology;

(b) Auxiliary electrodes: These may be used to guide the path of fibers, improve alignment, or form specific patterns.

(7) Material-specific adaptations

(a) Dissimilar solvent systems: For different polymers or composite materials;

(b) Additives: Like surfactants or nanoparticles to modify the properties of fibers.

(8) Post-treatment systems thermal treatments: Heat treatments applied after spinning enhance fibers' mechanical properties.

(9) Crosslinking or functionalization: This can modify the surface chemistry of the fibres. Such changes can be modulated according to specific research goals aimed at improving the uniformity of the fibers, increasing production rates, and achieving certain structural or functional features in the nanofibers. In this case, if there are specific goals or materials in mind, the setting-up can be tailored to meet such needs.

Modified electrospinning configurations include the following changes to the conventional electrospinning setup, either increasing fiber production efficiency or resulting in original structures of the produced fibers. One such modification includes the addition of a co-axial or multi-axial spinneret setup. This enables encapsulation of the core materials in the fibers, which will produce core-shell fibers having controlled release properties. Another modification is the incorporation of an electrospinning setup inside a controlled environment chamber, such as a glovebox or inert gas atmosphere, which allows for electrospinning of sensitive materials prone to reaction with moisture or oxygen. The modifications of the electrospinning parameters, in terms of voltage, flow rate, and collector speed, will also have an impact on the morphology and properties of the fibers. These may include the production of finer fibers, increased production rates, and structures with alignment. In general, modified electrospinning set-ups provide versatility and control of the electrospinning process; thus, they are capable of producing a wide variety of fibers with tailored properties for many tissue engineering, filtration, and even drug delivery applications [35,37].

3. Far Field Electrospinning

Far-field electrospinning is one of the techniques in the production of nanofibers by using an electric field that is imposed on a polymer solution or melt. Unlike conventional electrospinning, where the electric field is applied close to the spinneret, far-field electrospinning applies the electric field from some distance. This allows the formation of longer and more aligned nanofibers. In far field electrospinning, typically, a solution of the polymer is pumped through a spinneret toward a grounded collector while an electric field is applied over a longer distance. This stretches the polymer fibers and aligns them in flight toward the collector, ultimately forming nanofibers. Far field electrospinning offers advantages in terms of scalability and continuous production of nanofibers over large areas. It has a wide range of applications in tissue engineering, filtration, textiles, and drug delivery. Therefore, far field electrospinning is expected to be one of the prospective technologies for the production of advanced materials with special functionalities since it enables the production of well-aligned nanofibers with controlled properties. Far Field Electrospinning (FFES) is a variant of the traditional electrospinning process wherein the distance between the needle and the collector is considerably increased to values over 20 cm. Therefore, it impacts the resultant nanofiber morphology and its properties at this extended distance [20,36].

3.1. Key features and benefits of Far Field Electrospinning

(1) Enhanced fiber uniformity: Increasing the distance allows more time for the solvent to evaporate completely, leading to more uniform fibers with fewer defects or beading.

(2) Greater fiber alignment: With a longer travel path, the fibers have more time to align due to the stretching and whipping motion caused by the electrostatic forces.

(3) Reduction in jet instabilities: The extended distance can help reduce jet instabilities, which are common in close-proximity electrospinning setups, leading to more consistent fiber formation.

(4) Customization of fiber properties: By varying the distance between the needle and the collector, as well as other parameters like voltage and flow rate, researchers can tailor the diameter and surface morphology of the fibers.

(5) Applications in large-scale production: The technique can be advantageous in scaling up the electrospinning process, as the increased distance allows for a broader area of fiber deposition.

3.2. Challenges and considerations in Far Field Electrospinning

(1) Need for precise control: Precise control over the solution properties (viscosity, conductivity), environmental conditions (temperature, humidity), and electrospinning parameters (voltage, distance) is crucial to achieve desired fiber characteristics.

(2) Potential for fiber breakage: The longer travel distance may increase the likelihood of fiber breakage if the mechanical properties of the polymer are not well-suited to the setup.

(3) Collection efficiency: Ensuring efficient collection of fibers over a larger area requires careful design of the collector system, which might include moving collectors or specific designs to focus the fiber deposition.

(4) Electrical considerations: A higher voltage may be required to maintain a stable jet over the increased distance, which can raise safety concerns and require careful handling.

(5) Experimental setup for Far Field Electrospinning: High-Voltage Power Supply: Typically ranging from 10-30 kV, depending on the solution properties and distance.

Needle-to-Collector Distance: Often set beyond 20 cm; exact distance depends on the desired fiber properties.

(6) Solution delivery system: Syringe pumps or pressurized systems to control the flow rate of the polymer solution.

(7) Collector design: Can be flat, rotating, or patterned, depending on the application and desired fiber orientation.

(8) Environmental controls: Enclosed chambers with temperature and humidity control can help stabilize the process and improve fiber consistency.

4. Near Field Electrospinning

Near Field Electrospinning (NFES) is a technique used in nanotechnology to produce nanofibers with diameters ranging from a few nanometers to several micrometers. Unlike traditional electrospinning, which operates in the far-field regime, NFES works in the near-field region, where the distance between the spinneret and the collector is much shorter. In NFES, a high voltage is applied to a polymer solution or melt at the tip of a spinneret to create an electric field. The electric field induces a charge on the surface of the polymer, causing the polymer to form a Taylor cone. As the polymer jet is ejected from the cone, it elongates and solidifies into nanofibers as it travels towards the collector. The proximity of the collector to the spinneret in NFES allows for better control over the deposition of the nanofibers, resulting in improved alignment and patterning. This technique is used in various applications such as tissue engineering, filtration membranes, sensors, and drug delivery systems due to the high surface area and porosity of the nanofibers produced. Near Field Electrospinning (NFES) is a variation of the traditional electrospinning technique where the distance between the needle and the collector is significantly reduced, typically to a range of a few millimeters to centimeters. This close proximity enables precise control over the deposition of nanofibers, making NFES suitable for applications that require fine patterning and alignment of fibers [38].

4.1. Key features and advantages of Near Field Electrospinning

(1) High-precision fiber deposition: The short needle-to-collector distance allows for precise control over the placement of fibers, enabling the creation of well-defined patterns and structures.

(2) Enhanced fiber alignment: NFES facilitates the production of highly aligned fibers due to the limited whipping motion of the jet, which is constrained by the reduced distance.

(3) Micro/Nano-scale patterning: The technique is particularly useful for applications that require micro- and nano-scale patterning, such as in the fabrication of sensors, microelectronic devices, and tissue engineering scaffolds.

(4) Reduced electrical requirements: Lower voltage levels are typically required in NFES compared to conventional electrospinning, as the electric field strength needed to initiate fiber formation can be achieved with a smaller gap.

(5) Material versatility: NFES can be used with a wide range of materials, including polymers, composites, and even biomolecules, enabling the fabrication of functionalized and multi-material fibers.

4.2. Challenges and considerations

(1) Process control: Maintaining stable jet formation and consistent fiber deposition requires precise control of process parameters, such as voltage, flow rate, and needle-to-collector distance.

(2) Limited production scale: NFES is generally more suitable for small-scale production and research applications, as the deposition area is limited by the proximity of the setup.

(3) Complex setup: The need for precise alignment and control systems can complicate the setup and operation, requiring careful calibration and adjustment.

(4) Potential for needle clogging: The proximity and small orifice size can increase the likelihood of needle clogging, particularly with high-viscosity solutions.

4.3. Experimental setup for Near Field Electrospinning

(1) High-voltage power supply: Lower voltage range compared to conventional electrospinning, typically around 0.5–2 kV.

(2) Needle-to-collector distance: Ranges from a few millimeters to centimeters, depending on the desired precision and fiber properties.

(3) Micro-manipulators: To position and control the needle or collector with high precision, enabling detailed patterning.

(4) Substrate/Collector: Can include various materials, such as conductive or non-conductive substrates, depending on the application.

(5) Solution delivery system: Often involves syringe pumps for controlled flow of the polymer solution.

NFES is particularly advantageous for applications in microfabrication, biomedical engineering, and the creation of complex fibrous structures with high precision.

5. Electromechanical spinning

Electromechanical spinning is a process combining electrical and mechanical elements to perform controlled spinning. It is used for a variety of purposes, from textile production processes to fiber manufacturing and nanotechnology. In relation to textile production, electromechanical spinning is used to produce yarns and threads. Electrical elements in spinning machines help control the parameters of speed, tension, and twist to produce yarns that are consistent and of high quality. The electromechanical spinning method is applied in producing nanofibers with well-controlled properties in nanotechnology. The application of electrical fields during spinning will help the researchers orient and align nanofibers, hence developing enhanced mechanical, electrical, or optical properties. The overall result of this process is that it provides a versatile and efficient method of producing fibers and nanomaterials with tailored characteristics, hence securing value for technology in a number of industries. Electromechanical spinning, otherwise referred to as electro-mechanical spinning or electro-spinning with mechanical assistance, is a hybrid technique combining the working principles of conventional electrospinning with mechanical spinning methods. This technique aims to increase the control of fiber morphology, alignment, and production efficiency by involving mechanical forces in addition to the conventional electrostatic forces used in electrospinning [39].

5.1. Key features and principles

(1) Combination of forces: In electromechanical spinning, both electrostatic and mechanical forces are used to draw the fibers. The mechanical forces can come from rotating drums, rollers, or other mechanical means that assist in stretching and aligning the fibers.

(2) Improved fiber control: The mechanical component provides additional control over the fiber formation process, allowing for more precise manipulation of fiber diameter, alignment, and orientation.

(3) Enhanced alignment and orientation: Mechanical forces help in aligning fibers, which is beneficial for applications requiring highly oriented fiber structures, such as in textiles, filtration, or reinforced composites.

(4) Scalability: The integration of mechanical systems can enhance the scalability of the fiber production process, making it more suitable for industrial applications.

5.2. Applications

(1) Textiles and fabrics: The technique is used to produce nanofiber fabrics with enhanced mechanical properties, uniformity, and specific functional properties.

(2) Biomedical engineering: It can be used to fabricate scaffolds for tissue engineering with aligned fibers that mimic the structure of natural tissues, enhancing cell growth and tissue regeneration.

(3) Filtration systems: Electromechanical spinning can create filter materials with precise pore sizes and high mechanical strength, useful for air and water filtration.

(4) Composites: The technique is applied in producing composite materials with reinforced nanofiber structures, which improve the mechanical and thermal properties of the composites.

5.3. Experimental setup

(1) High-voltage power supply: Similar to conventional electrospinning, a high-voltage power supply generates the electrostatic field required to draw the fibers.

(2) Mechanical components: This can include rotating drums, rollers, or other mechanical stretching systems that assist in the drawing and aligning of fibers.

(3) Solution delivery system: Syringe pumps or pressurized systems are used to control the flow rate of the polymer solution.

(4) Collector: The collector may include additional mechanical components to assist in fiber alignment and collection. These can be stationary or moving, depending on the desired fiber orientation.

(5) Environmental Controls: Controlling temperature and humidity is important to maintain the consistency and quality of the fibers produced.

5.4. Challenges and considerations

(1) Complexity of setup: The integration of mechanical systems adds complexity to the setup, requiring precise calibration and maintenance.

(2) Process control: Ensuring consistent fiber quality requires careful control of both the electrostatic and mechanical parameters.

(3) Material limitations: Not all materials are suitable for electromechanical spinning, and the choice of materials can affect the feasibility and quality of the fibers produced.

6. Application of electrospun scaffold

Electrospun nanofibers are extremely versatile materials with a wide range of applications across various fields. Here are some of the key applications:

6.1. Biomedical applications

(1) Tissue engineering: Electrospun nanofibers provide a scaffold that mimics the extracellular matrix, promoting cell attachment, growth, and differentiation, making them suitable for tissue engineering applications such as skin, bone, and vascular grafts.

(2) Drug delivery: Nanofibers can be used to create drug delivery systems that allow for controlled release of pharmaceuticals. This can improve the efficacy and reduce the side effects of various drugs.

(3) Wound healing: Due to their high surface area and porosity, electrospun nanofibers can be used in wound

dressings that facilitate faster healing and provide a barrier against infections.

6.2. Environmental applications

(1) Filtration: Nanofibers are highly effective in air and water filtration systems due to their large surface area and small pore size, which allow them to trap very fine particles and contaminants.

(2) Oil spill cleanup: Electrospun nanofiber mats can be used to absorb oil from water surfaces, providing a method for cleaning up oil spills efficiently.

6.3. Energy applications

(1) Battery separators: Electrospun nanofibers are used in lithium-ion batteries as separators that prevent short circuits while allowing ions to pass through, enhancing battery performance and safety.

(2) Fuel cells: Nanofibers can be used in fuel cells to improve the efficiency of the electrochemical reactions that generate electricity.

6.4. Textile and apparel

(1) Smart textiles: Incorporating electrospun nanofibers into fabrics can impart special properties such as water resistance, breathability, and antimicrobial activity, leading to the development of smart textiles for clothing and medical applications.

(2) Protective clothing: Nanofiber layers can be added to protective clothing to enhance their barrier properties against biological and chemical hazards without compromising comfort.

6.5. Sensors

Electrospun nanofibers can be used to develop highly sensitive sensors for detecting chemicals, biological agents, and physical parameters such as pressure and temperature. Their high surface area-to-volume ratio makes them particularly effective in sensing applications.

6.6. Agriculture

In the controlled release of fertilizers and pesticides, nanofibers can be engineered to release fertilizers and pesticides in a controlled manner, improving efficiency and reducing environmental impact.

6.7. Cosmetics

In skin care products, electrospun nanofibers can be used in face masks and other skin care products to deliver active ingredients more effectively to the skin.

6.8. Food industry

In terms of food packaging, nanofibers can be used in food packaging to enhance the shelf life of products by providing better barriers to oxygen and moisture and incorporating antimicrobial agents.

6.9. Electronics

In terms of the flexible electronics, electrospun nanofibers are used in the development of flexible electronic devices, such as wearable sensors and flexible displays, due to their excellent mechanical properties and conductivity.

7. Conclusion

In summary, scaffolds in tissue engineering offer a temporary matrix guiding cell attachment, growth, and differentiation toward the overall growth of a new tissue. The scaffolds are fabricated from naturally occurring and synthetic polymers whose material characteristics such as biocompatibility, biodegradability, mechanical strength, and porosity can be attained. Development of more complex and functional scaffolds has been enabled by advancements in scaffold design and manufacturing methods for tissue engineering applications like electrospinning. It offers a versatile technique to produce highly porous, larger surface area scaffolds in the form of nanofibers, which can potentially mimic the extracellular matrix of different tissues. Voltage, flow rate, and distance from the spinneret to the collector can be manipulated to get fibers with the desired characteristics for applications in tissue engineering, filtering, wound healing, and drug release. Presently, consistency and mechanical strength have remained two big challenges in this field, and thereby in scale-up; innovations include multicomponent fibers, functionalized fibers, creating 3D structures. Electrospinning is gaining increasing interest in the field of regenerative medicine due to its versatility and suitability for the fabrication of nanotextured fibrous scaffolds. One of the main limitations of this technique is that of the enhanced bending instability, which is responsible for buckling/curling and leads to the formation of under-controlled tortuous fibrous morphologies, which may compromise the fidelity of the final nanofibers.

Generally, several attempts have been made to reduce these instabilities by modulating the process parameters within their optimal range or by using coaxial spinnerets. Understanding and control of these instabilities have huge potential to improve mechanical properties, porosity, and functionality of electrospun nanofibers for tissue engineering, filtration, and targeted drug delivery. Modified electrospinning setups allow for flexibility and control in the process in producing unique fiber structures and improved fiber production efficiency. Far-field electrospinning made the manufacture of long, straighter oriented nanofibers possible, which immediately found applications in tissue engineering, filtration, textiles, and drug delivery. Near-field electrospinning provides very high precision of fiber deposition and increased alignment for the dispensing of micro- and nano-scaled fibers for patterning applications. Electromechanical spinning, without deviating from the synergistic electrical and mechanical effects, produces fibers with controlled properties, so its applications are found in textiles, biomedical engineering, and composites. Electrospun nanofibers are found to have taken up an application since the last few decades in such vital areas as biomedical, environmental, and energy, in textile and apparel industries, and in sensors; agriculture; cosmetics; food packaging; and the like.

Disclosure statement

The authors declare no conflict of interest.

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