CURRENT CONCEPTS REVIEW

Helical, Spring and Curled Nano/Micro Fibrous Structures for Tissue Engineering Application

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Abstract

Over the past few decades, the engineering of helical, spring, curled, and hierarchically structured nano/microfibers has attracted considerable attention due to their unique characteristics and potential applications in tissue engineering and various industrial fields. Understanding the parameters and processes involved in the fabrication of these fibers is essential. This comprehensive review outlines recent advancements in research on helical nano/microfibers, focusing on processing techniques, fiber structure, and property characterization, and their applications in fields such as tissue engineering and regenerative medicine. The study also investigates the mechanical and hydrodynamic parameters that influence the fabrication of helical fibers using contemporary techniques. It highlights that helical structures form when electric and elastic forces are balanced due to non-uniform electric fields. The coaxial electrospinning technique, along with the use of polymers with varying elastic and conductive properties, plays a crucial role in producing these structures. The distinctive properties of helical nanofibers, such as their mechanical strength, high porosity, biocompatibility, and ability to promote cellular activities, make them promising candidates for developing scaffolds in bone tissue engineering.

Level of evidence: III

Keywords: Bi-component, Co-electrospinning, Elastic force, Electrospinning, Helical nanofiber, Tissue engineering

Introduction

In recent years, nanotechnology has emerged as a significant area of interest across various fields. The attention received by nanotechnology is due to its capacity to produce innovative devices and nanomaterials with unique properties.[1,2] In addition, it has numerous applications in several industries, including electronics, materials science, tissue engineering, and polymer engineering.[3] Among the various categories of nanomaterials, nanofibers exhibit unique properties that have attracted the attention of researchers and prompted several published experimental studies and useful review articles on their applications and remarkable properties.[4-9] Nanofibers are characterized as fibers with diameters ranging from micrometers to nanometers, making them promising scaffolds for applications in bone tissue engineering (BTE). Their ability to be fabricated with physical properties that closely resemble the extracellular matrix (ECM) enhances their potential in this field.[10] They offer several advantages, including high specific surface area, small pore size and high porosity.[11] Furthermore, when utilized as mats or nonwoven structures, nanofibers demonstrate significantly enhanced mechanical performance compared to conventional fibers.[12] Additionally, nanofibers have a wide range of applications in many fields, including nanoelectronics, filtration processes, protective clothing, and medicine. The emerging areas of application include artificial organs, tissue engineering, and drug delivery systems.[13,14] As a result, nanofibers are increasingly recognized as promising candidates for tissue engineering and medical applications.[15-17]

Main body

Nanofibers can be produced by various techniques, including top-down methods such as melt blowing,[18] electrospinning,[19,20] as well as bottom-up methods like drawing,[21] template synthesis,[22,23] and phase separation.[24]

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As mentioned before, there are various methods for fabricating nanofibers, including electrospinning, self-assembly, template-based synthesis, phase separation, and melt blowing. Each of these methods has its own advantages and limitations that need to be understood in order to choose the most suitable fabrication technique for specific applications, as detailed in [Table 1].

A wide range of natural and synthetic polymers with suitable properties for producing nonwoven nanofibrous structures across a vast range of fiber diameters have been identified.[25] This versatility, combined with the simplicity of the production process, has made the electrospinning process a distinctive and cost-effective technique compared to other methods of nanofiber fabrication.[11] Nanofibers are applicable in a variety of fields based on their structure and morphology. The morphology, as well as the physical and mechanical properties of nanofibers, can be improved by modifying their structural parameters.

Therefore, by modifying and enhancing the structure, as well as the physical and mechanical properties, the effectiveness of nanofiber scaffolds can be improved across a range of applications. In this regard, the fibers with engineered structures can be classified into two categories:

1) Hierarchically structured fibers, which include helical, buckled, and beads-on-a-string fibers.
2) Secondary structures, which encompass nanopores, nanopillars, and nanorods fibers.[26]

Among these engineered fibers, the helical fibrous structure is particularly fascinating. Its structural similarity to biological molecules such as proteins and DNA contributes to its appeal, along with its unique potential applications.[27]

Table 1. Synthesis methods of the nanofibrous structure

Methods	Advantage	Disadvantage
Electrospinning	- Utilize various materials including synthetic and natural polymer, emulsions, suspensions, ceramics, metals, and composite systems -Cost-effective technology - Simple technology - Fast technology - Versatile technology	- Low productivity - Small pore size
Self-assembly	- Eliminates the need for complex and energy-intensive processes - Simplicity - Efficiency - High degree of control on nanofiber structures	- Limited to certain materials with certain intrinsic properties - Tuning the properties of the fibers
Template-based synthesis	- Fabrication of complex structures - Diverse range of materials, including metals, polymers, and ceramics - Efficiency - Reproducibility - Environmentally friendly approach	- Limited to the separation of nanofibers and template
Phase separation	- Wide variety of materials, including polymers, ceramics, and composites - Creation of nanofibers with diverse properties and functionalities - Precise control on morphology and porosity of nanofiber - Simplicity - Cost-effectiveness	- Limited to specific materials which can be processed into phases
Melt-blowing	- Efficient - Scalable - High-throughput process - Simplicity in operation - Versatility in material	- Limited to thermoplastic polymers - Limited to control over the properties of nanofibers - Achieving ultrafine fibers

These materials with novel structures are expected to possess distinctive electrical, optical, and mechanical properties, with possible applications in the production of nanoscale sensors, components of filtration media, solar cells, microelectrochemical systems (MEMS), and nanoelectrochemical systems (NEMS)[26,28] as shown in [Figure 1]. It is noted that bone is primarily composed of nanophases organized into intricate hierarchical architectures with dimensions that span from the nanoscale to the macroscale. These complex structures possess exceptional mechanical properties, combining both stiffness and toughness. The meticulous arrangement of fibers at the nanoscale creates nanomechanical inhomogeneities that enhance fracture resistance, making them suitable for tissue engineering applications.

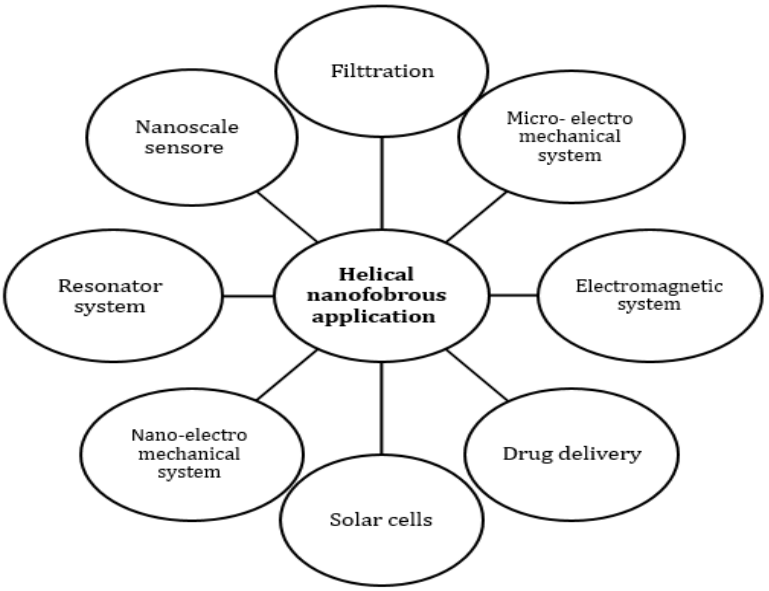

Figure 1. Application of the helical nanofibers structure

Helical nanofiber structures can be fabricated using various techniques, including mechanical stretching, ultrasonication, and physical methods such as electrospinning.[29] Kong et al. successfully created a helical structure of indium oxide through vapor processing.[30] Additionally, similar studies have demonstrated the production of helical nanostructures of zinc oxide and silicon dioxide using this method.[31,32] Notably, helical nanofibers produced via electrospinning have garnered significant interest in recent years due to their excellent mechanical and electrical properties.[26]

In the previously mentioned technique, fiber collectors can be designed with various geometries to create different fiber morphologies, including alignment and pattern.[33] However, it is important to emphasize that this paper reviews the study of Godinho et al., which examines the formation of nanofiber structures through the electrospinning process, particularly due to the uniform shrinkage of components that resemble plant tendrils.[34]

The aim of this review was to investigate similarities between the production techniques of nanofibers and the intrinsic curvature of plant tendrils, which arises from the asymmetric contraction of the fiber ribbons, as illustrated in [Figure 2]. Additionally, the physicochemical properties and applications of helically structured nanofibers were investigated. Finally, the factors influencing the formation of helical structures, specifically mechanical and hydrodynamic parameters, were classified and discussed.

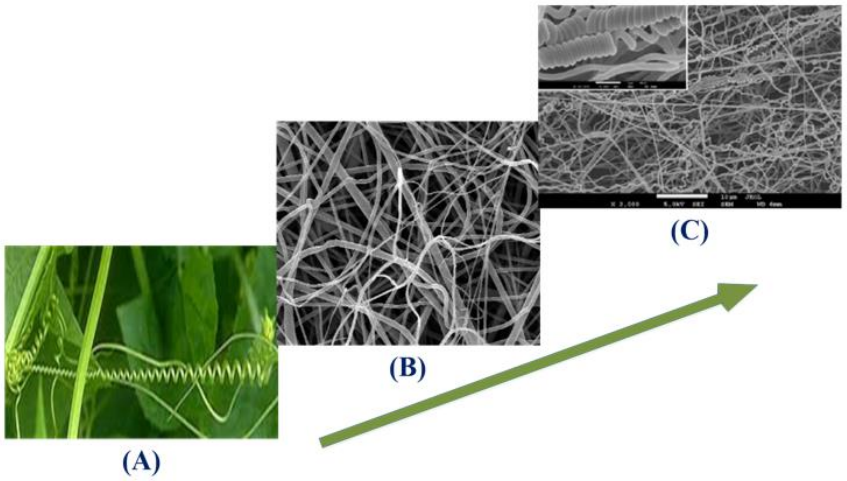

Figure 2. Comparison of the plant tendrils (A), straight (B) and helical nanofibers (C), reproduced from

This phenomenon can occur in two states according to [Figure 3]:

1- During the electrospinning process
2- After the electrospinning process

Electrospinning is an electrostatically driven process, as illustrated in the schematic set-up presented in [Figure 4]. In this technique, a polymer solution is charged by applying an electrical potential, resulting in a jet that flows away from the droplet in a nearly straight line. The formation mechanism of the helical or spring structures can occur either upon contact with the collector surface or during two electrically driven phenomena: bending instability and jet buckling.[35] This helical structure possesses significant potential and unique properties, including increased porosity, toughness, and elasticity. Additionally, these materials exhibit enhanced mechanical properties in terms of resiliency and flexibility.[36]

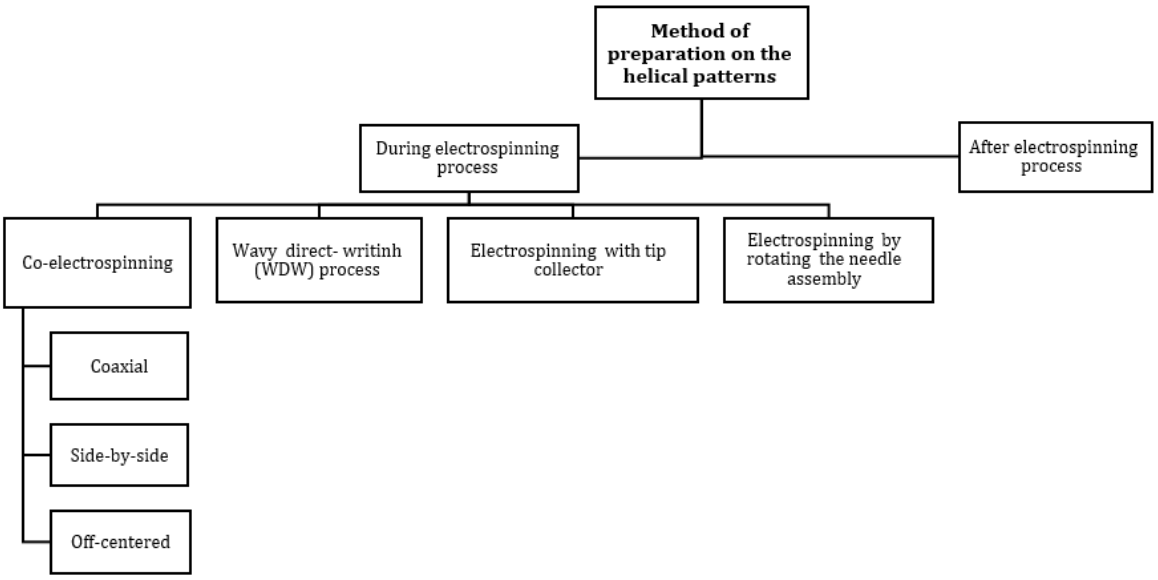

Figure 3. Helical patterns preparation methods

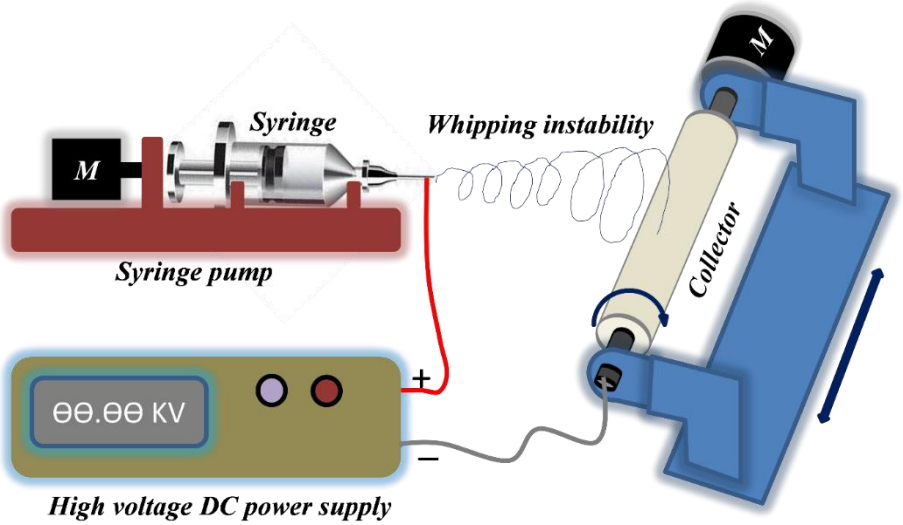

Figure 4. Schematic setup of an electrospinning process

As previously noted, the application of nanofibers is exceptionally diverse. However, producing uniform bi-component polymers with crimp morphology or helical structure and coil diameters on the nanometer scale has posed challenges in the fabrication of an electrospun structure. In this context, this review attempts to examine the techniques for producing stable helical micro/nanofibers and will address the factors that influence the morphological characteristics of the nanoscale helical fibers.

The formation of the helical structure in nanofibers using the electrospinning technique can occur during two distinct phases: during the electrospinning process and after it. The following section outlines the methods and details associated with these processes.

Formation of the Helical Pattern During the Electrospinning Process

This section focuses on various techniques for fabricating helical nanofibers with small coil diameters. In these methods, helical structures are created by modifying the electrospinning equipment and adjusting a series of operating parameters. As previously mentioned, the helical structure of nanofibers can be produced using different techniques, with electrospinning being one of the primary methods employed.[34] Zhu et al. investigated the effect of spinneret configuration on the production of composite nanofibers.[37]

In this regard, researchers suggested four distinct approaches for producing helical micro/nanofibers using the modified electrospinning process, according to [Figure 3]. These methods include:

1-Co-electrospinning
2-Wavy direct-writing (WDW) process (direct-writing using an electrospinning technique),
3-Electrospinning with a rotating needle assembly
4-Electrospinning with tip collector

Among these techniques, co-electrospinning is recognized as an effective and facile method for fabricating helical composite nanofibers.[38]

Several electrospinning models indicate that co-electrospinning with different spinneret configurations can be utilized to produce nanofibers with helical structures. Additionally, coaxial and side-by-side systems represent two variations of electrospinning designs that can be exploited for the production of bi-component helical structures. In these techniques, the crimped or helical structure is generated due to the introduction of interfacial interaction and varying physical behaviors during the electrospinning process. These parameters are significantly influenced by the strength of the electric field and the force exerted by the charged jet.[39]

Reneker et al. were the first to demonstrate that bending instability of the jet can occur after traveling a straight distance of approximately 2-5 cm from the nozzle tip, at which point the jet begins to follow a spiral path. Their findings were further validated by the formation of nanofiber garlands made from polycaprolactone.[40] On the other hand, Fang et al. developed a technique to create wavy micro/nanofiber structures through direct-writing using the electrospinning process.[39] They reported that the frequency of serpentine patterns and the wavelength of these patterns can be controlled by adjusting the electric field of low voltage AC-DC coupling and varying the speed of the collector, respectively. Additionally, they found that factors such as solution concentration, controllability of whipping jet instability, AC electric field strength, charge force status, and collector speed significantly influenced the formation behavior of the serpentine structures.

Senthilram et al. developed a simple modified structure for the fabrication of crimped fibers using the electrospinning process, which involved rotating the needle assembly.[41] They demonstrated that key parameters for producing a crimp pattern in polycaprolactone nanofibers include concentration, rotation speed, and the distance from the needle tip to the collector. Their findings indicated that fibers were formed at all polymer concentrations above 6% and at rotation speeds exceeding 7000 rpm. This can be attributed to the high shear force exerted on the polymer jet, which consequently created significant internal tension in the fibers, as well as the viscoelastic nature of the polymers used.[41] Also, Chum et al. reported the production of curled polyvinylpyrrolidone (PVP) by modifying both the tip and collector during the electrospinning process. In another study, Canejo et al. described the formation of helical twisting in cellulose fibers achieved through a high polymer solution concentration using electrospinning.[42]

Formation of the Helical Pattern After Electrospinning Process

In this case, straight fibers were produced using the electrospinning process, followed by the formation of a helical structure through secondary operations.

Denver et al. successfully spun self-crimping polymer microfibers after initially producing straight fibers via electrospinning.[43] They employed a rotating mandrel as a collection target in the electrospinning technique. Their study demonstrated that the resulting fibers exhibited a wave-like pattern, referred to as crimp; this crimping effect is attributed to residual stresses within the fibers. Furthermore, they indicated that the difference between the operating temperature of the polymer and its glass transition temperature is a critical factor in the production of self-crimping nanofibers. Self-crimping occurred when the operating temperature exceeded the polymer's glass-transition temperature ($T_{op} > T_g$). In fact, conventional microfibers were produced first, and then post-processing techniques were applied to create the crimp patterns on these fibers.

In a similar study, Chen et al., produced crimped fiber scaffolds by electrospinning poly(l-lactide-co-acryloyl carbonate) onto a rotating wire mandrel.[44] In both approaches, the researchers utilized an aqueous environment to induce self-crimp in the fibers. The electrospun fibers were crimped by immersing them in phosphate-buffered saline (PBS, 1×) for one hour at room

temperature.

An overview of the methods, along with details, conditions, and schematic setup of each process, is presented in [Table 2].

The Effect of Process Parameters

Electrical Field

Tensional electrostatic force plays a crucial role in the production of helical structures.[45] Bending instability arises as a result of the tensional electrostatic force induced by a modified electric field.

While researchers have shown that the distribution of the electric field is a significant factor in creating helical patterns, the model developed by Reneker et al.[24] indicates that the formation of curled and helical nanoscale structures is primarily due to perturbations in the electrospinning jet caused by the repulsive electrical forces from the charge carried by the jet.[46,47] This phenomenon occurs when bending instability of the electrospinning jet takes place after it has traveled a few centimeters in a straight line, followed by buckling instability when the jet comes to rest on the collector.

Consequently, at relatively higher operation voltages, both bending instability and curling will increase. In a similar study, Chun et al. demonstrated that an increase in the applied voltage led to a corresponding rise in the production of the helical structures, attributed to enhanced bending instability from electrical forces and mechanical jet buckling upon contact with the collector surface.[48] Xin and Reneker found that reducing the applied voltage diminished bending instability, resulting in the observation of only a straight electrical field jet at the end of the process, as shown in [Figure 5].[49]

Table 2. Electrospinning conditions for formation of the helical nano/micro-electrospun fibrous structure

Materials	Methods	Effective Factors	Conditions	Refs.
Polyethylene oxide (PEO)	Electrospinning	Bending instability	V= 20 kV Tip-collector distance= 20 cm PEO =6 wt.-% in water and ethanol	35
Polyurethane/ Poly(m-phenylene isophthalamide)	Co-electrospinning with an Off-centered core-shell spinneret	1- Asymmetrical electric field distribution 2- Applied voltage 3- Conductivity of system 4- Composite ratio	Voltage = 20-25 kV Tip-collector distance =15cm TPU=18 wt.% in MF/THF Nomex=12 % wt in DMAc	36
Polyethylene oxide (PEO)	Electrospinning via a direct-writing process	1- Low voltage wavy direct-writing (WDW) 2- AC-DC coupling electric field 3- Solution concentration 4- Collector speed	V(AC) =< 300V V(DC) =1.5 kV Tip-collector distance = 0 PEO = 3 wt.% & 8 wt.% in deionized water	39
Poly(L-lactide-co-acryloyl carbonate)	Electrospinning	1- Fiber alignment process 2- Difference between the operating temperature (*T*op) and glass-transition temperature (*T*g) of the polymer	V= 1 kV /cm Tip-collector distance =15 cm P(LLA-AC)= 20 to 35% (w/v) in dichloromethane/ Dimethylformamide (DCM/DMF)	44
Poly(3,4-ethylenedioxythiophene)/ poly(styrene sulfonate)/ poly(vinyl pyrrolidone) (PEDOT:PSS-PVP)	Electrospinning/ reciprocating-type electrospinning	1- Electrically driven bending instability 2- Mechanical jet buckling 3- Microfibers velocity vector	V= 8 kV Tip-collector distance = 3-4 cm PEDOT: PSS = 2.8 wt. % dispersion in H2O and absolute ethyl alcohol. dimethylsulfoxide (DMSO)	45
Polyurethane/ Polyacrylonitrile	Co-electrospinning (side-by-side)	1- Microfluid device as the electrospinning spinneret 2- Elastomeric and thermoplastic components	V= 22 kV Tip-collector distance = 15cm PAN=6.6 wt. % in DMF PU=10 wt% in DMF	46
Poly(ethylene glycol terephthalate)/ Poly(ethylene propanediolterephthalate)	Co-electrospinning (side-by-side) with microfluidic electrospinning nozzle	1- Whipping instability 2- Composite with distinction in mechanical property or shrinkage/with distinct stress-strain action	V= 15 kV Tip-collector distance = 12 cm HSPET= 14 wt.% in TFA PTT= 11 wt.% in DCM	47
Polycaprolactone	Electrospinning by rotating the needle assembly	1- Concentration 2- Speed of rotation 3- Distance between the needle and the collector	V= 8.8 kV Tip-collector distance = 8-16 cm PCL = 3 – 15 % w/v in chloroform	41
Polystyrene	Electrospinning	1- Jet buckling	V= 2.5 to 6 kV Tip-collector distance = 2 to 8cm PVP = 25 wt.% in dimethylformamide(DMF)	48

Table 2. Continued

Polycaprolactone	Electrospinning	1- Collector with atilted glass slide	V= 18 kV Tip-collector distance = 14 cm Nomex = 3.5 to 10wt.% in dimethyleformamide and tetrahydrofuran DMF/THF (1/1)	49
Polyethylene oxide/ Poly(L-lactide)/ nylon-6	Electrospinning	1- Jet buckling	V= 5.5 kV Tip-collector distance = 7.5 cm PEO= 6 wt.% distilled water PLLA= 6 %V in hexafluoroisopropanol (HFIP) Nylon-6= 10 %V in HFIP/Formic acid	50
Poly-2-acrylamido-2-methyl-1-propanesulfonic acid	Electrospinning	1- Physical forces caused by the bending instability 2- Tensional electrostatic forces	V= 8.8 kV Tip-collector distance = 10 cm PAMPS=5 wt.% in water and ethyl alcohol	51
Poly(p-phenylenevinylene) / poly(ethylene oxide)	Electrospinning	1- Viscosity 2- Conductivity 3- Surface tension of the solution	V= 12 kV Tip-collector distance = 20 cm (PPV)= 0.4 wt.% in ethanol/water (PEO)= 4 wt.% in water	52
Fluorescein/polyvinyl pyrrolidone (PVP)	Electrospinning	1- Jet buckling 2- Bending instability	V= 20 kV Tip-collector distance = 12 cm PVP = in ethanol with 0.17 to 5.0 wt.% Fluorescein	53
Poly(p-phenylenevinylene)/ Poly(vinyl pyrrolidone)	Electrospinning	1- Solution viscosity 2- Solution conductivity 3-Operating voltage	V= 7.5 & 15 kV Tip-collector distance = 20 cm PPV and PVP in ethanol or a mixture Of ethanol and dimethylformamide DMF	54
Polystyrene	Electrospinning	1- Conductive solutions	V= 4 or 6.5 kV Tip-collector distance = 13 cm PS = 6wt.% in tetrahydrofuran (THF) with 0.0, 1.0 and 2.0 wt.% lithium chloride (LiCl)	55

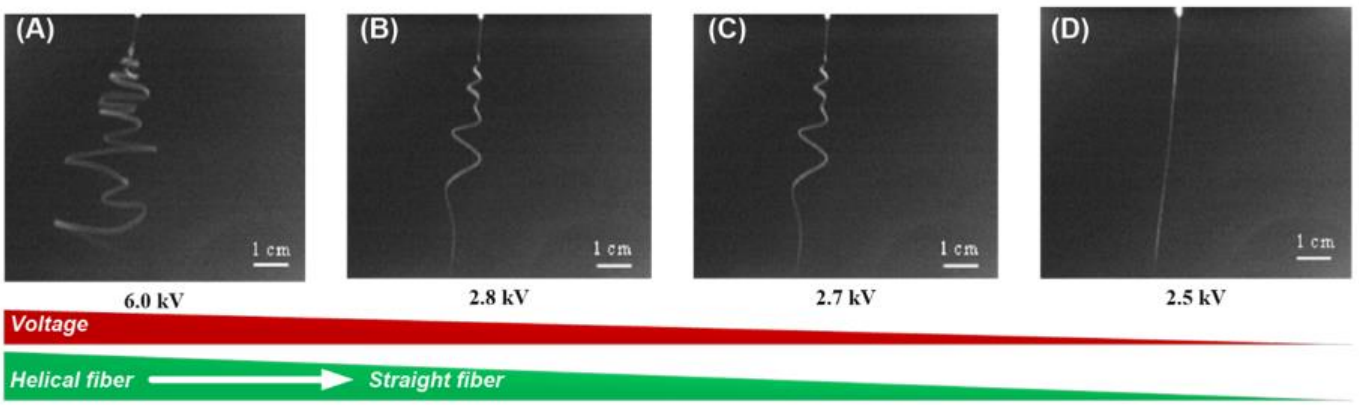

Figure 5. The effect of applied operating voltage on the helical structures formation. (A) 6.0 V, (B) 2.8 V, (C) 2.7 V, (D) 2.5. Reproduced from

Bending Instability

The formation of crimps in the fiber results from the rearrangement of the fiber material's internal molecular structure.[50] As previously mentioned, the factor influencing the production of a coiled jet path is electrically driven bending instability. This bending instability occurs due to charge transfer from the electrically charged fibers to a target, such as a metal electrode. The charged jet then experiences bending instability known as whipping instability.[46] Therefore, it can be concluded that the self-crimping nanofibers are produced when the fibers undergo significant whipping, causing them to stretch into very fine filaments. This phenomenon can be attributed to uneven stretching resulting from instability during the

electrospinning process.[35] Fibers with helical structures cannot be produced due to whipping instability.[50]

Jet Buckling

Reneker et al. demonstrated that, in addition to bending instability, the buckling of the jet due to a stopping of the jet on the collector is a significant factor in the formation of helical structures. Specifically, bending instability arises from a converging electric field, while jet buckling results from mechanical instability during impact with the target surface.[51] In another study, Yu et al., fabricated helical nanofibers from a single polymer on a modified collector using the electrospinning process.[52] They successfully created helical structures using a collector and a tilted glass slide, identifying the concentration of the electrospinning solution, the positioning of the slide, and its tilt angle as key factors influencing the morphology of the helical structures and loop diameters. Additionally, they demonstrated that the formation of helical structures was due to jet buckling during impact with the collector surface.

Additionally, Sun et al. developed an innovative technique that combined conventional electrospinning with linear simple harmonic motion to fabricate curled conductive polymer microfibers.[53] They showed that the patterns of curled fiber structures could be induced by both bending instability due to electrical forces and mechanical jet buckling during the impact with the target surface, as well as by the superposition of the velocity vectors of the microfibers upon hitting the collector surface.

Hua et al. have reported on the electrospinning of fluorescein/polyvinyl pyrrolidone (PVP) materials for producing composite nanofibers, indicating that both bending instability and buckling instability can contribute to the formation of helical nanofibers in some cases.[54]

Electrospinning of Bi-Component System

Researchers have found that a helical structure in fibers can be observed when two polymers with distinct properties are electrospun together. The fabrication of fibers with this helical morphology from a bi-component system is preferred over that from a single-component system.

Extruding two polymer solutions with varying properties, such as conductivity and elasticity, from the same spinneret is employed to create bi-component helical fibers that exhibit characteristics not found in single polymer fibers. Consequently, the production of a helical nanofiber structure from a polymer solution containing both a rigid component and a flexible component is considered one of the effective methods of electrospinning.[55] In this regard, Lin et al. reported a process utilizing a side-by-side nozzle in the electrospinning apparatus, incorporating a microfluidic system as a spinneret. They observed a self-crimping morphology in nanofibers fabricated from elastomeric polyurethane (PU) and thermoplastic polyacrylonitrile (PAN), with the two components exhibiting different shrinkage properties.[56] In contrast, Gupta et al. also employed a side-by-side nozzle in the electrospinning technique but did not observe any distinct fiber morphology.[55] Similar to Lin's findings,[56] Chen et al. reported the production of helical patterns from a composite of a flexible thermoplastic elastomer and a rigid thermoplastic component using a coaxial-electrospinning technique.[57] They noted that the formation of helical structures depended on the conductivity of the spinning solution, as well as the differential shrinkage. Moreover, utilizing the same technique, Chen et al. conducted additional research to examine the parameters influencing the formation and morphology of helical fibers by employing side-by-side and off-centered electrospinning methods.[58]

They confirmed that achieving the right balance between thermoplastic and rigid components, influenced by longitudinal compressive forces arising from rigidity, is crucial for the formation of helical nanosprings. Additionally, they showed that the helical formation is significantly dependent on the conductivity of the polymer solution, which in turn affects the mechanical properties. Binfei Zhang et al. utilized side-by-side electrospinning of two different polymers with varying mechanical properties and shrinkage to show that the helical structure was not the result of mechanical strategies but rather due to the distinct stress-strain effects of the two components.[50]

Conductivity of the System

Reneker and Yarin demonstrated that the coils formed in the jet path can disappear under certain conditions, such as solvent evaporation and a decrease in the ionic conductivity of the jet.[24] To evaluate the impact of conductivity on the formation of nanofiber garlands during the electrospinning process, they added lithium chloride to a polymer solution. They reported that, due to the increased conductivity of the solution under high voltage, the jet initially formed with small bending coils, which gradually increased in diameter.[59]

To examine the effect of solution conductivity on the production of the helical structure and the development of micro-scale polymeric helical structures fabricated by electrospinning, Kessick and Tepper utilized a solution containing a conducting polymer composite (polyaniline sulfonic acid) and a non-conducting polymer, poly(ethylene oxide).[60] They demonstrated that the formation of the microscale structure resulted from the viscoelastic contraction of a linear fiber upon the neutralization of partial charges.

In another study, Huihui et al. investigated the formation of helical nanofibers using the co-electrospinning technique with an off-centered core-shell spinneret. They suggested that the production of helical patterns is influenced by several factors, including the asymmetrical distribution of the electric field, the applied voltage, the conductivity of the system, and the ratio of the composite materials.[36] Unlike the nanoscale helical fibers fabricated by Kessick, Shin et al.[45] successfully produced a helical structure using a polyacrylamide (PAMPS) solution through a single non-conducting polymeric nanofiber.[53] Xin et al. produced composite nanofibers with helical structures, indicating that the viscosity and conductivity of the electrospinning solution, as well as the applied voltage, were key parameters affecting the fabrication of helical structures.[61]

Xin et al. produced a helical structure using a composite solution of poly (p-phenylene vinylene) (PPV) precursor and polyethylene oxide (PEO) in a mixture of ethanol and water. They identified viscosity, conductivity, and surface tension as the three key parameters of the electrospinning solution, along with the properties of the aqueous PEO solution, as critical factors influencing the morphology of the produced fiber.[48]

Bi-component Electrospinning Techniques (BCTs)

The curling mechanism of the self-crimp fibers in the electrospinning technique is attributed to whipping instability. As noted in [Table1], polymeric helical structures at the micro/nanoscale can be produced through the electrospinning process. On the other hand, co-electrospinning is a powerful and modified approach to electrospinning that employs a specially designed multichannel spinneret to produce helical nano/microfiber structures. In this system, the electrospinning spinnerets are configured with two tubes designated as the core and shell. There are three types of co-electrospinning: coaxial, off-centered, and side-by-side systems. The difference among these methods is attributable to the position of the nozzle within the spinnerets. In the coaxial system, the nozzle is centrally located, while in the other systems, the position of the inner tube of the coaxial nozzle is shifted from the center to the side. Additionally, in the side-by-side electrospinning system, the nozzle consists of two adjacent partitions, as shown in [Figure 6 A, B].

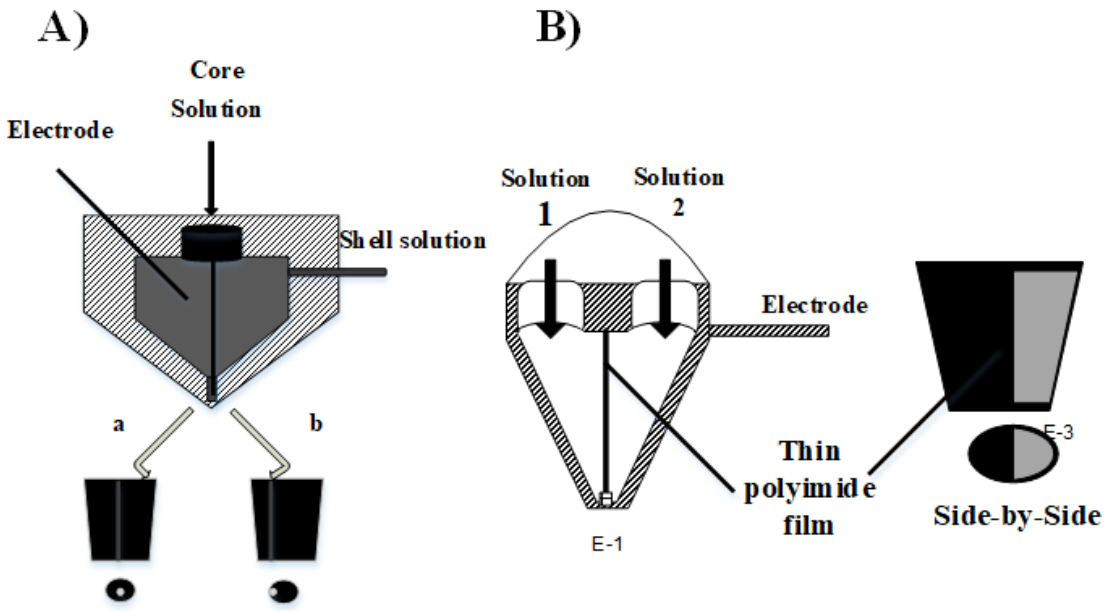

Figure 6. Shows a schematic diagram of electrospinning spinnerets with a bicomponent feed (A) coaxial (a), off-centered (b) and (B) side-by-side electrospinning spinnerets, after from

Chen et al. produced a fiber mat featuring a nanospring morphology using the electrospinning technique with off-centered and side-by-side needles, comparing these methods under optimal processing conditions.[58] They demonstrated that the production of nanospring morphology using off-centered and side-by-side nozzles in the electrospinning technique could be more effective than the coaxial technique under the same optimal conditions. Furthermore, they indicated that employing these two techniques, along with the use of both rigid and flexible polymer components, is essential for achieving highly efficient formation of nanosprings. Additionally, mechanical studies revealed that nanomats aligned with nanosprings exhibited greater elongation, toughness, and modulus compared to those without nanosprings.

The use of side-by-side and off-centered electrospinning spinnerets with different BCTs revealed that the efficiency of nanospring structure formation could be significantly improved.[58] The results indicated that the effectiveness of the process, as determined by the applied elastic force from one of the components, followed the order: side-by-side > off-centered > coaxial.[58] The application of different BCTs revealed that the elastic forces exerted by the thermoplastic component were greater for the side-by-side and off-centered nozzles compared to the coaxial electrospinning process, as illustrated in [Figure 7]. However, due to the offset of these forces, a lower elastic force was applied to the spring nanofibers during coaxial electrospinning. As a result, many of the generated nanofibers were drawn into either helical or straight forms as they approached the collector due to this phenomenon.

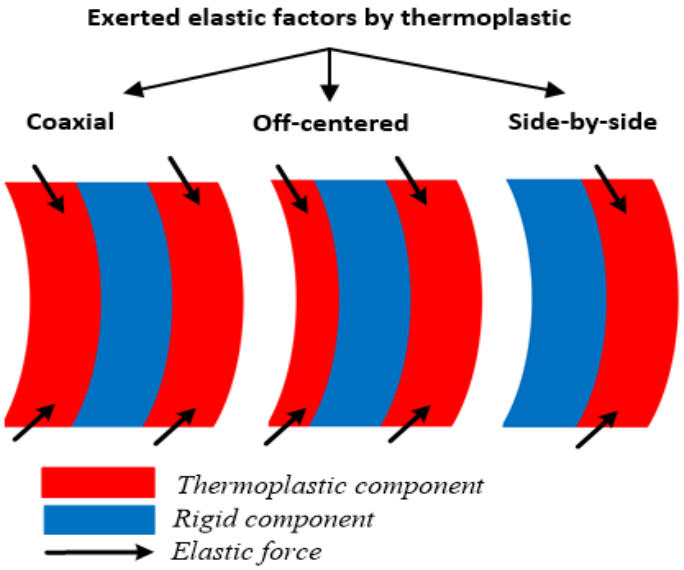

Figure 7. Schematic diagrams of elastic forces of thermoplastic component exerted on the helical nanofibers. After from, after from. [57]

Classification of Factors Influencing the Formation of Helical Structures

Analysis of helical structures under various processing conditions has confirmed that multiple factors influence the morphology of helical nano/microfibers. The parameters influencing the helical structure of electrospun nanofibers can be categorized into two groups: mechanical and hydrodynamic parameters. These categories encompass the characteristics of raw materials, solution properties, process conditions, and environmental factors, as illustrated in [Figure 8]. Key parameters influencing the formation of helical nanofibers include the distribution of the electric field, the configuration of the tip collector, the type of electrospinning setup (such as reciprocating type, direct writing, off-centered, coaxial, or side-by-side spinnerets), the conductivity of the polymers used, the applied voltage, and the relative ratios of the components involved. For instance, the distribution of the electric field significantly impacts jet motion and, consequently, jet formation. Research has shown that these factors play a critical role in the formation of helical fibers.[62]

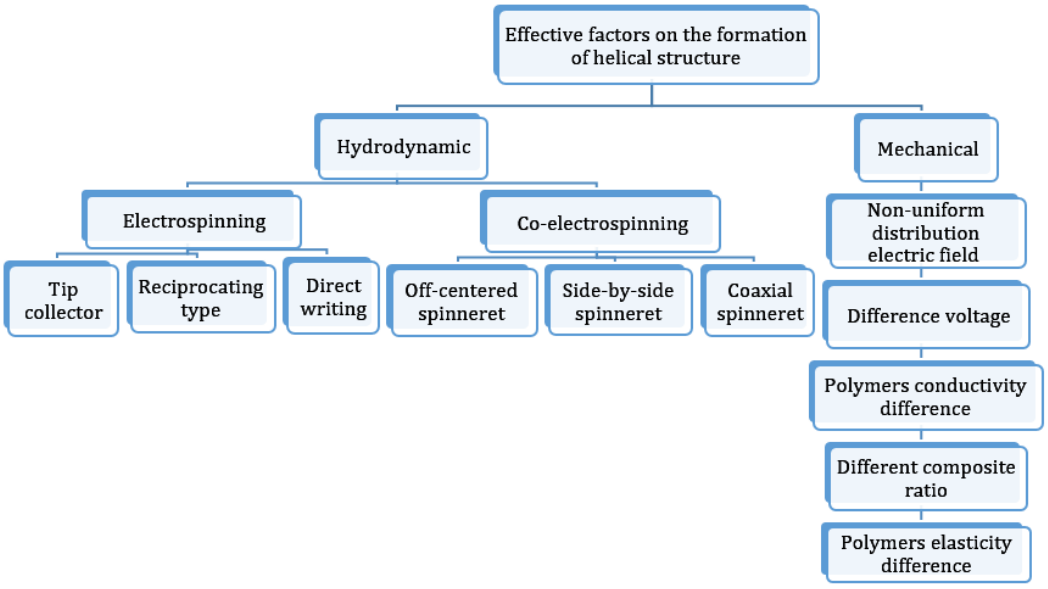

Figure 8. Affective factors in the formation of the helical structures

From a mechanical perspective, when two different polymer solutions (elastomeric and thermoplastic) are utilized, self-crimping occurs due to the interaction at the interface of the two phases, as well as the difference in shrinkage within the fibers. This phenomenon is attributed to the resilience of the compressed component in the bi-component fibers.[63] Additionally, in this mechanical framework, helical structures form based on the distinct physical behaviors of the two components, such as conductive and non-conductive polymers, when they come into contact with a conductive substrate. This is further influenced by viscoelastic contraction resulting from the partial neutralization of charges on the fibers. Consequently, free charges accumulate on the surface of the jet containing a conductive polymer solution, leading to the formation of coils in the composite jet. In addition to the previously mentioned parameters, several other factors, including the composite ratio, asymmetrical electric field distribution, and differential applied voltage, significantly influence the structures of the resulting helical nanofibers.[64]

On the other hand, hydrodynamic parameters play a crucial role in facilitating the formation of fibers with helical structures. Various electrospinning techniques, such as co-electrospinning with an off-centered core-shell configuration, side-by-side setups and microfluidic spinneret electrospinning, have been employed to achieve the production of helical structures. Researchers found that the distance between the collector and needle tip, as well as the polymer's molecular weight, influenced the loop size in the helical structures.[65]

Generally, numerous parameters affect the formation of these helical structures. Mechanical parameters impact the formation of helical structures in five distinct ways, as illustrated in [Figure 9]. Each method used to produce the helical structures included an influential parameter. Notably, all methods induced bending instability in the electrospinning jet, which ultimately led to the fabrication of helical fiber structures. Finally, bending instability resulting from the distribution of the electric field is a key factor in the preparation of nanofibers with helical structures.[66]

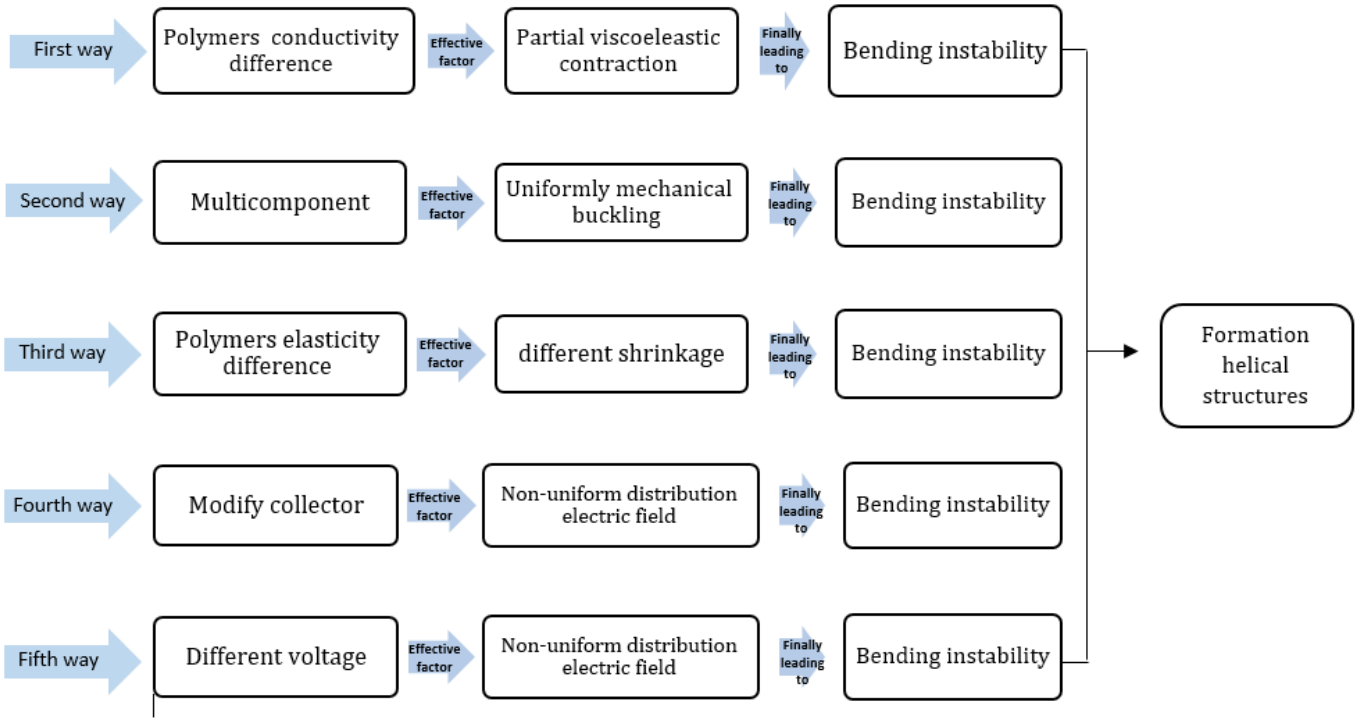

Figure 9. Different ways of affecting the mechanical parameters on the formation of the helical structures

Conclusion

This review discusses various concepts related to the formation of helical nano/microfibers and their applications. The production of helical, spring, or hierarchically structured nano/microfibers has been studied for over a decade. Research into different electrospinning set-ups aimed at obtaining helical fibrous structures has led to several innovative designs, and the current limitations of the production process have been clarified. With the advancement of novel techniques and the capability to produce a variety of helical fibrous structures, there is potential for these helical nano/microfibers to play a crucial role in enhancing current techniques and technologies. Investigating the mechanical and hydrodynamic parameters involved in the fabrication of helical fibers using current techniques has revealed that helical structures are produced when electric and elastic forces balance each other, resulting from non-uniform electric fields. Additionally, the coaxial electrospinning technique, combined with the use of

polymers exhibiting various elastic and conductive properties, plays a significant role in the production of these structures. While numerous experimental studies have been conducted on the fabrication of helical fiber structures, relatively few techniques have been developed. Given the unique properties of spiral nanofibers, such as their mechanical strength, structural integrity, and biocompatibility, these structures are recommended for applications in bone and cartilage tissue engineering. As the use of such fibers expands across various fields, more in-depth studies are needed to propose advanced manufacturing techniques and to identify new properties of these fibers.

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