International Journal of Pharmacy and Pharmaceutical Research (IJPPR)
Volume 32, Issue 5, May 2026 **ijppr.humanjournals.com** ISSN: 2349-7203

Mechanistic Insights into Fiber Formation: A Comparative Study of Electrostatics, Centrifugal and Aerodynamic Spinning Using Therapeutically Active Polymers

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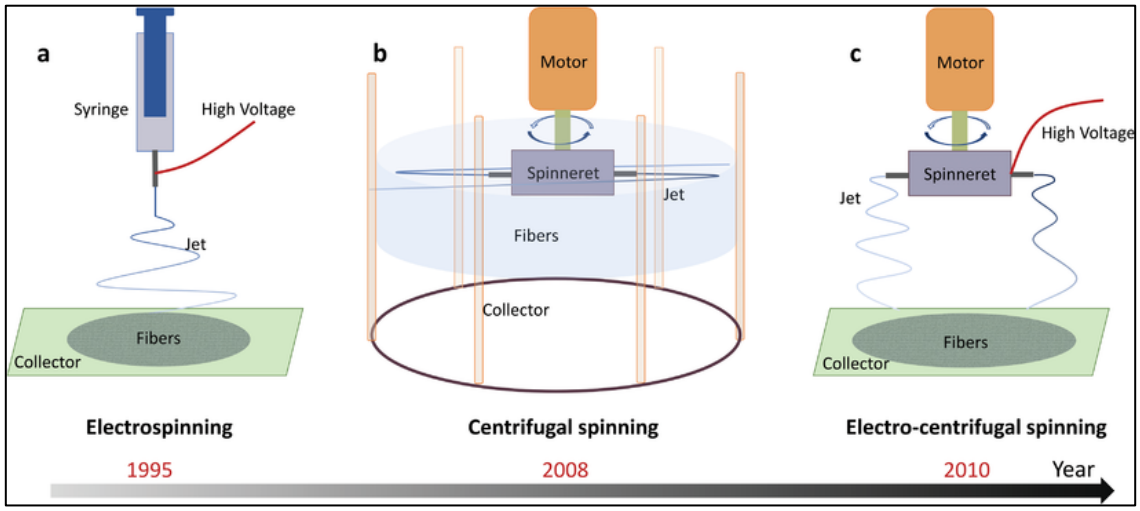
Received: 27 March 2026 Revised: 22 April 2026 Accepted: 28 April 2026

ABSTRACT

Nanofiber-based biomaterials have become a revolutionary means in pharmaceutical and biomedical fields, Due to their minuscule sizes, large specific surface areas, adjustable porosity, and anatomical resemblance to extracellular matrix (ECM). Although electrospinning is still the most popular method for creating nanofibers, centrifugal and aerodynamic spinning are also being considered as scalable and industrially feasible techniques. Initially, nanofibers were mainly used as drug delivery carriers; however, the latest developments focus on the use of bioactive polymers that can exert healing effects without the addition of drugs. Such polymer-only preparations have the benefits of greater stability, easier regulatory approval, and lower chances of sudden release of the drug. This paper reviews the mechanisms behind electrostatic, centrifugal, and aerodynamic spinning methods, focusing only on bioactive polymers without the presence of a drug. The overall mechanisms of jet start, jet stretch, solvent evaporation, and fiber solidification are explained in a methodical way. Also, the authors have analyzed polymer choices based on physicochemical properties such as molecular weight viscosity conductivity, surface tension, chain entanglement density, and mechanical stability. Electrospinning works best with ionic and polar polymers, for instance chitosan collagen, and quaternized cellulose derivatives. Centrifugal spinning is more effective for very sturdy biodegradable polymers like polycaprolactone and polylactic acid, and aerodynamic spinning is suitable for polymers with moderate viscosity that can form films.

Keywords: Nanofibers; Electrospinning; Centrifugal spinning; Aerodynamic spinning; Therapeutic polymers; Fiber formation mechanism



International Journal of Pharmacy and Pharmaceutical Research (IJPPR)
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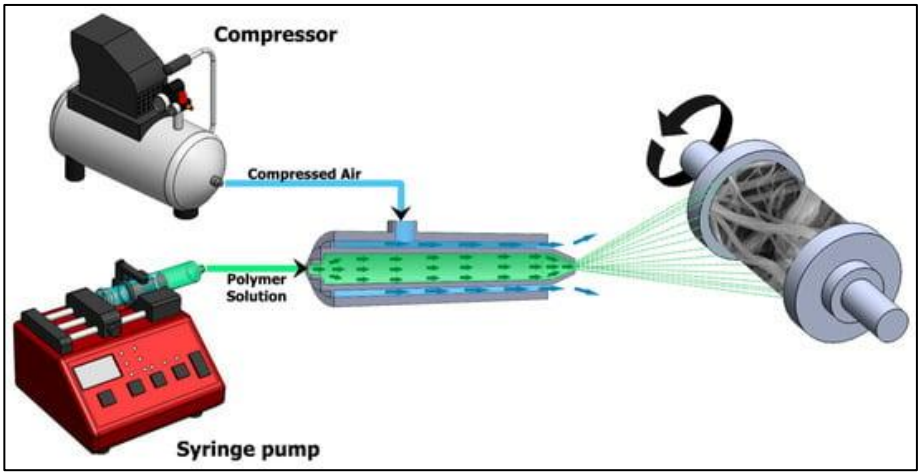

Systematic view of the a. Electrospinning b. Centrifugal spinning

c. Aerodynamic spinning

1. INTRODUCTION

Using nanotechnology, scientists have fundamentally changed the way they design biomedical materials, especially by creating nanoscale fibrous scaffolds that can emulate the structure of a natural extracellular matrix (ECM) (1,2). Polymeric nanofibers, in fact, have a dramatically increased surface-area-to-volume ratio, have interconnected pores, and their mechanical properties can be modified so as to support cell attachment, proliferation, and differentiation (3,4). Additionally, these structural features allow for improved oxygen permeability, nutrient transport, and exudate absorption, which is why nanofibers are extensively used wound healing and tissue engineering (5,6). At first, nanofibrous materials were mainly explored as drug delivery vectors capable of holding antibiotic anticancer anti-inflammatory drugs and growth factors (7,8). Despite the fact these materials had a good therapeutic potential, they also had a number of caveats such as sudden drug release, destabilization of the drug inside, toxicity from solvent residues, and complicated regulation that all contributed to limiting their practical success (9,10).Therefore, nowadays the focus of the latest studies has been placed on bioactive polymers that are inherently therapeutic without any added drug (11) Some studies have shown that chitosan kills bacteria by electrostatically interacting with the negatively charged bacterial membranes (12,13). On the other hand, collagen and gelatin can be used for cellular binding due to integrin-binding sites (14,15). At the same time, biodegradable polyesters such as polycaprolactone (PCL) and polylactic acid (PLA) are characterized by the ability to provide mechanical support and undergo controllable degradation that is suitable for the regeneration of tissue (16,17).

With these systems that contain only polymers, the formulation complexity is reduced whereas the biological efficacy is preserved. The technique of fiber fabrication greatly determines the final morphology, mechanical behavior as well as the biological performance (18). Electrostatic spinning, centrifugal spinning, and aerodynamic spinning make up three primary solution-based nanofiber fabrication methods where each of them is controlled by different physical driving forces (19-21). A thorough mechanistic comparison that systematically links the spinning dynamics with the polymer physicochemical properties is still necessary for a well-thought-out scaffold design.

2. FUNDAMENTALS OF FIBER FORMATION

Fiber formation requires sufficient polymer chain entanglement to maintain jet continuity during stretching (22).

Molecular weight directly affects entanglement density; below a critical entanglement concentration (Ce), jet breakup into droplets occurs due to Rayleigh instability (23,24).

Viscosity represents a dominant parameter governing morphology. At low viscosity, surface tension predominates, resulting in bead formation or electrospraying (25). Excessively high viscosity restricts jet elongation and may cause clogging (26). Therefore, each spinning technique requires an optimal viscosity window to balance stretching and stability (27).

Surface tension resists deformation of the polymer droplet. The applied driving force must exceed surface tension for jet initiation (28). In electrospinning, electrostatic force provides this energy; in centrifugal spinning, mechanical rotational force dominates; and in aerodynamic spinning, shear stress generated by compressed air acts as the stretching force (19,29).

Solvent volatility influences fiber solidification kinetics. Rapid evaporation stabilizes fiber morphology, whereas slow evaporation may cause fiber fusion at the collector (30). Environmental parameters such as humidity and temperature further affect solvent diffusion and fiber diameter distribution (31).

For therapeutic biopolymers, preservation of structural integrity is critical. High voltage, excessive shear stress, or thermal exposure may denature proteins such as collagen and gelatin, thereby affecting biological activity (14,32).

3. ELECTROSTATIC SPINNING

3.1 Mechanism of Jet Formation

Electrospinning is governed by electrohydrodynamic principles (20). Upon application of high voltage (typically 10–30 kV), charges accumulate at the polymer droplet surface. When electrostatic repulsion balances surface tension, a Taylor cone is formed (28). Beyond a threshold voltage, a charged jet is ejected toward a grounded collector (33).

The jet undergoes elongation through whipping instability, dramatically reducing fiber diameter to nanoscale dimensions (34). Coulombic repulsion between surface charges enhances jet stretching, while solvent evaporation leads to solid fiber deposition (35). Fiber diameter can be precisely tuned by adjusting voltage, flow rate, and tip-to-collector distance (36).

3.2 Polymer Suitability

Electrospinning favors polymers with sufficient conductivity and polar functional groups (37). Chitosan, containing protonated amine groups, demonstrates excellent electrospinnability and antimicrobial activity (12). Collagen and gelatin, rich in functional groups, exhibit stable jet formation under optimized solvent systems (14,15).

Quaternized cellulose derivatives possess permanent cationic charges that enhance electrical conductivity and antibacterial functionality (38). Synthetic biodegradable polymers such as PCL and PLGA are widely electrospun due to favorable viscoelastic characteristics and mechanical strength (16).

Despite superior nanoscale control, electrospinning suffers from low production rates and challenges in industrial scaling (21).

4. CENTRIFUGAL SPINNING

4.1 Mechanism of Fiber Generation

Centrifugal spinning (forcespinning) relies on mechanical rotational energy instead of electric fields (19). Polymer solution placed in a rapidly rotating spinneret is expelled through orifices when centrifugal force exceeds surface tension (39). Jet thinning occurs during radial flight, and solvent evaporation or melt cooling results in fiber solidification (40).

Unlike electrospinning, centrifugal spinning does not require electrical conductivity, expanding material compatibility (41). Fiber diameter is influenced by rotational speed, solution viscosity, and orifice geometry (39).

4.2 Polymer Suitability

High-viscosity and mechanically stable polymers are particularly compatible with centrifugal spinning (40). PCL and PLA exhibit excellent melt processability and biodegradability (17). Silk fibroin provides high tensile strength and biocompatibility suitable for tissue engineering (42). Cellulose acetate demonstrates strong entanglement behavior and wound-healing applications (43).

Centrifugal spinning offers significantly higher throughput compared to electrospinning, improving scalability and industrial feasibility (39).

5. AERODYNAMIC SPINNING

5.1 Mechanism

Aerodynamic or solution blow spinning utilizes high-velocity compressed gas to stretch polymer solutions (21). The polymer solution is extruded through a concentric nozzle, and shear forces generated by airflow elongate the jet into fibers (44). Rapid solvent evaporation stabilizes the fiber before deposition (45).

This method eliminates the need for high voltage and allows portable, in situ deposition for wound coverage (21).

5.2 Polymer Suitability

Moderate-viscosity polymers with good film-forming properties are compatible with aerodynamic spinning (45). Gelatin and PVA form stable fibers under airflow-induced shear stress (15,44). Cellulose derivatives and chitosan blends can also be processed with controlled rheological conditions (43).

Although fiber diameter distribution may be broader than electrospinning, production speed is considerably higher (44).

6. COMPARATIVE ANALYSIS OF SPINNING MECHANISMS

Electrospinning provides superior nanoscale precision and uniformity due to electrohydrodynamic stretching (34). Centrifugal spinning achieves higher production rates and broader polymer compatibility (39). Aerodynamic spinning offers rapid deposition and field applicability (21).

From a polymer–mechanism compatibility standpoint:

Ionic and conductive polymers → Electrospinning (12,38)

High-viscosity biodegradable polyesters → Centrifugal spinning (17,39)

Moderate-viscosity film-forming polymers → Aerodynamic spinning (44)

Mechanical properties also vary. Centrifugally spun fibers often exhibit higher tensile strength due to uniform mechanical stretching (40), whereas electrospun fibers show superior diameter control (34).

7. THERAPEUTIC IMPLICATIONS OF POLYMER-ONLY NANOFIBERS

Polymer-only nanofibers eliminate risks associated with drug encapsulation such as burst release and chemical degradation (9). Chitosan nanofibers disrupt microbial membranes through electrostatic interaction, providing broad-spectrum antimicrobial effects (12,13). Collagen and gelatin nanofibers support fibroblast proliferation and ECM remodeling (14).

Silk fibroin enhances mechanical strength and cellular compatibility (42). Biodegradable polyesters such as PCL provide structural scaffolding supporting gradual tissue integration (16). The selected spinning method influences pore size distribution, mechanical strength, and degradation rate, thereby affecting therapeutic efficacy (5).

8. FUTURE PERSPECTIVES

Future research should integrate rheological modeling to predict spinnability windows based on entanglement theory (22). Hybrid electro-centrifugal systems may combine scalability with nanoscale precision (40). Sustainable solvent systems and green biopolymers should be prioritized for environmental safety and regulatory compliance (43).

Advanced in-line monitoring and computational modeling could improve reproducibility and quality control during scale-up (24).

CONCLUSION

Electrostatic, centrifugal, and aerodynamic spinning differ fundamentally in jet initiation, elongation dynamics, and solidification mechanisms. These mechanistic differences dictate polymer compatibility and final nanofiber properties. Ionic and polar polymers are most suitable for electrospinning; mechanically robust biodegradable polymers favor centrifugal spinning; and moderate-viscosity film-forming polymers are compatible with aerodynamic spinning. Rational alignment of polymer physicochemical properties with spinning forces is essential for developing effective drug-free therapeutic nanofibrous scaffolds for scalable biomedical applications.

Acknowledgements

I express my sincere gratitude to Dr. J. Bagyalakshmi, Professor, Sri Ramakrishna Institute of Paramedical Sciences, College of Pharmacy, for her expert guidance, constructive feedback, and continuous support throughout the preparation of this review article.

I also thank Sri Ramakrishna Institute of Paramedical Sciences, College of Pharmacy, Coimbatore, affiliated with The Tamil Nadu Dr.M.G.R.Medical University for providing the academic environment and necessary resources that enabled the successful completion of this work.

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How to cite this article:
Nishanthini. M et al. Ijppr.Human, 2026; Vol. 32 (5): 132-137.
Conflict of Interest Statement: All authors have nothing else to disclose.