

ЕЛЕКТРООВЛАКНЯВАНЕ: ПРОИЗВОДСТВО НА НАНОВЛАКНА ЗА ТЕКСТИЛНИ ПРИЛОЖЕНИЯ

ELECTROSPINNING: NANOFIBER PRODUCTION FOR TEXTILE APPLICATIONS

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Abstract:

The growing demand for advanced textile materials with enhanced functionality has driven intensive research in nanofiber production technologies. Electrospinning has emerged as one of the most versatile, efficient, and cost-effective methods for fabricating nanofibers with controlled morphology and composition. This paper presents an overview of the principles, processes, and applications of electrospinning technology, emphasizing its integration into modern spinning systems and textile manufacturing. Special attention is given to the development of processes and devices for electrospinning that enable scalable production and the creation of innovative textile materials. The discussion highlights the potential of electrospun nanofibers for functional material design, including our work on magnetic polyacrylonitrile (PAN) composites that offer tunable properties for diverse applications in smart textiles, biotechnology, energy, and environmental engineering. The textile industry is undergoing a transformation driven by the need for lightweight, multifunctional, and sustainable materials. Traditional spinning technologies, while highly developed, face limitations in producing nanoscale fiber structures with unique surface area and mechanical properties. Electrospinning, a process that utilizes electrostatic forces to draw fine fibers from polymer solutions or melts, bridges this gap, allowing for the creation of fibers with diameters ranging from tens of nanometers to a few micrometers, opening new possibilities in textile engineering and material science.

Keywords: *Electrospinning; nanofibers; magnetic nanoparticles; polyacrylonitrile; textile engineering; functional textiles*

1. Introduction and Overview

Intense research into nanofiber production technologies is being driven by the increasing need for high-performance textile materials. As a high-precision fiber-formation technique, electrospinning has become a premier choice for fabricating nanofibers with precise control over their morphology and composition. It is renowned for its ability to efficiently generate continuous fibers across a wide diameter spectrum, typically from sub-100 nanometers to several micrometers, while remaining both versatile and cost-effective [1]. This capacity for producing continuous, ultra-fine fibers—a feature largely unmatched by conventional fiber drawing—has positioned electrospinning as a core strategic pathway for the future of the textile industry. The technology facilitates the creation of materials that meet rigorous new performance benchmarks, primarily through the exceptional high surface-area-to-volume ratio (often thousands of times greater than conventional fibers) and the readily customizable high porosity (often exceeding 70-90%) of the resulting nanofiber mats [2].

The exceptional versatility of electrospinning is its core strength, enabling the formation of functional textiles and advanced material matrices from an extraordinarily broad array of precursors, including synthetic and natural biopolymers, as well as crucial functional components like ceramics and metal oxides (such as iron oxide), which impart specialized properties such as thermal stability or magnetism [3]. These attributes yield unique collective properties in the resulting nonwoven mats, such as high flexibility, exceptional filtering capabilities, and extraordinary surface reactivity, opening doors to applications from medical filtration to energy storage. While the transformative potential is clear, a critical challenge remains: the viable and cost-effective integration of electrospun nanofibers into conventional, high-volume textile manufacturing [2]. This requires overcoming current scale-up limitations and

implementing recent device innovations focused on drastically increasing production throughput and optimizing material handling [2, 3].

This study summarizes the underlying fundamentals of the technology and the device innovations needed for industrial adoption, and the thermomechanical properties of confined magnetic nanoparticles within an electrospun polyacrylonitrile (PAN) nanofiber matrix. Additionally, the magnetic PAN composite nanofibers we previously reported serve as a case study to effectively illustrate the essential connection between the production method, the resultant morphology, and the final functional parameters of the material. [4].

2. Fundamentals of Electrospinning

2.1. Basic Principle and Electrostatic Forces

Electrospinning is an electrically driven process that harnesses electrostatic forces to draw a viscoelastic polymer solution or melt into continuous ultrafine fibers [1–3]. The fundamental laboratory setup (Figure 1) is deceptively simple, consisting of three main components: a high-voltage power supply, a spinneret (usually a metal needle) delivering the polymer fluid and a grounded collector (typically a flat plate or a rotating drum) [1–3].

The process begins when a high-voltage electric field (ranging typically from 5 kV to 50 kV, depending on the setup and material) is applied across the gap. This field induces charge accumulation on the surface of the polymer fluid droplet at the needle tip, which is then shaped by competing forces: the surface tension of the liquid trying to maintain a spherical droplet, and the electrostatic repulsion between the surface charges trying to force the liquid apart. When the repulsive electrostatic force overcomes the surface tension, the droplet elongates into a characteristic conical shape known as the Taylor cone. From the apex of this cone, a fine, charged liquid jet is ejected.

As this jet travels toward the collector, two critical

phenomena occur simultaneously: the solvent evaporates (or the polymer melt solidifies), and the jet undergoes a complex bending or whipping instability. This instability—a rapid, chaotic lateral deflection of the jet path—is crucial. It subjects the jet to immense tensile and shear forces, stretching the jet

by several orders of magnitude and causing its diameter to collapse from micrometers to nanometers before it is deposited onto the collector. This final process grants researchers and engineers high control over the resulting fiber orientation and the final morphology (e.g., solid, porous, core-shell) [1, 3].

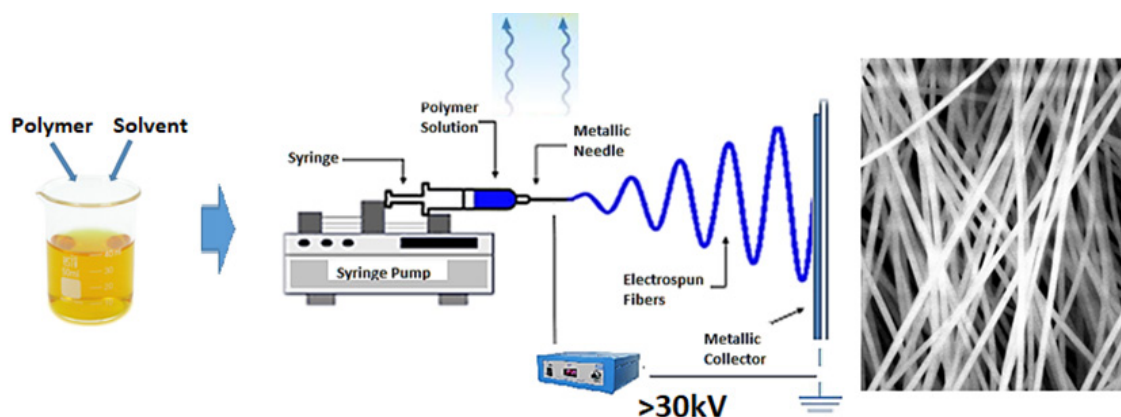


Figure 1. Basic electrospinning setup (Lab-scale)

2.2. Interplay of Critical Process Variables

The final characteristics of the nanofiber (including diameter, alignment, mat porosity, and surface quality) are determined by the precise and complex interplay of three major groups of variables [2, 3]:

1. Solution/Melt variables (material parameters): Polymer concentration and molecular weight (determining viscosity and entanglement), conductivity (enhancing stretching), and solvent volatility (influencing evaporation rate and fiber porosity).

2. Process variables (operational parameters): The applied voltage (influencing jet stability and stretching), polymer feed flow rate (affecting fiber thickness), and the tip-to-collector distance (allowing time for solvent evaporation).

3. Ambient factors (environmental conditions): The surrounding temperature and humidity (which influence mass transfer dynamics and final fiber morphology).

3. Process–Structure–Property Linkage and Scalability

3.1. Process–Structure–Property Linkage

For textile applications, the process–structure–property linkage is central. Tuning the process variables achieves desired structural features (fiber diameter, alignment, pore size, and mat porosity), which then directly govern final performance properties crucial for advanced textile integration [3]. Table 1 explains the structural characteristics that directly control the resulting textile performance of the fiber mats:

- **Breathability and filtration efficiency:** Governed by pore size; ultrafine fibers enhance particle removal while maintaining air permeability.
- **Mechanical strength and durability:** Influenced by fiber alignment and polymer matrix integrity.
- **Functional attributes:** Properties like conductivity, antimicrobial action, and sensing capability, imparted by incorporating functional additives or controlling fiber architecture.

Table 1. Structural feature of the fiber, its direct influence and resulting performance of the fibers

Structural Feature	Directly Governs	Resulting Textile Performance
Fiber diameter	Surface area, flexibility	High adsorption capacity, soft feel.
Pore size & porosity	Tortuosity, air permeability	Enhanced filtration efficiency while maintaining high breathability.
Fiber alignment	Anisotropy, mechanical properties	Aligned fibers create superior mechanical strength/directionality; random fibers provide isotropic strength.
Fiber morphology	Drug release kinetics, encapsulation efficiency	Core-shell fibers enable sustained drug release or self-healing functionality.

3.2. Device innovations for scalability

To overcome the low throughput of single-needle systems and facilitate roll-to-roll continuous industrial manufacturing, focus has shifted entirely to high-throughput device innovations [2, 3]:

- Needleless electrospinning systems: Generate multiple, stable polymer jets simultaneously from a free surface (e.g., a rotating wire or disk), significantly mitigating flow rate limitations [5].
- Continuous collection and hybrid spinning lines: Utilize rotating drums or endless belt conveyors for continuous deposition onto moving substrate belts. Hybrid spinning lines deposit the nanofiber web directly onto pre-existing conventional textile substrates for mechanical support.
- Controlled manufacturing environments: Enclosed chambers that maintain precise control over ambient factors, incorporate solvent recovery systems for safety, and allow for essential in-line

post-treatments (e.g., crosslinking, lamination) to ensure durability [2].

4. Specific Polymers in Electrospun Nanofibers

Polymers are classified into synthetic and natural categories. Synthetic polymers offer reproducibility and tunable mechanical properties [5, 6], while natural polymers are favored for their inherent biocompatibility and resemblance to the native extracellular matrix.

A compilation of synthetic and natural polymers employed in electrospinning is provided in Tables 2 and 3, which summarize their key characteristics, advantages, and primary applications across several fields, including tissue engineering, drug delivery, filtration, and protective textiles.

4.1. Synthetic Polymers

Table 2. List of some of synthetic polymers used in electrospinning

Polymer Name	Abbreviation	Key Characteristics & Advantages	Primary Applications
Polycaprolactone	PCL	Semi-crystalline, highly biocompatible, very slow degradation rate.	Long-term drug delivery, tissue engineering for minimally stressed implants [7, 8]
Poly(lactic acid)	PLA	Excellent mechanical strength, FDA-approved, derived from renewable resources.	Scaffolds for orthopedic applications, food packaging [9]
Poly(lactic-co-glycolic acid)	PLGA	Amorphous copolymer; degradation rate is easily tuned by LA:GA ratio.	Controlled release drug delivery systems, surgical implants [10, 11]
Polyethylene Oxide	PEO	Highly water-soluble, non-toxic; frequently used as an electrospinning aid.	Hydrophilic blends, fast-dissolving drug delivery [12, 13]
Polyvinyl Alcohol	PVA	Highly crystalline, excellent tensile strength when crosslinked; water-soluble.	Filtration membranes, humidity sensors, hydrogel-based wound dressings [14, 15]
Polyurethane	PU	Excellent elastomer properties, outstanding fatigue resistance, tailored biocompatibility.	Flexible medical implants (vascular grafts), high-performance protective textiles [16, 17]

4.2. Natural Polymers

Table 3. List of some of natural polymers used in electrospinning

Polymer Name	Type	Key Characteristics & Advantages	Primary Applications
Collagen	Protein	Main component of the natural ECM; promotes high cell adhesion.	Tissue engineering (skin, bone), advanced wound healing scaffolds [18, 19]
Gelatin	Denatured Collagen	Excellent cell attachment and proliferation promoter; easier to process than native collagen.	Drug encapsulation, general tissue scaffolds [20, 21]
Chitosan	Polysaccharide	Naturally antimicrobial and hemostatic properties; degrades into harmless products.	Antimicrobial filters, wound dressings [22]
Silk Fibroin	Protein	Exceptional combination of mechanical strength and toughness; slow and controllable degradation.	Hard tissue scaffolds, high-performance sutures [23]
Fibrinogen	Protein	Key component of the blood-clotting cascade; high native cell affinity.	Vascular and neural tissue engineering, hemostatic agents [24]

5. Applications in Textile Engineering

5.1. Smart and Functional Fabrics

The demand for smart and functional fabrics necessitates the integration of responsive and conductive materials (e.g., Graphene oxide, magnetic particles, etc.) to achieve advanced properties [3]. The fabrication of functionalized textiles is essential for advanced technologies, including wearable electronics, EMI shielding, and self-cleaning surfaces. Our magnetic PAN nanofiber system [4] specifically addresses the requirement for EMI Shielding materials and provides responsive functionalities. The literature has previously demonstrated the significant potential of these responsive materials for remote sensing and actuation [25, 26, 27].

5.2. Sustainable and Green Textiles

Demand for sustainability is met through green-process electrospinning, focusing on bio-based/biode-

gradable polymers (e.g., chitosan, silk fibroin) and water-based or low-toxicity solvent systems [3, 12]. Additionally, electrospinning enables structurally colored fibers—a dye-free solution where color derives from light manipulation by engineered nanostructures (photonic crystals), eliminating hazardous chemical colorants [3].

5.3. Biomedical and Medical Textiles

Polymer nanofibers are revolutionizing drug delivery and tissue regeneration (Figure 2). Their high surface area allows for stable incorporation and sustained, localized, and controlled release of drugs [10, 28, 29, 30]. Electrospun mats closely mimic the natural extracellular matrix (ECM), promoting cell proliferation essential for tissue repair, serving as advanced wound dressings or tissue-scaffold materials [32].

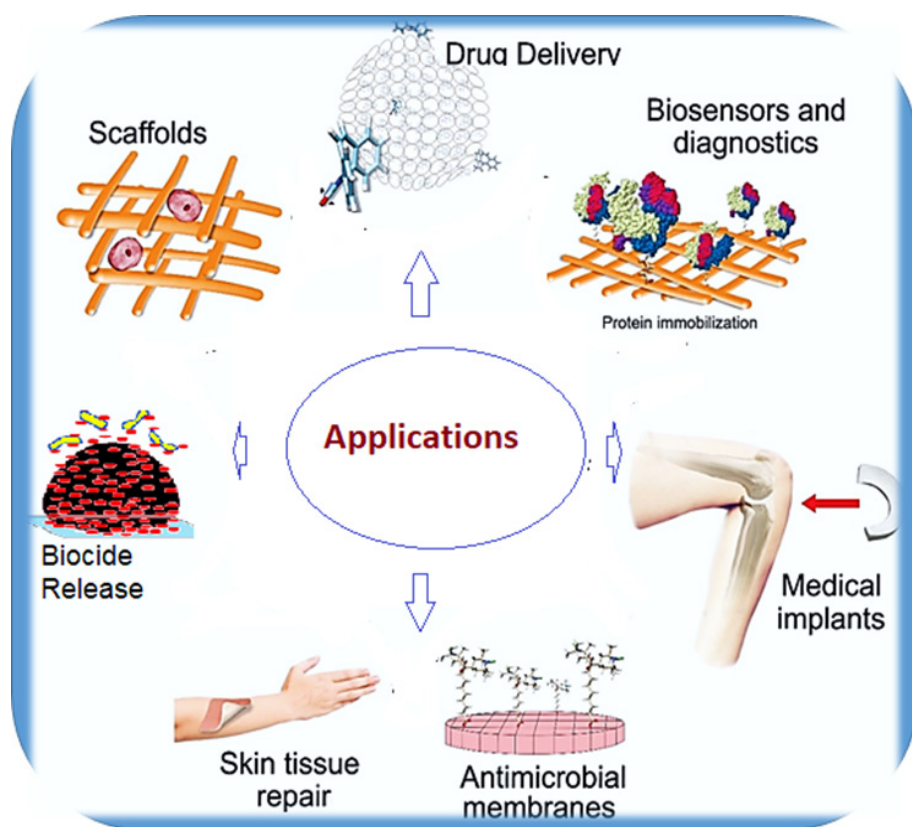


Figure 2. Future fabric: Developing advanced textiles through electrospinning & Revolutionizing textiles for biomedical and beyond

6. Key Research Results: Magnetic PAN Nanofibers

Our research is centered on enhancing Polyacrylonitrile (PAN) nanofibers through the incorporation of magnetic ferrite nanoparticles directly into the fiber matrix [4]. This modification integrates advanced functional capability into the textile

structure, as detailed in our comprehensive study of the thermomechanical properties of these confined particles. Figures 3 and 4 show the SEM, EDX, FTIR, and thermomechanical (DMA) results (comparison in Table 4) obtained for the PAN nanofibers containing some ferrite nanoparticles.

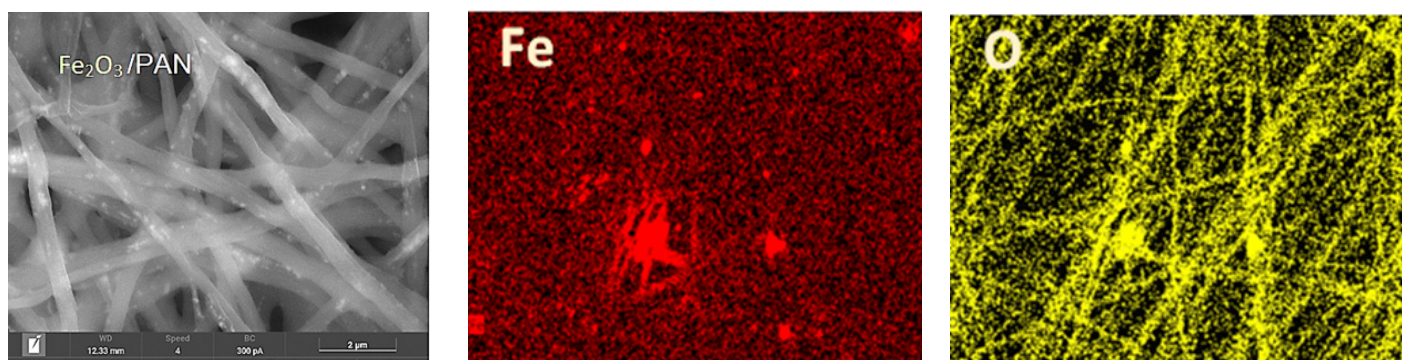


Figure 3. SEM and EDX of γ -iron oxide nanoparticles containing Polyacrylonitrile composite nanofibers. [Adapted from B. Sarac, V. Soprunyuk, G. Herwig, S. Gümrükçü, E. Kaplan, E. Yüce, W. Schranz, J. Eckert, L. F. Boesel and A. S. Sarac, *Nanoscale Adv.*, 2024, 6, 6184, DOI: 10.1039/D4NA00631C. Reproduced from an open access article under a Creative Commons Attribution (CC BY) license (RSC).]

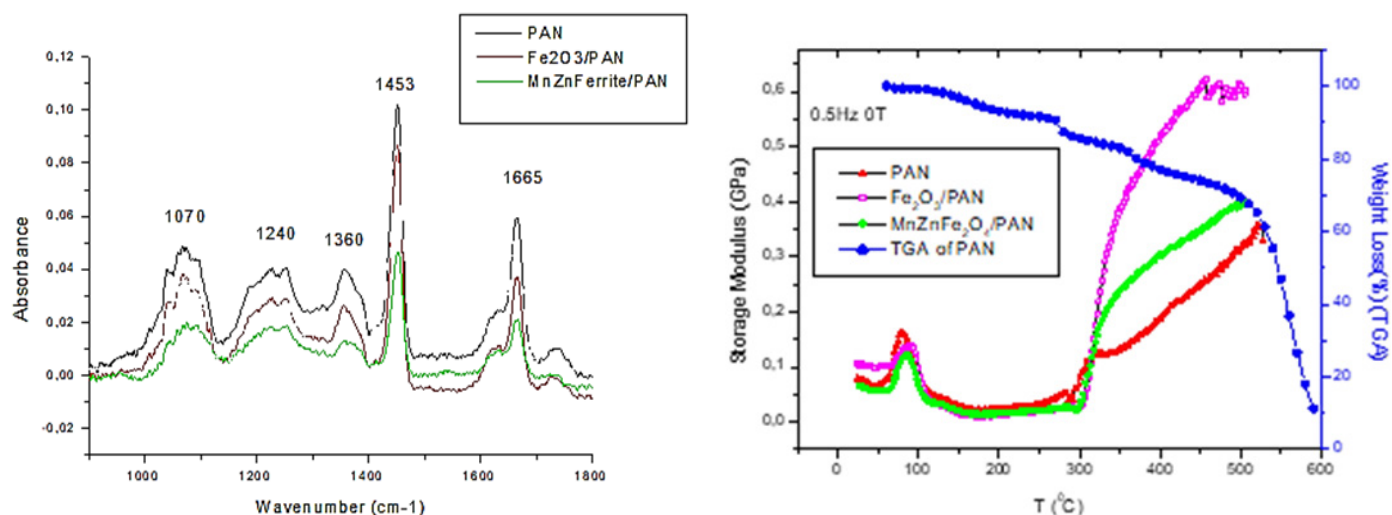


Figure 4. Comparative FTIR and thermomechanical measurements of Polyacrylonitrile(PAN) and composite (γ -iron oxide, MnZn-Ferrite nanoparticles containing) nanofibers[6]. [Adapted from B. Sarac, V. Soprunyuk, G. Herwig, S. Gümrükçü, E. Kaplan, E. Yüce, W. Schranz, J. Eckert, L. F. Boesel and A. S. Sarac, *Nanoscale Adv.*, 2024, 6, 6184, DOI: 10.1039/D4NA00631C. Reproduced from an open access article under a Creative Commons Attribution (CC BY) license (RSC).]

Table 4. Thermomechanical Properties of Magnetic PAN Nanofibers (4)

Study/Method	Key Finding / Result	Textile Relevance
Dynamic Mechanical Analysis (DMA)	The magnetic Polyacrylonitrile (PAN) nanofibers exhibited pronounced magneto-mechanical coupling when subjected to a magnetic field, resulting in an observable increase in both the glass transition temperature (T_g) and the storage modulus (E')	DMA confirms that the material's stiffness and damping can be changed remotely using an external field. This feature is crucial for applications requiring adjustable mechanical performance, such as wearable actuators and tunable shock absorbers.
Thermal Treatment (Cyclization)	Controlled thermal treatments promoted cyclization of the PAN polymer chains.	Leads to improved thermal stability and modified chemical bonding, making fibers suitable for high-temperature processing or carbon fiber precursors.
Microstructural Analysis	Confirmed structural changes (cyclization) and strong physicochemical interactions between the magnetic domains and the polymer matrix.	Validates the stabilization strategy and confirms the potential for designing robust, multifunctional devices where fiber properties can be actively controlled.

7. Industrial Adoption, Challenges, and Future Directions

Industrial adoption faces hurdles, including low production rate, the necessity of replacing toxic solvents, cost-effective scalability, ensuring uniformity, managing HSE (Health, Safety, and Environment) concerns, and achieving durability against textile handling [2, 6].

The future trajectory of electrospun textiles will focus on:

- 1. Process Innovation:** Development of needleless systems and roll-to-roll continuous production lines [5].
- 2. Sustainability:** Prioritizing water-based systems and biodegradable polymers [6].
- 3. Product Evolution:** Advancing toward hybrid textile–nanofiber systems for smart textiles and IoT integration [5].

Conclusion

Electrospinning is confirmed as a critical and transformative fabrication platform for the future of textiles, offering capabilities that move significantly beyond traditional manufacturing methods. Its ability to produce continuous nanofibers with controlled morphology is key to functional enhancement, delivering materials with an exceptional high surface-area-to-volume ratio and tunable porosity. This technology is a fundamental enabler of sustainable and smart textile innovation through:

- **Structurally colored fibers:** A sustainable, dye-free alternative using engineered photonic nanostructures.
- **Self-healing materials:** Enhancing durability via autonomous damage repair mechanisms.
- **Advanced smart textiles:** Providing flexible, conductive, and responsive fabrics ideal for wearable electronics and advanced sensing capabilities, exemplified by the magneto-responsive PAN

composite systems.

However, the major obstacles to market penetration remain low production rates, the necessity of replacing toxic solvents with greener alternatives, and the need to improve economic feasibility for large-scale manufacturing. Overcoming these scale-up issues through innovations in needleless and continuous processing is essential for widespread commercial adoption. In summary, electrospinning integrates nanotechnology, material science, and textile engineering to redefine functional textiles, promising a new generation of high-performance, sustainable, and sophisticated materials.

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