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REVIEW PAPER

Electrospinning for Smart Textile Applications

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ABSTRACT

Electrospinning has emerged as a transformative technology in textile engineering, enabling the production of ultra-fine nanofibres with unique properties and a wide range of applications. This technique leverages an electric field to produce continuous fibres from polymer solutions or melts, creating structures with high surface area-to-volume ratios, tunable porosity, and potential for diverse functionalization. Advancements in electrospinning techniques, including needleless, coaxial, tri-axial, and portable setups, have expanded their potential, allowing for enhanced control over fibre morphology, diameter, and composition. Such innovations have led to electrospun textiles that are lighter, more breathable, and multifunctional, addressing needs in filtration, biomedical applications, smart textiles, and energy storage. For instance, in smart textile applications, electrospun fibres are being combined with phase-change materials (PCMs) to enable thermal regulation, while conductive nanomaterials embedded within electrospun fabrics are paving the way for wearable electronics. However, challenges remain in terms of scalability, mechanical stability, and production cost, especially as the focus shifts towards industrial applications. Continued research in optimizing material properties, improving fibre strength, and reducing costs are essential to fully leverage the capabilities of electrospinning in the textile sector. This article critically examines the progress in electrospinning technology, its adaptation in textile applications, and future directions for advancing electrospun textiles for multifunctional and sustainable use.

HIGHLIGHTS

- Electrospinning creates versatile nanofibers with tunable properties for smart textiles.
- Enables integration of sensing, conductivity, antimicrobial, and thermal regulation features.
- Supports diverse polymers and composites, enabling hybrid textiles with superior performance.
- Advances in electrospinning expand smart textile use in healthcare, energy, and monitoring.

Keywords: electrospinning, electrospun fibres, textile applications

The textile industry is experiencing a profound transformation driven by advanced technologies, with electrospinning emerging as a leading method for producing nanofibres. Electrospinning is a highly adaptable and innovative technique for producing fibres that range in diameter from nanometres to micrometres. This process uses controlled electrical forces to fabricate fibres from polymer solutions or melts, offering precise manipulation over the formation of fibres (Wang *et al.* 2023). One of its key advantages is the ability to generate fibres with an exceptionally high surface area-to-volume ratio, making them valuable in various fields, including materials science, nanotechnology, biomedicine, and textiles. To ensure successful electrospinning, several key factors must be precisely controlled. First, the

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fibre diameters must be uniform and adjustable to maintain consistency in the final product. Achieving fibres with minimal or manageable surface defects is essential for enhancing their quality. Additionally, the collection process should ensure the continuous production of individual nanofibres. Finally, minimizing the presence of pores or beads in the fibres is crucial for producing high-quality nanofibres suitable for advanced applications (Yan *et al.* 2021). As the demand for multifunctional, high-performance textiles continues to rise, the significance of electrospinning in this evolving landscape becomes increasingly apparent.

Electrospinning process

The first step in electrospinning involves preparing a polymer solution or melt. The polymer is dissolved in a suitable solvent to create a viscous solution. Alternatively, the polymer can be heated until it melts. The choice of polymer and solvent plays a crucial role in determining the properties of the fibres, such as their diameter and morphology (Keirouz *et al.* 2023). The polymer solution is loaded into a syringe equipped with a small nozzle or spinneret and is mounted on to a pump that controls the flow rate of the polymer solution, ensuring a consistent supply of material during the spinning process. A high-voltage electric field is applied between the polymer solution in the syringe and a grounded collector. As the voltage increases, the electrical forces overcome the surface tension of the polymer solution at the tip of the nozzle, causing it to stretch and form a thin, charged jet. At a critical voltage, the polymer droplet at the nozzle tip elongates into a conical shape known as the Taylor Cone. From this cone, a fine jet of polymer solution is ejected. The charged jet is stretched and thinned as it travels toward the collector, resulting in the formation of ultrafine fibres (Jose *et al.* 2024; Jose and Ravindra, 2025).

As the polymer jet travels through the air, the solvent evaporates (in the case of a polymer solution), or the polymer cools and solidifies (in the case of a melt). This results in the formation of solid fibres (Fig 1.). The electrostatic forces cause the fibres to whip and stretch further, reducing their diameter to the nanoscale. The solidified fibres are collected on a grounded surface, such as a flat plate or a rotating drum (Fig 2a) (Sharma and James, 2022; Wang *et al.* 2023).

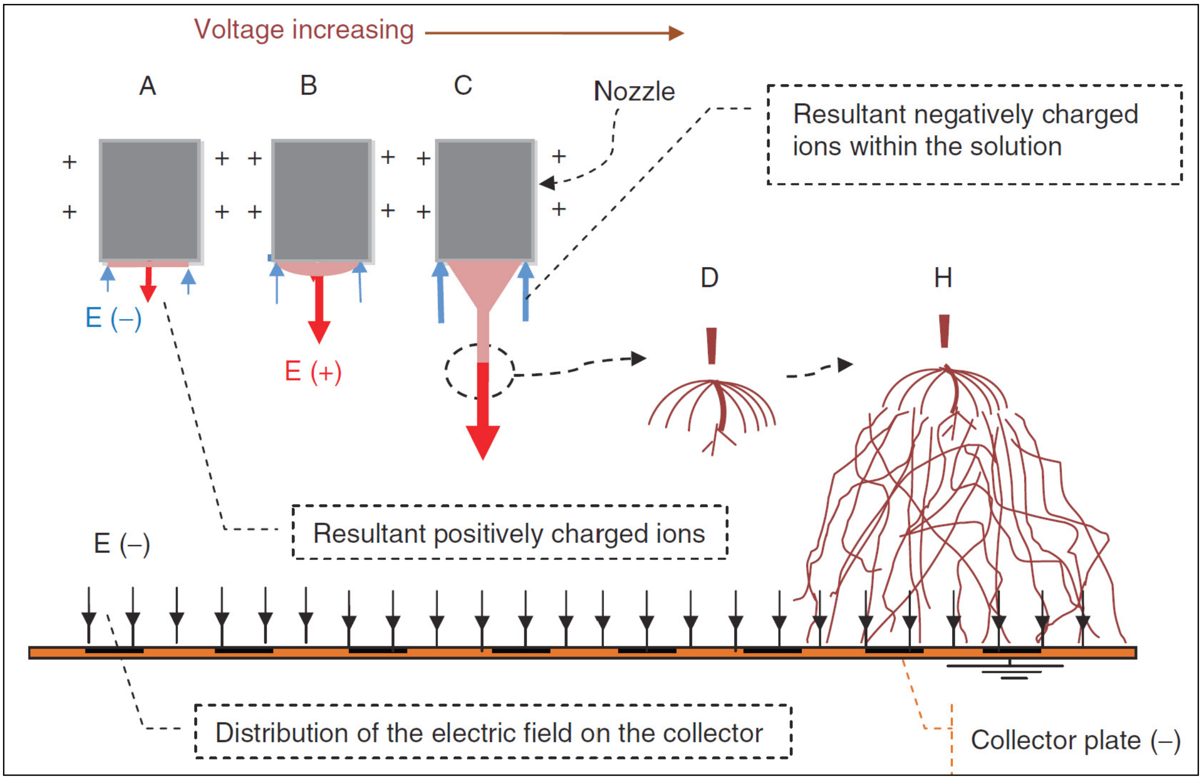
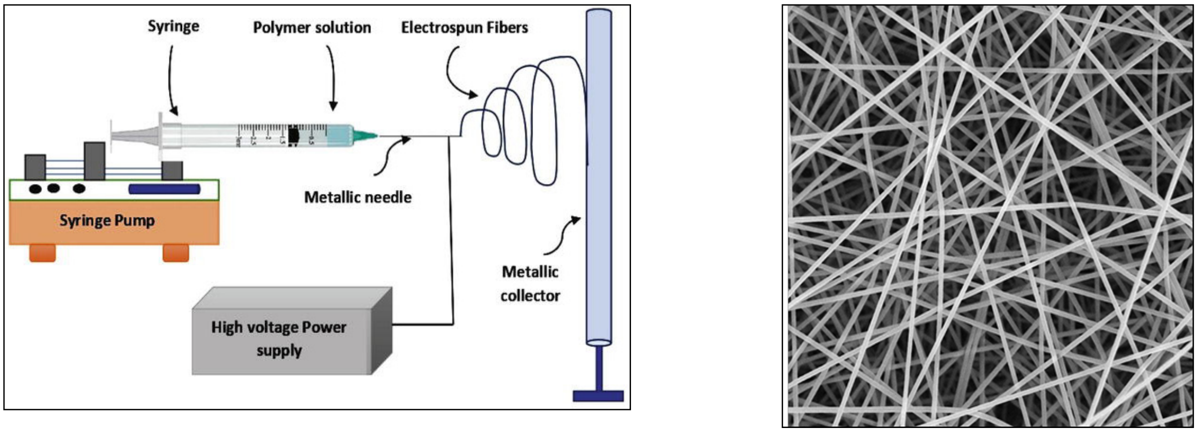
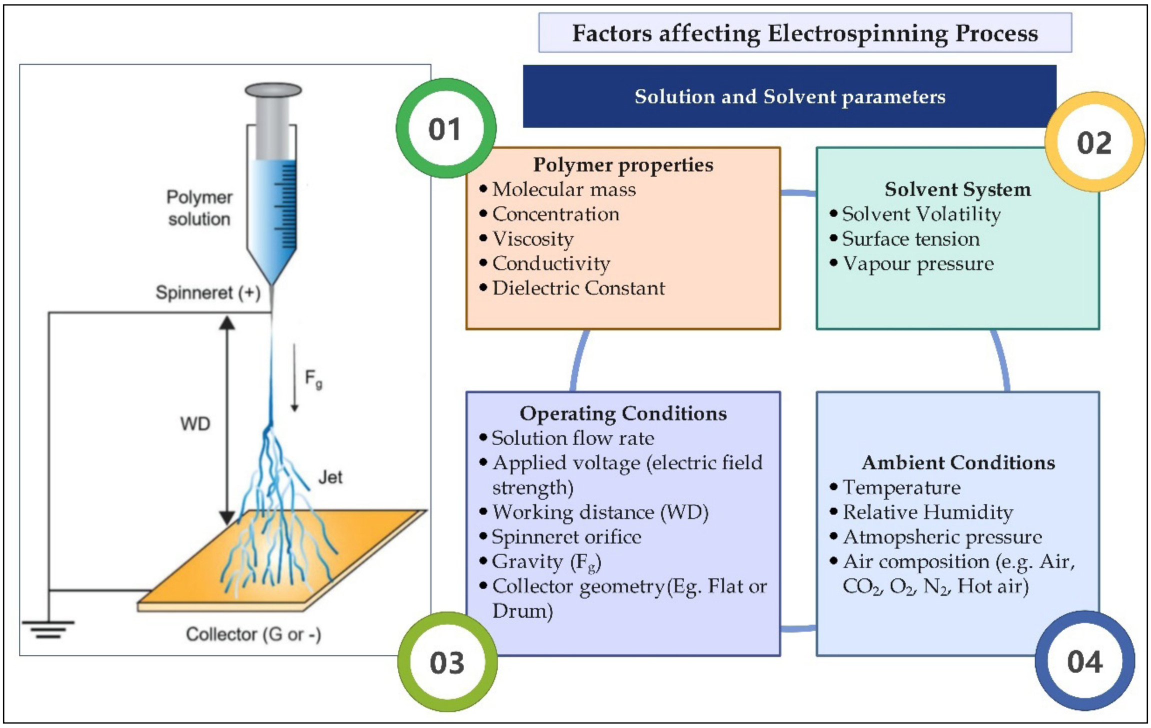


Fig. 1: Formation process of electrospun fibres (Hamzeh *et al.* 2014). Reprinted with permission from SAGE, copyright 2014



(a) Electrospinning setup

(b) Electro spun nano-fibres



(c) Factors influencing the process of electrospinning

Fig. 2: Illustration of **(a)** electrospinning process **(b)** SEM image of electrospun nanofibres **(c)** Factors influencing electrospinning process

Factors affecting the electrospinning process

The applied voltage influences the fibre diameter and morphology. Too low voltage may not generate fibres, while too high voltage can lead to bead formation or fibre breakup. A controlled flow rate is necessary to maintain a steady jet of polymer solution. If the flow rate is too high, beads or defects can form on the fibres. The distance must be optimized to allow sufficient time for fibre solidification before it reaches the collector. Too short a distance can result in fibres that are not fully formed. A mixture of beads and fibres is formed when the concentration is on the lower side, and as it rises, the beads will be transformed into fibres. Extremely low concentrations lead to electrospray rather than electrospinning, which occurs because of the solution's low viscosity and high surface tension (Keirouz *et al.* 2023). In addition, other factors which majorly affect the electrospinning process include (Fig. 2(c)):

1. **Solution parameters:** polymer structure, surface tension, molecular weight distribution, viscosity, conductivity.
2. **Process parameters:** Feeding rate/flow rate, electric field strength, speed of the plate movement, hydrostatic pressure in the capillary, distance between the tip and collector
3. **Environmental parameters:** Temperature of solution, air flow rate, ambient temperature, humidity (Xue *et al.* 2019)

Influence of different process parameters on the fibre formation and electrospinning process is detailed in Table 1. Effect of the voltage applied, solution flow rate and tip to collector distance on the morphology of nanofibres is explained in Fig. 3.

Types of Electrospinning

Electrospinning can be broadly classified into needle-based and needle-less electrospinning.

1. Needle based electrospinning

(a) Mono-axial electrospinning: It is a well-studied and easy-to-operate process, allowing for the evaluation of electrospinning ability of new materials and optimization of parameters while producing morphologically consistent nanofibres (NFs). However, it suffers from low productivity, simple fibre architecture, and a single fibre configuration that results in a compact, high-density, and low-porosity structure.

(b) Co-axial electrospinning: It enables the creation of novel core-shell or hollow structures, allowing for tunable drug release profiles and the use of materials that are otherwise not suitable for electrospinning. Yet, it also faces low productivity and a more complicated spinneret design that complicates the balancing of fluid flow rates.

(c) Tri-axial electrospinning: This process offers the potential for tri-layer structures that enhance mechanical stability and biocompatibility alongside complex drug release systems but share similar challenges of low productivity and intricate spinneret structures (Sharma & James, 2022).

(d) Centrifugal electrospinning: It allows the production of homogeneous nanofibres with varying diameters and loosely packed microfibrous structures, facilitating better cell infiltration while combining the benefits of both traditional electrospinning and centrifugal techniques.

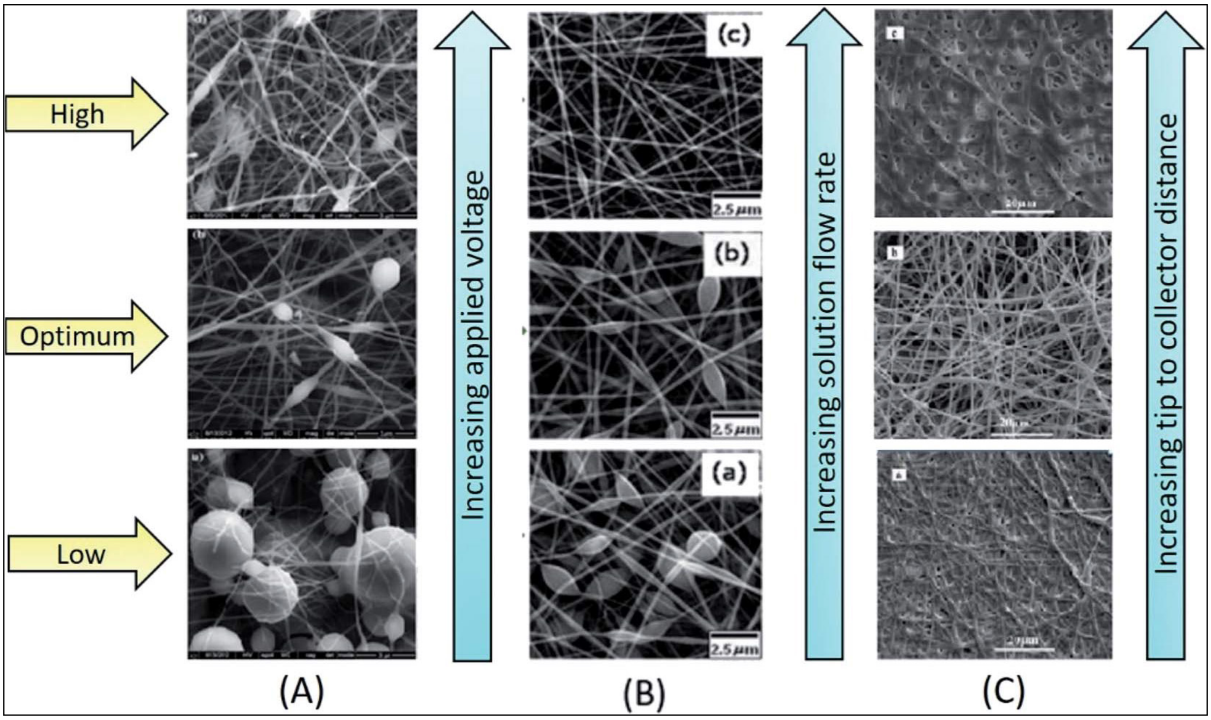


Fig. 3: Effect of the varying parameters (voltage, flow rate and tip to collector distance on the morphology of the developed nanofibres (Subrahmanya *et al.* 2021). Reproduced under the Creative Commons license

Table 1: Parameters significantly affecting the electrospinning process

Parameters	**Effect on the electrospinning process**
Solution parameters	
1. Concentration	◆ Low polymer concentrations hinder fibre formation due to insufficient surface tension, resulting in jet fragmentation ◆ Higher polymer concentrations lead to uniform, elongated fibres with reduced or absent secondary morphologies (e.g., beads, spider webs) and lower fibre diameter variability.
2. Surface tension	◆ Major driving force of the electrohydrodynamic events in the electrospinning process ◆ Surfactants improve electrospinnability by enhancing polymer spreadability and/or increasing solution conductivity ◆ Higher surface tension demands a stronger electric field to start the process, which can be managed by initially applying higher voltage and reducing it once a stable jet forms ◆ High voltage requirement for needless electrospinning for overcoming the increased surface tension and inducing jet formation
3. Viscosity	◆ Temperature and shear rate significantly affects the viscosity ◆ Viscosity rises with high molecular weight and stronger intermolecular interactions ◆ Achieving optimal viscosity in electrospinning prevents issues like polymer spraying (from low viscosity) or the creation of large-diameter fibres (from high viscosity)
4. Molecular weight	◆ Polymers with higher molecular mass typically result in more uniform but thicker fibres. ◆ Low molecular mass can disrupt electrospinning or lead to the formation of non-uniform fibre mats.
5. Permittivity and conductivity	◆ Taylor cone formation is directly depended on coulombic force and electrostatic repulsion ◆ Higher conductivity promotes thinner fibre formation while lower permittivity enhances electric field density ◆ Salts (e.g., NaCl, LiCl) improve conductivity, permittivity, and fibre output in needleless electrospinning
Solvent Parameters	
1. Volatility of solvent	◆ Solvent evaporation influences morphology and fibre solidification, ensuring dry membranes and reduced entrapment of solvent ◆ High volatility causes defects like porous fibres, hindering electrospinning process ◆ Rate of evaporation directly relates to relative humidity, working distance, solvent volatility and spinneret setup
2. Dielectric constant	◆ Dielectric constant indicates solvent's ability to influence surface charge distribution and manage electrostatic repulsions ◆ High dielectric constant enhances jet stability and surface charge distribution ◆ Water, commonly used as solvent, due to its high dielectric constant which reduces electrostatic repulsions
Operating conditions and Environmental parameters	
1. Flow rate	◆ Flow rate directly affects the surface tension and fibre formation ◆ Higher flow rates can lead to inadequate fibre stretching, resulting in wet, thicker fibres with larger pores ◆ Critical factor in multi-axial systems
2. Voltage	◆ Critical voltage is the minimum voltage requirement to overcome the solution's surface tension and generate a stable jet ◆ Low voltage often results in polymer solution spraying onto the collector or jet path ◆ Higher voltage reduces jet flight time, leading to instability and larger or secondary fibre morphologies
3. Working distance	◆ The gap between the spinneret and collector that determines the jet path ◆ Provides additional time for solvent evaporation and polymer solidification, often resulting in thinner fibres ◆ Exceeding the optimal distance can disrupt electrospinning, causing defects or excessive bending instabilities that affect fibre formation

4. Spinneret design	◆ Determines structural attributes like 3D macrostructures or alignment, especially with rotating spinnerets ◆ Influences fibre production rates and the complexity of fibre architectures (e.g., co-axial designs)
5. Collector geometry	◆ Macro and micro morphology of the deposited fibres are affected by collector geometry ◆ Rotating mandrels facilitate fibre alignment and cylindrical collectors combined with rotating spinnerets enable precise orientation ◆ Dual-cylinder systems are suitable for large-scale textile production
6. Relative humidity	◆ Low humidity results in rapid solvent evaporation which shortens the jet path and finally resulting in thicker fibres ◆ High humidity disrupts charge distribution and reduces surface charge density, hindering the process ◆ High humidity also causes non-uniform fibres and unique configurations (e.g., porous, dimpled) with hygroscopic polymers
7. Temperature	◆ Surface tension and viscosity of the solution is influenced by chamber temperature ◆ Depending on polymer and solvent properties, temperature can enhance or hinder the electrospinning process ◆ Temperature affects the evaporation rate, impacting jet solidification

Source: *Keirouz et al., 2023; Ji et al., 2024; Valizadeh & Mussa Farkhani, 2014.*

However, this relatively new method requires further exploration of process parameters.

(e) 3D electrospinning: This process is unique in its capability to produce three-dimensional fibrous structures in a single step, allowing for the creation of woven or nonwoven structures, though it requires highly conductive polymer systems and faces challenges regarding mechanical stability and precision as the height of the structure increases (Keirouz *et al.* 2020). A combined approach utilizing electrospinning and additive manufacturing is recently gaining popularity (Fig. 4.).

2. Needless electrospinning

(a) Roller electrospinning: This offers a promising approach for the high-throughput production of micro- and nanostructured fibres, facilitating continuous manufacturing suitable for industrial applications. This method allows for easy manipulation of both production rates and fibre diameters and has been extensively researched in the literature. However, it predominantly produces larger fibre diameters with a high standard deviation, resulting in less morphologically consistent fibres compared to needle-based methods. Additionally, roller electrospinning requires higher voltages to initiate jetting and is sensitive to ambient conditions, with solvent volatility impacting fibre homogeneity due to the exposed open surface (Shi *et al.* 2021).

(b) Bubble electrospinning: It is characterized by its capability to achieve high production rates and can operate at lower voltages than other needleless methods, making it effective for mass production. However, this emerging technology has not been thoroughly researched, and its large, exposed area raises safety concerns when toxic solvents are involved. Like the needleless roller method, bubble electrospinning is also susceptible to ambient conditions and air pressure, which can compromise fibre uniformity during extended operations.

(c) Corona electrospinning: This features a low-free liquid surface spinneret that facilitates continuous, high-throughput fibre production. Its unique spinneret design shields the polymer solution while promoting efficient electrospinning. Nonetheless, this method requires specific rotational speeds to prevent overflow and operates at extremely high voltages, necessitating further research to fully understand its advantages and limitations.

(d) High-speed electrospinning: This method boasts impressive productivity, reaching approximately 0.5 kg/h, and enables continuous fibre production. The incorporation of fibre fragmentation in the collector cyclone can streamline downstream processing. However, this technique cannot produce complex fibre structures, such as core-shell configurations, and demands extremely high rotational speeds and voltages. As a relatively new process, high-speed electrospinning also requires additional

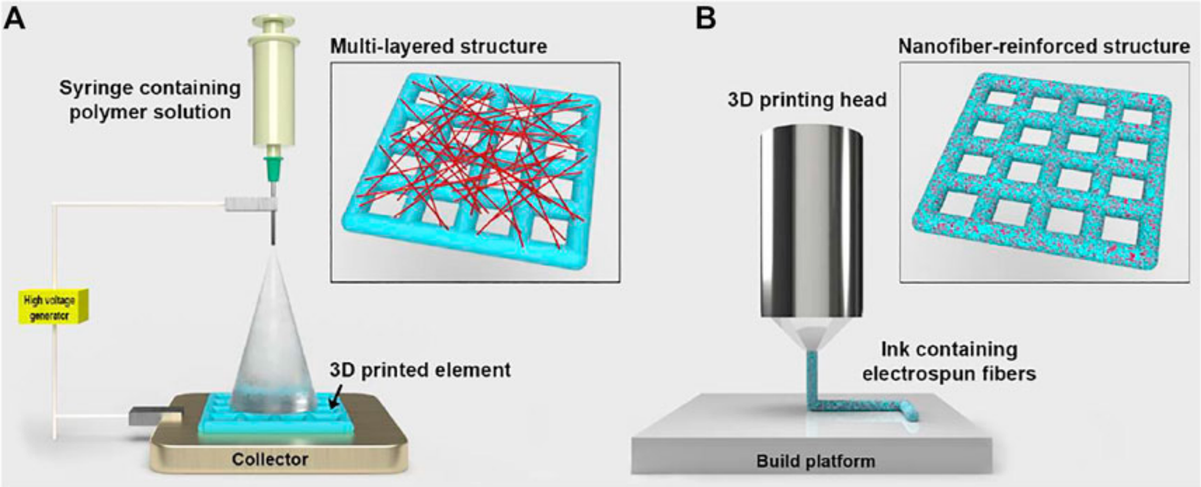


Fig. 4: Schematic illustration of integrated electrospinning and 3D printing process **(A)** Electrospun nanofibres are deposited onto one side of a 3D-printed element placed in contact with the metallic collector of the electrospinning setup. Inset: A 3D-printed layer coated with a low-density layer of electrospun fibres. **(B)** A 3D printing nozzle deposits polymeric ink reinforced with electrospun fibres. Inset: A composite 3D-printed structure with nanofibres encapsulated within the printed struts (Smith and Mele, 2021)

investigation to uncover its potential benefits and drawbacks (Keirouz *et al.* 2023). Fig. represents the different types of spinnerets used in both needle and needless electrospinning.

(e) Melt electrospinning: Melt electrospinning presents a sustainable alternative to solution-based electrospinning by avoiding issues like solvent toxicity, environmental hazards, and the need for solvent recovery. In this technique, molten polymer is directed through a capillary tube, with the charged jet traveling within a vacuum-sealed system to a metallic collector. However, its adoption has been limited compared to traditional solution electrospinning due to challenges such as the high viscosity of molten polymers, the need for elevated processing temperatures, and difficulties in producing nanoscale fibres. These high temperatures also restrict its use in applications like tissue engineering and drug delivery, where heat sensitivity is crucial (Bhardwaj and Kundu, 2010; Karakas, 2015). Despite these challenges, further research and innovation could unlock its broader potential. Different types of spinnerets used in needle and needle-less electrospinning is illustrated in Fig. 5.

Applications of the electrospun nanofibres

1. Nanofibres for enhanced performance

Electrospinning produces nanofibres with diameters in the nanometer range, which significantly increases their surface area-to-volume ratio. This unique feature makes them suitable for high-performance textiles. The fine fibres improve moisture wicking and breathability, which are essential properties in sportswear and activewear. Fabrics made with electrospun nanofibres can rapidly transport sweat away from the body, ensuring that wearers remain dry and comfortable during physical activities. Furthermore, nanofibres can be engineered to have hydrophobic or hydrophilic properties, influencing how the fabric interacts with moisture. For example, outdoor apparel may require hydrophobic coatings to repel water, while healthcare fabrics may use hydrophilic nanofibres to promote the absorption of wound exudate in bandages.

Wang *et al.* (2020) developed a SiO_2-TiO_2 sponge with a unique gradient porous structure by electrospinning PVP, TEOS, and TBT, followed by calcination. The sponge displayed a micro-meso-macroporous arrangement, where interconnected pores progressively shifted from the fibre's core to its outer wall, contributing to high porosity, low density, and enhanced compressibility. This structure demonstrated excellent thermal stability, remaining cool even after 30 minutes above a 500°C flame, highlighting its potential in flame-retardant applications. Similarly, Zhang *et al.* (2020) created nickel oxide (NiO) porous nanofibres via electrospinning and pyrolysis, where the mesoporous structure facilitated strong interactions with a polylactic acid matrix, leading

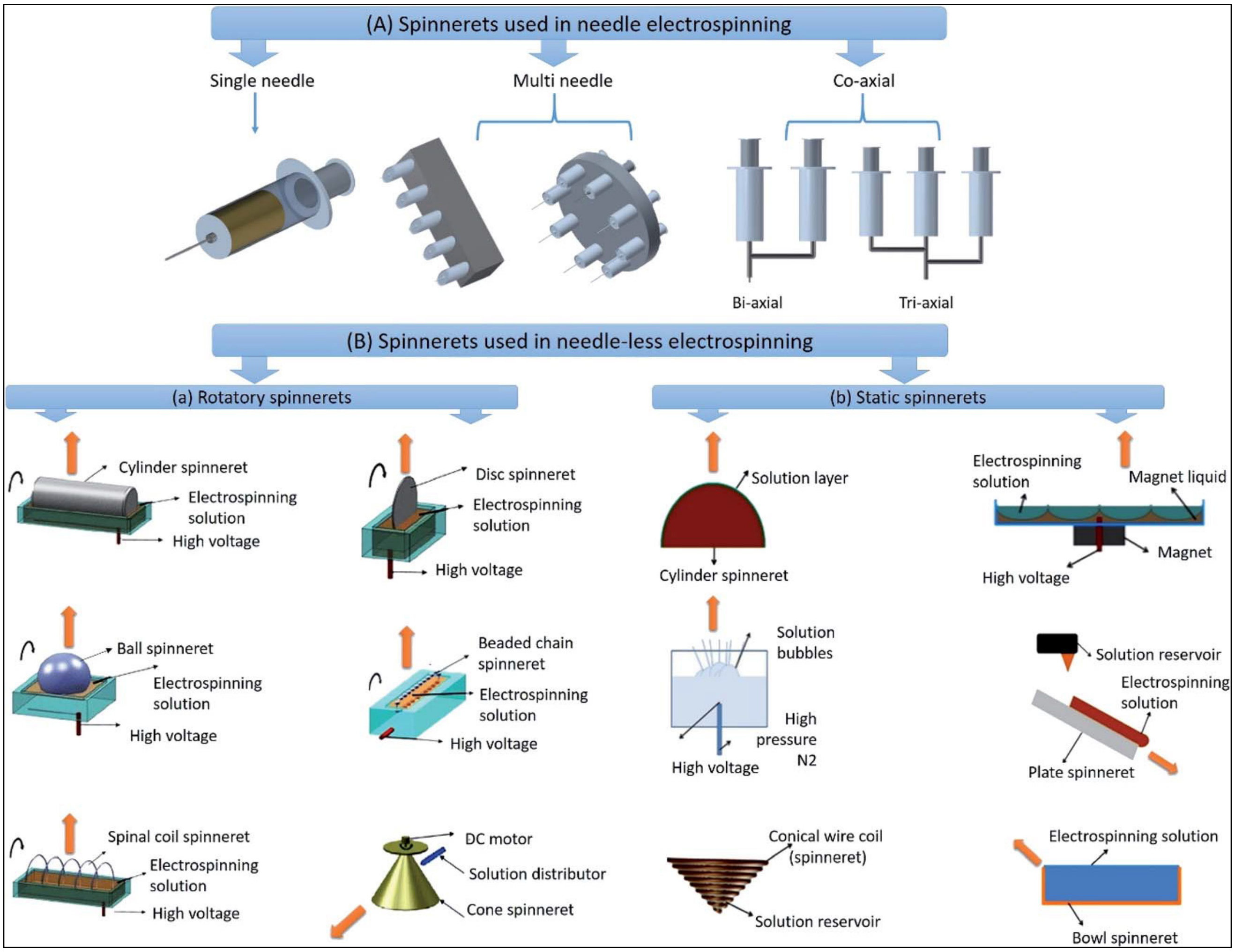


Fig. 5: Illustration representing different types of spinnerets used in (A) Needle electrospinning and (B) Needleless electrospinning (Fashandi & Karimi, 2014). Reproduced with permission from ACS, copyright 2014

to improved dispersion and load transfer. These NiO fibres outperformed commercial NiO particles in flame resistance, showcasing how tailored porosity enhances material performance. Future advancements may explore the combination of such porous designs with multi chamber electrospun structures, like chimeric Janus configurations, to yield multifunctional nanomaterials with diverse application potentials. Additionally, electrospun fibres can enhance the durability of fabrics, making them more resistant to wear and tear while maintaining a lightweight structure. This combination of high surface area and mechanical strength is particularly useful for creating high-performance textiles with long lifespans.

Cho and Lee, (2018) synthesized macroporous silica nanofibres through electrospinning followed by high-temperature calcination. Calcination at 500°C resulted in a porous structure that significantly enhanced the fibres' sound absorption capabilities, especially in the 4.0–5.1 kHz frequency range, outperforming commercial sponges. These porous nanofibres also hold promise for electromagnetic wave absorption. Sun *et al.* (2023) developed hollow porous carbon nanofibres by incorporating Fe-ZIF into a PAN precursor solution before high-temperature calcination. The Fe-ZIF and hollow porous structure provided optimal impedance matching, enabling the nanofibres to absorb electromagnetic waves more effectively than conventional nanofibres, showing great potential for applications in wave attenuation.

2. Protective and smart textiles

Electrospinning enables the integration of various functional additives into nanofibres, positioning it as a valuable method for creating protective and smart textiles. For example, fibres can be infused with antibacterial agents to produce fabrics resistant to microbial growth. This feature is especially advantageous in medical textiles, where hygiene is paramount, such as in hospital gowns, wound dressings, and bedding. Protective textiles can also be developed by incorporating UV-blocking agents into electrospun fibres, resulting in garments that shield against harmful ultraviolet radiation. Furthermore, flame retardant chemicals can be embedded in nanofibres to create fabrics suitable for industrial workers, firefighters, and military personnel.

Smart textiles, or e-textiles, represent another significant area where electrospinning is essential. By incorporating conductive materials into electrospun fibres, these textiles can respond to external stimuli, such as temperature changes, humidity, or electrical signals. Such smart fabrics can be utilized in wearable electronics, fitness trackers, and medical monitoring devices that provide real-time vital sign measurements. A smart textile combining PEG as a phase change material, PA6, and TiO_2 for UV protection and temperature regulation was developed (Wang *et al.* 2021). Fabricated by single-nozzle electrospinning, the textile showed effective UV shielding, thermal stability, and a latent heat of 51.14 J/g, retaining reliability over 500 heating-cooling cycles. This innovation holds promise for multifunctional, comfortable smart wear. Similarly, a thermo-regulated smart textile was designed using paraffin wax (PW) as a phase change material, effectively addressing leakage through coaxial electrospinning. The resulting core-sheath structure, with PW as the core and polyacrylonitrile (PAN) as the sheath, ensured high encapsulation efficiency (54.3%) and stable latent heat (60.31 J/g), even after 500 heating-cooling cycles. Enhanced with hexagonal cesium tungsten bronze for efficient near-infrared absorption, this textile advances smart fabric technology, offering potential for comfortable, energy-efficient wear (Lu et al., 2019). Additionally, some smart textiles are being designed to change color or adapt their thermal insulation based on environmental conditions, enhancing their responsiveness to the wearer's needs.

3. Energy harvesting and storage

Electrospinning has paved the way for integrating nanotechnology into textiles for both energy harvesting and storage. Piezoelectric fibres, which generate electric charge when subjected to mechanical stress, can be produced through electrospinning and woven into fabrics. These fabrics have the potential to convert body movements into electrical energy, which can then be stored in small batteries or used to power wearable electronics. This technology shows great promise for wearable health devices, where continuous energy harvesting could reduce the need for frequent recharging. Shan *et al.* (2020) developed nitrogen-doped graded carbon nanofibres (CZIF-8/PAN) by utilizing ZIF-8 particles as a template through electrospinning. The incorporation of ZIF-8 resulted in a layered, porous structure after carbonization and acid treatment, which enhanced the surface area for electrolyte contact and improved sodium ion transfer speed. Additionally, the introduction of nitrogen atoms increased the number of active sites and boosted electrical conductivity. The fibre membrane exhibited exceptional cycling performance, maintaining a stable discharge capacity of 186.2 mAh g^{-1} after 600 cycles. Wang *et al.* (2022) developed three types of porous silicon@heteroatom-doped porous carbon fibres using coaxial electrospinning, creating structures that effectively mitigated silicon's volume expansion and provided ample channels for lithium-ion transmission and diffusion. After 100 cycles, the material exhibited excellent cycling performance, retaining a capacity of 1145 mAh g^{-1}. This study underscores how the addition of a porous structure can significantly improve the electrochemical properties of electrode materials, offering a promising pathway for enhanced energy storage solutions.

Similarly, thermoelectric materials can be incorporated into textiles to generate electricity from the temperature difference between the body and the surrounding environment. This could enable the development of clothing that powers small devices by harnessing the heat produced by the wearer. Beyond energy harvesting, electrospun fibres are also being explored for use in energy storage systems, such as supercapacitors and batteries. The high surface area of these nanofibres enhances the performance of energy storage devices, allowing for more efficient energy retention and release. A porous carbon nanofibre anode for lithium and sodium ion batteries was developed by integrating a Sn-MOF organic framework into a PAN precursor solution, followed by electrospinning and carbothermic reduction. This process yielded a layered, porous fibre membrane (Sn@C@CNF) with structural benefits that optimize battery performance. The porous configuration facilitated rapid ion and electron transport while effectively buffering volume expansion within the carbon inclusions and MOF skeleton, thus enhancing cycling stability. The improved ion mobility and structural resilience in this setup resulted in notable electrochemical stability and increased capacity for Li+ and Na+ storage, demonstrating the potential of tailored porous nanostructures in advancing energy storage technologies (Zhu *et al.* 2021).

4. Filtration and environmental applications

Electrospun nanofibres are widely used in creating high-performance filtration media due to their fine structure and large surface area. In the textile industry, nanofibre membranes enhance the effectiveness of air and water filters by trapping microscopic particles, pollutants, and contaminants more efficiently than traditional filters. For instance, electrospun nanofibres are incorporated into face masks and protective clothing to guard against airborne pathogens, allergens, and pollutants. These fine fibres provide better filtration efficiency while maintaining breathability, a crucial factor for industries where workers need to wear protective gear for extended periods. Kadam *et al.* (2021) explored a sustainable approach by creating electrospun gelatin/β-cyclodextrin (CD) composite nanofibres from a protein-polysaccharide mixture, designed to capture aerosols ranging from 0.3 to 5μm. The gelatin/CD nanofibres achieved filtration efficiencies of 95% with a favourable quality factor of 0.029/Pa. Similarly, Yu *et al.* (2020) developed bio-based zein nanofibres through chemical crosslinking, achieving a robust surface morphology that withstands high humidity. These nanofibres demonstrated an impressive filtration efficiency, capturing over 97% of fine particles smaller than 0.3 μm and over 98% of other airborne pollutants, marking their effectiveness for air filtration. This green, breathable air filtration solution provides a highly efficient and low-resistance alternative, contributing to advancements in sustainable filtration technology.

In water purification, electrospun nanofibres are utilized to make filters capable of capturing bacteria, viruses, and harmful substances while allowing clean water to flow through. These filters contribute to the creation of eco-friendly textiles, addressing the issue of water contamination often seen in textile production. By combining electrospinning with vapor-induced phase separation (VIPS), a highly efficient filter membrane was created for intercepting waterborne pollutants, including TiO_2 particles and *Escherichia coli*. Carefully controlling solvent and humidity conditions resulted in a submicron pore size of 0.19 μm, 93.2% porosity, an ultra-thin 700 nm thickness, and strong interconnectivity. At 5 kPa pressure, the membrane achieved an impressive permeation flux of 3907 L m^2/h and a filtration efficiency of 99.75% (Tang *et al.* 2020). This innovative membrane outperformed current commercial sterile membranes, demonstrating its potential for high-quality filtration in diverse applications. In addition, electrospinning can produce biodegradable filtration materials that help minimize the environmental impact of the textile industry. By developing effective and sustainable filtration systems, the textile sector can reduce its impact on air and water quality, supporting environmental responsibility and promoting circular economy practices. Other filtration applications of the nanofibres in detailed in Table 2.

5. Applications in composites

Electrospun fibres play a significant role in enhancing the performance of structural composites due to their remarkable mechanical and functional properties. These fibres, with their nanoscale diameter and high aspect ratio, offer a unique mechanism for reinforcing composite materials. Electrospun fibres improve the tensile strength, stiffness, and impact resistance of composite materials. When integrated into a polymer matrix, the fibres distribute stress uniformly, reducing the risk of material failure. This makes them suitable for applications demanding high mechanical reliability, such as aerospace

Table 2: Filtration applications of the electrospun nanofibres

Polymer	**Solvent**	**Processing conditions**	**Properties of nanofibre**	**Application**	**Reference**
Poly Vinyl alcohol	De-ionized water	Applied voltage: 10 kV Flow rate: 2.5 mL/h Tip to collector distance: 6 cm Concentration of polymer: 18 wt%	Fibre diameter: 400 nm Weight of fibre: 7.55–10.79 m^2/g	Dye and heavy metal removal	Elhousseini *et al.* 2020
Chitosan	Acetic acid	Applied voltage: 23 kV Flow rate: 0.1 mm/min Tip to collector distance: 6.8 cm Concentration of polymer: 5 wt%	Fibre diameter: 75 nm Weight of fibre: 0.18–2 m^2/g	Heavy metal removal	Li *et al.* 2016
Polyethylenimine	Dimethyl formaldehyde/ N-methyl-2-pyrrolidone	Applied voltage: 25 kV Flow rate: 1 mL/h Tip to collector distance: 10 cm Concentration of polymer: 20 wt%	Fibre diameter: 637 nm-3.47 μm Weight of fibre: 0.71–5.64 m^2/g	Microfiltration	Li *et al.* 2015
Poly(acrylonitrile-co-glycidyl methacrylate)	Dimethyl formaldehyde	Applied voltage: 15-20 kV Flow rate: 1.1 mL/h Tip to collector distance: 25 cm Concentration of polymer: 20 wt%	Fibre diameter: 100-126 nm	Separation of enzyme and protein from water	Homaeigohar *et al.* 2013
Polyvinylidene fluoride	Dimethylacetamide/ Acetone	Applied voltage: 13 kV Flow rate: 0.055 mL/min Tip to collector distance: 15 cm	Fibre diameter: 0.57–0.61 μm	Ultrafiltration	He *et al.* 2014
Polyether sulfone	N-methyl-2-pyrrolidone	Applied voltage: 18-30 kV Flow rate: 20 mL/min Tip to collector distance: 10 cm Concentration of polymer: 9-22 wt%	Fibre diameter: 610-1090 nm	Microfiltration	Abdelsamad *et al.* 2017
Poly(amidoamine) (PAMAM)/ Polyacrylonitrile (PAN)/	Dimethyl formaldehyde (DMF)	Applied voltage: 16-23 kV Flow rate: 1.2 mL/hr Tip to collector distance: 16 cm Concentration of polymer: PAMAM = 5-30 wt%, PAN = 10 wt%	Fibre diameter: 240-355 nm Weight of fibre: 12-26.2 m^2/g	Removal of Dye from water	Almasian *et al.* 2015
Polysulfone	Dimethyl formaldehyde (DMF)	Applied voltage: 20 kV Tip to collector distance: 15 cm Concentration of polymer: 15-20 wt%	Fibre diameter: 130-630 nm	Separation of oil from water	Obaid *et al.* 2015

Poly vinyl alcohol (PVA)	Deionized water	Applied voltage: 17.5 kV Flow rate: 1 mL/hr Tip to collector distance: 15 cm Concentration of polymer: 10 wt%	Fibre diameter: 180-280 nm Weight of fibre: 88-130 m^2/g	Removal of heavy metal ions	Hallaji *et al.* 2015
Poly lactic acid (PLA)	Acetone	Applied voltage: 20 kV Flow rate: 0.5 mL/hr Tip to collector distance: 10 cm Concentration of polymer: 11-13 wt%	Fibre diameter: 500-1200 nm	Microfiltration	Li *et al.* 2013
Poly vinyl alcohol (PVA)	Deionized water	Applied voltage: 15 kV Flow rate: 1 mL/hr Tip to collector distance: 12 cm Concentration of polymer: 8 wt%	Fibre diameter: 50-90 nm	Degradation of dye	Ghasemi *et al.* 2015
Poly vinyl alcohol (PVA)	Deionized water	Applied voltage: 24-32 kV Flow rate: 10 mL/min Tip to collector distance: 10 cm Concentration of polymer: 6-12 wt%	Fibre diameter: 50-90 nm	Microfiltration	Liu *et al.* 2013

and automotive industries. Electrospun fibres contribute to lightweight composite structures. Their low density, combined with high mechanical performance, reduces the weight of components without compromising strength. In addition to mechanical reinforcement, electrospun fibres can impart other functionalities to composites, such as thermal stability, electrical conductivity, or chemical resistance. These features extend their application to advanced engineering fields. Rojas *et al.* (2009) incorporated cellulose whiskers into electrospun polystyrene-based microfibres, creating nanocomposites with highly porous structures and large surface areas. Polybenzimidazole (PBI) nanofibres have been utilized as reinforcements in both epoxy and rubber matrices, showcasing improved material properties (Kim and Reneker, 1999). In addition, Bergshoef and Vansco (1999) demonstrated that nanocomposites created using electrospun Nylon-4,6 nanofibre membranes embedded in an epoxy matrix exhibited significantly higher stiffness and strength compared to the reference matrix film. These nanocomposite fibres and nonwoven structures are highly promising for high-performance applications due to their enhanced mechanical properties and functional versatility.

6. Biomedical textiles

Electrospun fibres are widely utilized in biomedical textiles due to their ability to imitate the structure of human tissue. These fine fibres are used to create scaffolds in tissue engineering, fostering cell growth and aiding in the repair of damaged tissues. Since electrospun scaffolds closely resemble the extracellular matrix, they are particularly effective in wound healing by promoting tissue regeneration and speeding up the healing process.

In wound care, electrospun fibres serve as a foundation for antimicrobial dressings, which help prevent infections while maintaining a breathable environment conducive to healing. These dressings are often embedded with antimicrobial substances, such as silver nanoparticles, to combat bacterial infections in chronic wounds. Additionally, electrospun fibres are being developed into bioactive fabrics that can release therapeutic agents over time, facilitating wound healing or acting as a medium for drug delivery. Yang *et al.* (2019) incorporated ciprofloxacin into chitosan/graphene oxide/PVA nanofibrous textiles, achieving strong antibacterial properties and excellent cytocompatibility with melanoma cells, showing its potential for wound healing applications. Ciprofloxacin was absorbed into graphene oxide, preventing burst releases.

Electrospun fibres are also investigated for drug delivery systems, where they can encapsulate medications and provide controlled, gradual release. This controlled release is particularly beneficial for topical and transdermal drug applications. Amiri *et al.* (2020) designed chitosan/PEO electrospun textiles loaded with teicoplanin, showing sustained antibiotic release for up to 12 days in vitro and 1.5 to 2 times higher antibacterial activity than free teicoplanin. These textiles promoted better wound healing in a rat model without causing cytotoxicity to human fibroblasts. Fazli and Shariatinia (2017) introduced cefazolin and fumed silica into electrospun chitosan/PEO textiles, which demonstrated significant bactericidal effects, while silica slowed the burst release of cefazolin. These textiles healed the wounded skin of female rats almost completely within 10 days. Their biocompatibility and flexibility make electrospun fibres suitable for a broad range of medical uses. The fibres can be tailored to degrade at specific rates, allowing them to remain in the body for a predetermined period before safely breaking down.

FUTURE PERSPECTIVES

Electrospinning is a highly adaptable method for producing micro- and nanoscale materials with unique properties. However, it still faces several challenges that limit its full potential. One major issue is the lack of a universally accepted simulation model to accurately predict the parameters for both needle-based and needleless electrospinning techniques. This gap forces researchers to depend on trial-and-error methods and empirical studies to optimize the process. In needleless electrospinning, for example, it is particularly difficult to produce fibres that are uniform in size and structure while maintaining high output and application-specific properties. To overcome these challenges, researchers should prioritize sharing detailed results, both successes and failures, on optimizing various factors, including solution composition, processing conditions, and environmental parameters. Such an approach can significantly improve the understanding of fibre formation, jet behaviour, and reproducibility across different electrospinning technologies.

Another critical challenge lies in the environmental and economic impact of electrospinning processes. Many solvents used in electrospinning are volatile and harmful, posing risks to human health and ecosystems. This problem is especially pronounced in needleless electrospinning, where large liquid surfaces are exposed to air, causing significant solvent evaporation. While aqueous polymer solutions offer a safer alternative, they are not always compatible with all polymers (Karakaş, 2015). To address this, researchers should explore the use of "green" solvents that are less harmful and more sustainable. Melt electrospinning, which avoids solvents altogether, is another promising alternative. However, it comes with its own limitations, such as difficulties in producing fine, complex fibres, the risk of polymer degradation at high temperatures, and compatibility issues with high-throughput systems. Addressing these challenges requires a collaborative effort to innovate and refine electrospinning processes. By focusing on sustainability, reproducibility, and process efficiency, electrospinning can become a more reliable and environmentally friendly technology for industrial applications.

CONCLUSION

Electrospinning has become a crucial technique in nanofibre production, valued for its ease of use, controllability, and reproducibility. This technology enables the creation of nanofibres with extensive surface areas, particularly when porous structures are incorporated, enhancing performance across applications. Electrospinning is transforming the textile industry by offering innovative solutions for enhancing performance, creating protective and smart textiles, enabling energy harvesting, improving filtration, and contributing to biomedical advancements. The versatility of this technology continues to open new doors for the creation of advanced textiles that cater to both consumer and industrial needs. Porous structures developed through electrospinning provide not only increased surface area and adsorption capacity but also effective diffusion channels, advancing applications in areas like air filtration, water purification, biomedical fields, energy storage, and food packaging. However, challenges remain, particularly in optimizing internal structures, balancing mechanical strength with porosity, and improving cost efficiency for industrial-scale production. Addressing these challenges through innovative designs, structural stability enhancements, and advances in scalable production techniques will further broaden the scope of electrospun porous nanofibres, allowing them to meet the evolving demands of modern science and technology and enriching their potential in life-enhancing applications.

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