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Electro spun Nanofibers for Biomedical Use: Fabrication Approaches and Functional Insights

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ABSTRACT

Electrospinning is a versatile and efficient method for producing nanofibers that exhibit unique characteristics suitable for various medical uses. Electrospun nanofibers (EN) fabricated using biopolymers have revolutionized modern platforms for drug delivery due to their controlled drug release kinetics and structural mimicry of extracellular matrices. By understanding the intricacies of fabrication and functionality, we can better harness the potential of electrospun nanofibers in the biomedical field. This review aims to provide a comprehensive overview of electrospun nanofibers with particular emphasis on their fabrication approaches, use of polymers, and functional insights in the biomedical domain. Various fabrication approaches, including solution electrospinning, melt electrospinning, coaxial and triaxial electrospinning, and emulsion electrospinning, have been developed to optimize fiber morphology and impart multifunctionality. The choice of polymer-natural, synthetic, or blended-further enables tailoring of mechanical strength, biodegradability, and bioactivity. Functional modifications, such as surface coating, incorporation of bioactive molecules, and nanoparticle embedding, extend the scope of nanofibers toward drug delivery, wound healing, tissue engineering, and biosensing.In addition, researchers are advancing the design of multifunctional hybrid structures by integrating electrospinning with complementary fabrication techniques such as 3D printing, green electrospinning, and layer-by-layer assembly. These approaches allow for the creation of highly customized scaffolds with tailored properties and enhanced functionality.Overall, electrospun nanofibers represent a promising platform that bridges materials science and biomedical engineering, offering innovative solutions for next-generation therapeutics and regenerative medicine.

Keywords: Nanofibres, Tissue engineering, Biosensing, Electrospinning, Polymers.

INTRODUCTION

The last decade has witnessed a surge in advanced delivery of drugs as researchers strive to enhance therapeutic efficiency while reducing side effects. Nanotechnology is becoming one of the most revolutionary areas of contemporary biomedical research due to the ongoing hunt for cutting-edge biomaterials that can solve the expanding problems in healthcare. Using electrospun nanofibers made of naturally occurring biopolymers is one of the most promising approaches[1,2]. By leveraging the qualities of natural polymers nanofibers like biocompatibility, biodegradability, and their capacity to replicate the extracellular matrix-modern are emerging as a powerful tool in the delivery of drugs[3]. Although, concept of electrospinning can be traced back over a century, its full potential was only recognized in recent decades. The first patents related to electrospinning appeared in the early 20th century, but it wasn't until the 1990s-with advancements in nanotechnology and microscopy-that interest in the process surged[4]. Today, electrospun nanofibres offer tunable physical, chemical, and biological characteristics tailored for specific applications[5,6](Figure 1).

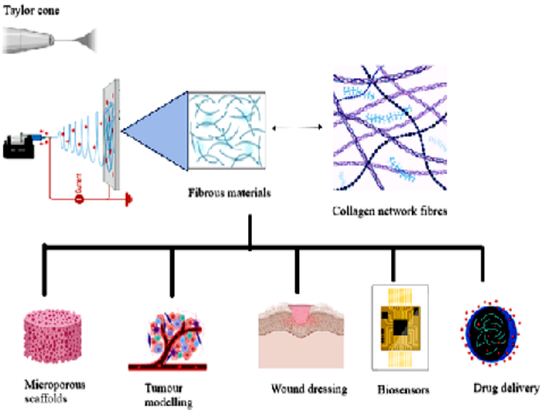

Fig. 1. A schematic diagram representing biomedical applications produced by the electrospun nanofibres technique

Drug delivery systems have evolved to offer controlled, sustained, and targeted release to improve therapeutic outcomes. Electrospun nanofibers-fibers with diameters in the nanometer scale-present an innovative approach due to their porous structure and ease of fabrication[7,8] (Fig. 2). Their use in localized and systemic drug delivery has gained substantial attention in recent years. Electrospun nanofibers offer a solution by providing high surface area, customizable porosity, and flexible drug loading strategies[9].

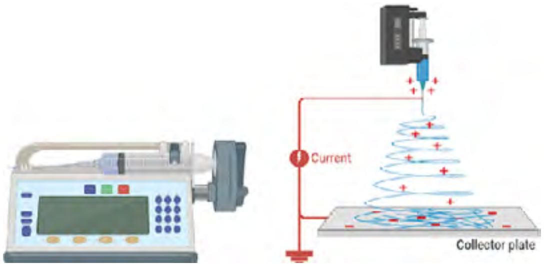

Fig. 2. Electrospinning instrument for synthesizing nanofibers

Electrospinning has emerged as a bridge between polymer science and biomedical engineering by providing a flexible platform to process diverse polymers-natural, synthetic, or their composites-into fibrous scaffolds. While synthetic polymers, such as polycaprolactone, polylactic acid, and poly(lactic-co-glycolic acid), offer controlled degradation and mechanical strength, natural polymers, including collagen, gelatin, chitosan, and silk fibroin, offer intrinsic biocompatibility and bioactivity.When made from biocompatible polymers, these fibers not only enhance therapeutic efficiency but also ensure safety and biodegradability[10]. The unique characteristics of nanofibers, including their porous structure, customizable functionalization, morphology, and ability to incorporate functional molecules, make them especially valuable in areas such as drug delivery, wound healing, tissue engineering, and biosensors. A major advantage of electrospinning lies in its ability to process the use of polymers, and even blends. Moreover, functional agents like proteins, API, or nanoparticles can be directly incorporated into the fibers during the electrospinning process, allowing for controlled and sustained release[11,12].

Principle of Electrospun Nanofibers

Electrospinning is a fiber production technique that uses a high-voltage electric field to draw a charged solution of polymer or melt into fine fibers with diameters ranging from nanometers to micrometers. In this process, the solution of polymer is placed in a syringe fitted with a metallic needle, which is connected to a high-voltage power supply. When the electric field overcomes the surface tension of the polymer droplet at the needle tipforms, and a thin charged jet is ejected toward a grounded collectorthe solvent evaporates (or the melt solidifies), resulting in the deposition of continuous fibers[13,14] (Figure 3).

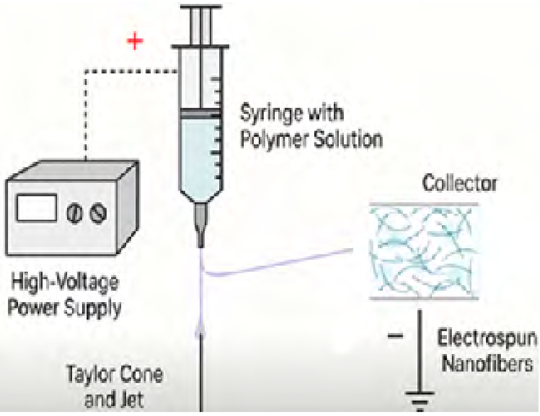

Fig. 3. Synthesis of Electro-spun nanofibers

Key Steps in Electrospinning Process:

High-Voltage Application: Ametallic needle holding the polymer solution is attached to a high-voltage power source, usually 10–30 kV.

Taylor Cone Formation: The polymer droplet's surface tension is overcome by electrostatic repulsion, creating the Taylor cone, a conical shape.

Jet Ejection: From the cone's tip, a jet which is charged is released and moves in the direction of the collector.

Jet Thinning and Solidification: The jet's diameter is reduced to nanoscale as it moves because it expands and the solvent evaporates.

Fiber Deposition: The solidified nanofibers are collected as a non-woven mat on a grounded collector (usually a rotating or static plate)[15,16].

Mechanisms for Release of Drug

Drug release from electrospun nanofibers generally occurs through multiple mechanisms, often operating simultaneously. The mechanisms are discussed below[17] (Figure 4).

1. **Diffusion-controlled release**: Diffusion is one of the most basic processes, in which drug molecules move from the inside of the fibre to the surrounding media. The concentration differential between the surrounding fluid and the nanofiber matrix controls this process. Drug solubility, hydrophilicity, and polymer porosity all affect the rate of diffusion. While hydrophobic polymers, like polycaprolactone (PCL), slow down diffusion and lengthen release duration, hydrophilic fibres, like those formed of polyvinyl alcohol (PVA), allow faster diffusion, leading to rapid release[18].
2. **Degradation or erosion-controlled release:** Drugs can be released through degradation or erosion of biodegradable polymers such as polylactic acid (PLA), polyglycolic acid (PGA), and their copolymer PLGA.During bulk erosion, water penetrates the whole fiber, causing uniform degradation, while during surface erosion, degradation occurs only on the surface of the fiber. As the polymer degrades, entrapped drugs are progressively liberated. The mechanism is particularly beneficial for long-term therapeutic applications requiring sustained drug release[19].
3. **Swelling-controlled release:** Hydrophilic polymers, including gelatin, alginate, and chitosan, can absorb water and swell upon contact with aqueous environments. Swelling speeds up drug molecule mobility by increasing the free volume inside the fibres. When a quick therapeutic effect is sought, this mechanism is beneficial for localised therapies and wound dressings since it frequently offers a reasonably rapid release profile[20].
4. **Stimuli-responsive release:** It is possible to construct sophisticated functional nanofibers that react to environmental stimuli like light, temperature, pH, and magnetic fields. Acidic or basic environments cause the polymer to dissolve or swell in pH-sensitive systems, releasing the medication. While photo- or magnetically responsive systems allow for on-demand, externally prompted release, thermo-responsive fibres release medications at predetermined temperatures. These intelligent systems hold great promise for intelligent wound dressings and targeted cancer treatment[21].

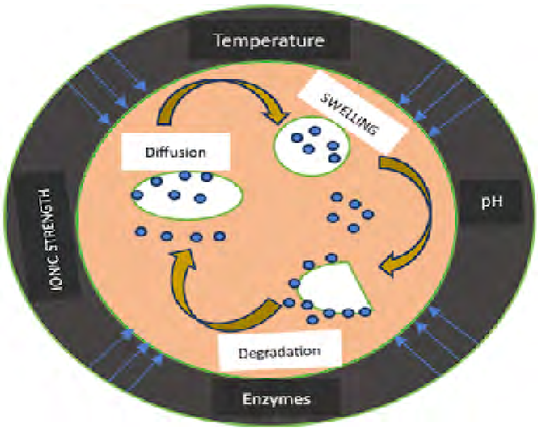

Fig. 4. Drug release mechanism from nanofibers

Table 1: Drug fabrication Techniques for Electrospun Nanofibres

Method	Working Principle	Key Features	Applications	References
Blend Electrospinning	Drug is mixed directly with the polymer solution to form a uniform blend before electrospinning	Simple, scalable; may cause burst release; drug distributed throughout the fibre matrix	Wound healing, local antibiotic delivery, anti-inflammatory drug release	22,23
Co-axial Electrospinning	Two separate solutions (core: drug; shell: polymer) are electrospun through a concentric nozzle, forming core–shell fibres	Protects sensitive drugs; enables sustained/controlled release; reduces burst effect	Protein/peptide delivery, dual-drug systems, tissue regeneration	23,24
Emulsion Electrospinning	Fibres with core-shell structures are created by electrospinning a drug and polymer-containing (W/O) or (O/W) emulsion	Encapsulates hydrophilic drugs in hydrophobic polymers; moderate drug protection	Hydrophilic drug delivery, tissue scaffolding, prolonged release systems	23,25
Surface Immobilization	Drug is loaded onto the surface of pre-formed fibres via physical adsorption or chemical conjugation (post-spinning)	Enables post-spinning functionalization; suitable for fragile drugs or fast local release	Growth factors, enzymes, wound dressing, anti-infective surfaces	26,27

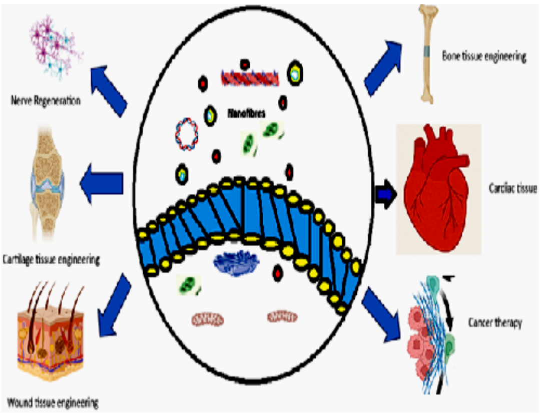

Fig. 5. Structure of Chitosan

Biopolymers in Electrospinning

Biopolymers are either naturally derived or synthetic materials that are biocompatible, biodegradable, and often bioactive.

Natural Biopolymers

Chitosan: Chitosan is widely used in electrospun nanofibres for its antimicrobial, biocompatible, and biodegradable properties. It promotes wound healing, supports cell adhesion, and is ideal for skin and bone tissue engineering. Its pH-responsive nature enables controlled drug release, making it effective in wound dressings, cancer therapy, and regenerative medicine applications[28,29].

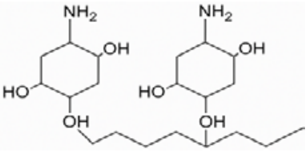

Fig. 5. Structure of Chitosan

Gelatin: Gelatin is commonly used in electrospun nanofibres because of their biocompatibility. Derived from collagen, it supports cell adhesion and proliferation, which is good for wound healing. Its ability to encapsulate drugs or bioactive agents also enables controlled delivery in biomedical applications[30,31].

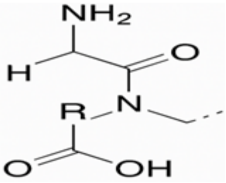

Fig. 6 Structure of Gelatin

Alginate: Alginate is used in electrospun nanofibres for its biocompatibility, gel-forming ability, and moisture retention. Derived from seaweed, it supports wound healing and tissue regeneration. Often blended with other polymers due to poor spinnability alone, alginate-based nanofibres are ideal for wound dressings, drug delivery, and skin and cartilage engineering[32,33].

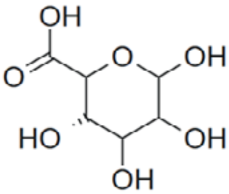

Fig. 7. Structure of Alginate

Silk fibroin: Silk fibroin is used in electrospun nanofibres for its exceptional mechanical strength, biocompatibility, and slow biodegradation. It supports cell attachment and proliferation, which is good for bone, skin, and nerve tissue engineering. Its qualities to incorporate the drugs or other factors enhance its role in regenerative medicine[34,35].

Collagen: Collagen is widely used in electrospun nanofibres for its biocompatibility and for mimicking the extracellular matrix (ECM). It supports the applications especially in skin, bone, and cartilage regeneration. Its natural origin promotes integration with host tissues and accelerates healing[36,37].

Synthetic Biopolymers

Polycaprolactone (PCL): Polycaprolactone (PCL) is another polymer used in electrospun nanofibres because of their mechanical strength as well as slow biodegradability. It supports long-term tissue regeneration and is ideal for bone, vascular, and nerve engineering. PCL nanofibres can encapsulate drugs or biomolecules, enabling controlled release in drug delivery and wound healing applications[38,39].

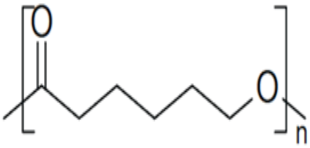

Fig. 8. Structure of Polycaprolactone

Polylactic acid (PLA)–commonly used in electrospun nanofibres for its biodegradability, biocompatibility, and ease of processing. Derived from renewable sources, PLA supports cell growth and is ideal for scaffolds in bone, cartilage, and skin tissue engineering. Its fibres also enable controlled drug release for therapeutic applications[40].

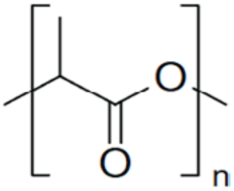

Fig. 9. Structure of Polylactic acid

Poly(lactic-co-glycolic acid)–Another synthetic polymer used in electrospun nanofibres for its tunable biodegradation rate, biocompatibility, and FDA approval. It supports tissue regeneration and enables sustained drug, gene, or protein delivery. PLGA nanofibres are ideal for wound healing, bone repair, and cancer therapy due to their controlled release capabilities[41].

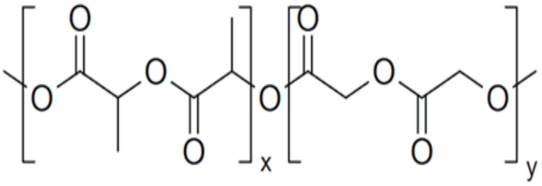

Fig. 10. Structure of Poly(lactic-co-glycolic acid)

Polyvinyl alcohol (PVA) – commonly used in lectrospun nanofibres for its excellent spinnability, biocompatibility, and water solubility. PVA is often blended with natural polymers to enhance mechanical properties and support cell adhesion and proliferation[42,43].

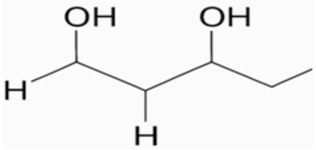

Fig. 11. Structure of Polyvinyl alcohol

Role of tissue engineering in modern therapeutics

Tissue engineering has emerged as a transformative approach in modern medicine, aiming to restore, maintain, or enhance the function of damaged tissues and organs. By integrating principles of biology, materials science, and engineering, tissue engineering creates biomimetic scaffolds which provide attachment of cell[44].

In therapeutic applications, tissue engineering offers promising solutions for chronic diseases, trauma, congenital defects, and age-related degeneration. It addresses limitations associated with conventional treatments, like tissue shortages and dependence on drugs or prosthetics[45].

With the introduction of electrospun nanofibers to tissue engineering, a new generation of biomimetic scaffolds has revolutionized modern therapeutics by closely resembling native extracellular matrix both structurally and functionally. They are perfect for promoting cell adhesion, proliferation, and differentiation because of their distinct nanoscale design, high surface-to-volume ratio, and adjustable porosity[46,47].

In modern therapeutics, electrospun nanofibers are utilized not only as passive structural matrices but also as active biofunctional platforms. By adding bioactive substances to the nanofiber matrix or to their surface, such as growth factors, cytokines, or medications (via techniques like blend, coaxial, or surface-immobilization electrospinning), these scaffolds enable spatiotemporally controlled delivery, enhancing therapeutic outcomes while reducing systemic side effects[48,49].

Applications span a wide range of tissues (Figure 12):

Skin tissue engineering: In skin tissue engineering, electrospun nanofibres are frequently utilised for medication administration, scaffolding, and wound dressings. They assist healing, encourage cell development, and imitate the extracellular matrix. Their high porosity and biocompatibility enable controlled release of bioactives, making them ideal for treating burns, ulcers, and chronic skin wounds[50,51].

Bone tissue engineering: Electrospun nanofibres in bone tissue engineering provide a scaffold that mimics bone ECM, supporting osteoblast adhesion and proliferation. They can be reinforced with bioactive ceramics like hydroxyapatite and deliver growth factors such as BMP-2, promoting osteogenesis. Their porous structure aids vascularization, crucial for effective bone regeneration and healing[52,53].

Cartilage tissue engineering: Electrospun nanofibres aid by mimicking the zonal structure of native cartilage and supporting chondrocyte attachment and growth. Their tunable mechanical properties and porosity enable nutrient diffusion and matrix deposition. Functionalization with bioactive molecules enhances chondrogenesis, making them ideal scaffolds for repairing articular cartilage defects and injuries[54].

Nerve regeneration: Electrospun nanofibres support nerve regeneration by mimicking the extracellular matrix, guiding axonal growth with aligned fibres, and enhancing neuron adhesion. They can deliver neurotrophic factors like NGF and BDNF for sustained support. Their biocompatibility and customizable architecture make them ideal for repairing peripheral nerves and spinal cord injuries[55].

Cardiac tissue engineering: Electrospun nanofibers enhance cardiomyocyte alignment, adhesion, and contraction by providing scaffolds that resemble the heart's extracellular matrix. Conductive fibres enhance electrical signal transmission. They also enable delivery of growth factors and drugs, promoting vascularization and repair, making them ideal for myocardial patches and post-infarction cardiac regeneration[56,57].

Cancer Therapy: In cancer treatment, electrospun nanofibres provide targeted, long-term medication delivery to tumour locations while reducing systemic toxicity. Their high surface area enhances drug loading, while targeting ligands enable site-specific action, making them effective platforms for post-surgical cancer treatment and recurrence prevention[58,59].

Table 2: Applications of Nanofibres in drug delivery

Type of Drug Delivery	Purpose	Target/Application Area	References
Topical drug delivery	Localized treatment, enhanced absorption	Wound healing, burns, skin infections	60,61
Transdermal delivery	Sustained drug release through skin	Pain relief, hormone therapy, anti-inflammatory drugs	62
Oral drug delivery	Controlled gastrointestinal release	Antibiotics, anticancer drugs	63
Implantable drug delivery systems	Long-term sustained release at target site	Cancer therapy, orthopedic implants	64
Inhalable nanofibres	Targeted pulmonary delivery	Respiratory diseases (e.g., tuberculosis, asthma)	65
Ocular drug delivery	Localized delivery to the eye	Glaucoma, infections, dry eye treatment	66
Vaginal/rectal delivery	Mucosal adhesion and localized therapy	Antiviral, HIV infections, contraceptive delivery	67
Cancer-targeted delivery	Site-specific drug release, reduced toxicity	Breast, skin, and colon cancer	68
Gene and protein delivery	Tissue regeneration, gene therapy	Bone repair, nerve regeneration, stem cell therapy	69
Antibiotic delivery	Prevent or treat infection	Post-surgical sites, bone infections, chronic wounds	70

Recent Advances and Innovations

Nanofibre functionalization

Involves modifying the surface or composition of electrospun fibres to enhance their biological, chemical, or physical properties. This process can include chemical grafting, plasma treatment, or coating agents, or antibiotics[71]. Functionalization improves cell adhesion, targeted drug delivery, and antimicrobial activity, making nanofibres more effective for biomedical applications. For example, ligand-functionalized fibres can direct drug release to specific cells or tissues, while surface-immobilized proteins can promote tissue regeneration. Such modifications tailor nanofibres for advanced roles in tissue engineering, wound healing, and localized therapeutics with enhanced performance and biocompatibility[72].

Smart Nanofibers: Advanced electrospun fibres known as "smart nanofibers" are designed to react to external stimuli like pH, temperature, or enzymes. These stimuli-responsive fibres are perfect for targeted therapy because they allow for controlled and on-demand medication release73. Smart nanofibers can also exhibit properties like self-healing, shape memory, or environmental sensing, increased their utility in wound healing, and precision medicine. By integrating functional polymers and bioactive agents, they offer dynamic and adaptable platforms for next-generation biomedical applications[74].

Gene and Protein Delivery: Electrospun nanofibres offer a versatile platform for gene and protein delivery, enabling sustained and localized release of sensitive biomolecules. Because of their large surface area and adjustable shape, they can effectively encapsulate and shield proteins, RNA, or DNA from deterioration[75]. Techniques like coaxial electrospinning or surface immobilization ensure bioactivity retention and controlled release. These nanofibres support cell transfection, tissue regeneration, and therapeutic protein delivery, making them valuable in gene therapy, cancer treatment, and regenerative medicine applications76.

Green Electrospinning: Green electrospinning focuses on environmentally friendly practices by using non-toxic, biodegradable polymers and eco-friendly solvents like water or ethanol. It aims to reduce environmental impact while ensuring biocompatibility for biomedical applications. This sustainable approach supports safer fabrication of nanofibres for drug delivery, tissue engineering, and wound healing[77,78].

3D Electrospun Structures: 3D electrospun structures are engineered scaffolds with enhanced thickness, porosity, and mimicking extracellular matrix more effectively than 2D fibres[79]. Achieved through modified collectors or layered deposition, they support improved cell infiltration, vascularizationfor advanced tissue engineering applications[80].

CONCLUSION

A flexible and effective method for creating nanofibrous scaffolds for a range of biological purposes is electrospinning. Electrospun nanofibers represent one of the most promising classes of biomaterials at the interface of nanotechnology, polymer science, and biomedical engineering. Over the past two decades, they have transitioned from a laboratory curiosity to a mainstream research focus due to their ability to mimic the natural extracellular matrix (ECM), provide controlled release of bioactive agents, and act as multifunctional scaffolds in tissue engineering, wound healing, drug delivery, and biosensing. The fabrication versatility of electrospinning-ranging from conventional solution and melt techniques to advanced coaxial, emulsion, and triaxial approaches-has enabled the design of highly tunable nanofibers with tailored morphology, porosity, and surface chemistry. By judicious selection of polymers, additives, and fabrication parameters, researchers have been able to achieve scaffolds that meet specific mechanical, biological, and therapeutic requirements.

The functional insights derived from these nanofibers highlight their ability to act as more than just structural scaffolds. They can be functionalized with drugs, proteins, growth factors, nanoparticles, or signaling molecules, thereby extending their role into therapeutic delivery and biosensing.The range of nanofibre applications in tissue engineering, wound healing, drug administration, and regenerative medicine has increased due to recent developments such as stimuli-responsive smart fibres, 3D electrospun architectures, and green electrospinning techniques. Despite remarkable progress, challenges remain in terms of scalability, regulatory approval, and clinical translation.

Future research should focus on integrating advanced materials, improving biological performance, and exploring personalized nanofibre-based therapies. With ongoing innovation, electrospun nanofibres hold immense promise as next-generation biomaterials for improving patient outcomes in modern medicine.

Abbreviations

EN: Electrospun nanofibers
PCL: Polycaprolactone
PLA: Polylactic acid
PLGA: Poly(lactic-co-glycolic acid)
PGA: Polyglycolic acid
PVA: Polyvinyl alcohol
ECM: Extracellular matrix
TE: Tissue engineering
RNA: Ribonucleic acid
DNA: Deoxyribonucleic acid

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Conflict of interests

The authors declare that they have no conflict of interests.

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