# Nanofibers: Emerging Fabrication Technologies and Application Frontiers

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***Abstract*—Nanotechnology has swiftly progressed as a prominent domain, with nanofibers arising as ultra-fine filaments distinguished by nanoscale dimensions and distinctive structural configurations, including core shell, hollow, and porous varieties. These nanofibers demonstrate exceptional qualities, such as increased mechanical strength, electrical conductivity, thermal stability, optical characteristics, and magnetic responsiveness, rendering them very adaptable for biomedical and industrial uses. Diverse manufacturing methods, including as electrospinning, self-assembly, phase separation, and template synthesis, are extensively utilised to generate nanofibers with regulated morphology and functionality. Their characterisation employs advanced analytical techniques including X-ray diffraction (XRD), light spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), differential scanning calorimetry (DSC), as well as assessments of thickness and tensile strength. In the pharmaceutical sector, nanofibers have garnered significant interest as sophisticated drug delivery systems owing to their capacity to properly encapsulate medicines, reduce burst release, and facilitate prolonged and regulated drug release over longer durations. They have exhibited effective uses in wound dressing, cancer treatment, gene and growth factor administration, and tissue engineering for the regeneration of bone, cartilage, tendons, dental, cardiovascular, neural, and skin tissues. This overview emphasises the fabrication techniques and several biomedical applications of nanofibers.**

***Index Terms*—Nanofibers, Electrospinning, Pharmaceutical delivery, Sustained release, Tissue engineering, Characterisation, Nanotechnology, Biomedical applications**

## I. INTRODUCTION

The rapid development of nanoscale materials has garnered significant scientific attention, especially with the proliferation of Nanotechnology research in the late 20th century. In the International System of Units, the prefix nano signifies one billionth of a meter ($10^{-9}$ m), emphasising the minuscule scale at which these materials are found. To comprehend this dimension more well, a sheet of paper is roughly 100,000 nanometres in thickness, whereas a DNA strand has a diameter of approximately 2.5 nanometres. Nanoscale structures are not solely synthetic; they are prevalent in nature. For instance, haemoglobin, the oxygen-transporting protein in red blood cells, is approximately 5.5 nanometres in diameter. These examples underscore that nanoscale phenomena are essential to both biological systems and manmade materials [1].

Nanomaterials display a diverse array of forms and sizes, encompassing nanoparticles, nanotubes, nanowires, nanofilms, nanoflakes, nanofibers, and nano shells. This structural diversity enhances their remarkable versatility and functionality across various applications. Nanofibers are notably important and can be defined as ultra-fine filaments or thread-like structures with diameters in the nanometre scale. Their unusual form yields unique physicochemical features, including a high surface area-to-volume ratio, increased porosity, and adjustable mechanical strength. These attributes render nanofibers exceptionally appropriate for sophisticated applications in domains such as filtration, biomedical engineering, and energy systems. The capacity to customise their composition and structure further amplifies their utility in specialised domains [2].

Numerous manufacturing processes have been established to produce nanofibers, including phase separation, self-assembly, template synthesis, and notably, electrospinning. Electrospinning is favoured for its simplicity, cost-efficiency, and capacity to generate continuous fibres with regulated diameter and morphology. The resultant nanofibers exhibit critical

characteristics, including diminutive pore size, extensive surface area, and effective functionalisation potential, which greatly enhance their wide-ranging applicability. These attributes facilitate their application in medication delivery systems, wound healing, tissue engineering, and environmental remediation. As research progresses, nanofibers remain integral in connecting material science and biological innovation, providing potential solutions for next-generation technology[3].

## II. CLASSIFICATION OF NANOFIBERS

a. Based on size

Nanofibers can be categorised according to their dimensions in Fig.1 which are often assessed using several analytical tools that evaluate diameter, length, or both. Diameter-based classification frequently depends on the aerodynamic characteristics of nanofibers, as reduced diameters demonstrate unique motion and interaction with adjacent media. Conversely, length-based classification is assessed using characteristics like screen penetration, gravity settling, and notably, electrostatic classification techniques. These methodologies facilitate the comprehension of the dispersion, alignment, and application-specific efficacy of nanofibers, particularly in filtration and medicinal systems where dimensions are paramount[4].

b. Based on Morphology and Construction

1 Core Shell Nanofibers

Core shell nanofibers comprise two discrete layers an inner core and an outer shell in Fig1, which may be constructed from different materials. This structure facilitates functional segregation, enabling the core to enclose active substances (such as pharmaceuticals or biomolecules) while the shell offers protection and regulated release. Numerous fabrication approaches have been investigated, such as template synthesis and surface-initiated polymerisation; still, Coaxial Electrospinning is regarded as the most effective and adaptable method. These nanofibers are extensively utilised in drug delivery systems owing to their capacity to diminish burst release and attain prolonged therapeutic benefits[5].

2 Hollow Nanofibers

Hollow nanofibers possess an empty core, resembling tubular or nanotube formations in Fig1. This void can be employed to incorporate medications, catalysts, or other functional elements, rendering them exceptionally important in biomedical and industrial purposes. These nanofibers are generally produced via methods such as Chemical Vapour Deposition (CVD) and coaxial electrospinning. Their distinctive architecture improves attributes such as surface area, permeability, and load-bearing capability, which are advantageous for targeted drug administration and sophisticated filtration systems[6].

3 Porous Nanofibers

Porous nanofibers possess interconnected pores throughout their structure, resulting in an extraordinarily large surface area and improved capacity for absorption and interaction with adjacent substances in Fig1. This renders them especially appropriate for applications in filtration, membrane technology, tissue engineering, and regulated medication delivery. The creation of porous structures is predominantly accomplished via Phase Separation, which can be triggered by several methods including vapor-initiated, nonsolvent-driven, thermally induced, or rapid phase separation. The meticulous choice of polymers and solvent solutions is essential for customising pore size, distribution, and the overall functionality of nanofibers[7].

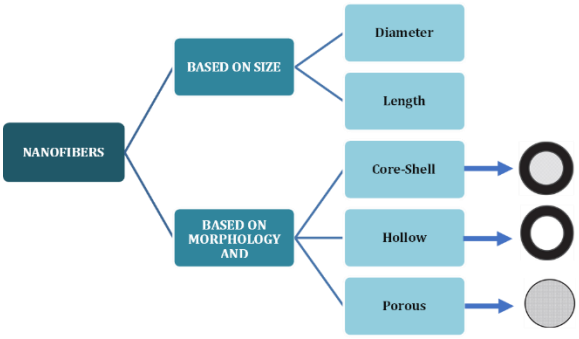


Figure 1. Classification of Nanofibers

## III. ADVANTAGE OF NANOFIBER

1. Nanofibers exhibit an extraordinarily high surface area-to-volume ratio, rendering them very efficient for applications like sensors. Their elevated porosity further improves liquid and gas permeability, which is especially advantageous in industrial applications like as filtering systems.
2. They provide significant diversity in material selection, allowing for the incorporation of a

diverse array of substances throughout manufacture. Although polymer-based nanofibers are predominantly utilised, ceramic and metal nanofibers offer considerable functional benefits in specialised applications.

3. Nanofibers can be fabricated into many structural configurations. Altering parameters in techniques such as Electrospinning can yield many morphologies, including tubular structures, coatings, and three-dimensional networks.
4. They may be readily deposited onto diverse substrates, including metals, glass, and even liquid surfaces, hence expanding their use across numerous domains.
5. Nanofibers facilitate scalable manufacturing methods and are appropriate for integrating heat-sensitive substances, rendering them exceptionally beneficial in pharmaceutical and biological fields[8].

## IV. LIMITATIONS OF NANOFIBERS

1. Challenges in Recycling and Disposal:

Nanofibers are novel materials, and standardised protocols for their recycling and disposal are currently being formulated. Furthermore, data on long-term exposure is scarce, leaving the possible toxicity and environmental effects as subjects of continued investigation.

2. Elevated Production Expenses:

In comparison to traditional fibres, the production of nanofibers is costly due to the necessity for advanced technology, specialised apparatus, and comparatively lower output rates, which may hinder widespread commercial implementation.

3. Ecological and Health Issues:

During fabrication techniques like electrospinning, solvent vapours may be emitted, necessitating appropriate management and ecologically safe disposal methods. Moreover, inhaling fine fibres or vapours may provide health hazards, requiring stringent safety protocols and protective gear.

4. Management and Processing Challenges:

The intricate structure and lightweight characteristics of nanofibers render them difficult to manipulate, package, and transport. Their fragile structure may result in aggregation or destruction, hindering industrial processing and storage.

Notwithstanding these constraints, continuous research and technological progress aim to surmount these obstacles to provide more economical, secure, and scalable applications of nanofibers[9].

## V. PROPERTIES OF NANOFIBERS

a. Mechanical Characteristics

Nanofibers demonstrate distinctive mechanical properties owing to their ultra-fine diameter (often 20–100 nm), extensive surface area (ranging from tens to hundreds of $m^2/g$), elevated porosity, and diminutive pore size, rendering them appropriate for applications including tissue engineering, drug delivery, and composite reinforcement. Nonetheless, numerous applications require enhanced mechanical strength. The mechanical performance is typically assessed through tensile strength and Young's modulus, with nanofibers generally exhibiting tensile strength below approximately 300 MPa and Young's modulus under approximately 3 GPa. The diminished strength is mostly due to inadequate alignment and restricted extension of polymer chains along the fibre axis, resulting in ineffective stress transfer and insufficient intermolecular overlap[10]. Supplementary metrics, including hardness (resistance to surface deformation) and elastic modulus (stiffness of the polymer network), are also significant. Nanofibers exhibit greater hardness owing to the heightened nucleation of crystalline areas, facilitated by their extensive surface area which offers various nucleation sites. Advanced strategies such as polymer chain alignment, post-drawing, crosslinking, and incorporation of reinforcing fillers (e.g., carbon nanofibers or graphene) can significantly improve mechanical properties. Recent investigations indicate that aligned electrospun nanofibers can attain tensile strengths more than 500 MPa and modulus values above 5-10 GPa. Future research increasingly emphasises single-fiber characterisation (e.g., nanoindentation, AFM-based tensile testing) over bulk mats to enhance understanding of intrinsic mechanical behaviour[11].

b. Electrical properties

Nanofibers exhibit favourable electrical characteristics, especially when integrated with conductive fillers or electroactive polymers. When integrated into a polymer matrix, nanofibers can establish percolation networks, facilitating efficient

charge transport and markedly enhancing electrical conductivity. Conductivity levels may vary from insulating (~$10^{-12}$ S/cm) to highly conductive (~$10^{2}$–$10^{3}$ S/cm) according on composition and filler content. Conductive nanofibers are extensively utilised in applications including pressure sensors, actuators, electromagnetic interference (EMI) shielding, and flexible electronics. Their elevated surface area and anisotropic architecture confer advantages over alternative nanostructures by enhancing electron transport routes. Moreover, nanofibers demonstrate sophisticated electrical properties, including electrochromic (colour alteration under voltage) and electroluminescence, facilitating their use in displays, memory devices, and energy storage systems such as rechargeable batteries and supercapacitors. The integration of materials like carbon nanotubes, graphene, or metal nanoparticles significantly improves conductivity and functional efficacy[12].

c. Optical properties

At the nanoscale, materials display modified optical properties as a result of quantum confinement and surface phenomena. Nanofibers can be designed with precise surface roughness and internal architectures to influence light–matter interactions. This facilitates applications in optical sensors, photodetectors, imaging systems, and solar cells. Generally, nanofibers have a diminished refractive index relative to bulk materials owing to enhanced porosity and air trapping. They may also demonstrate characteristics including light scattering, photoluminescence, and waveguiding. Advanced nanofiber systems infused with fluorescent dyes or quantum dots have adjustable emission characteristics, rendering them valuable for bioimaging and optoelectronic applications[13].

d. Magnetic properties

Nanofibers exhibit distinctive magnetic characteristics when constructed from magnetic materials or infused with magnetic nanoparticles. At the nanoscale, diminutive size and structural alterations can elicit magnetism in materials that are non-magnetic in their bulk state, such as platinum (Pt) and palladium (Pd). Furthermore, surface phenomena such as charge localisation can elicit magnetic properties in materials like gold nanoparticles when appropriately functionalised. Magnetic nanofibers have substantial biological uses, encompassing targeted drug administration (utilising external magnetic fields), increase of magnetic resonance imaging (MRI) contrast, and magnetic hyperthermia for oncological treatment. These applications depend on characteristics like superparamagnetism, wherein particles display magnetism solely in the presence of an external field, hence reducing aggregation hazards[14].

e. Thermal properties

Thermal conductivity in nanofibers is determined by electron transport in metals, phonon transport in non-metals, and interfacial phenomena. In contrast to bulk materials, nanofibers demonstrate reduced thermal conductivity owing to enhanced phonon dispersion and interfacial thermal resistance. This resistance stems from inadequate adhesion or a discrepancy in thermal expansion between the nanofiber and the adjacent matrix. Standard thermal conductivity values for polymeric nanofibers vary from 0.1 to 0.5 W/m·K, which is inferior to those of microfibre equivalents. The use of thermally conductive fillers like graphene or boron nitride can markedly improve heat transfer capabilities. Nanofibers are consequently advantageous in thermal insulation, heat management systems, and protective coatings[15].

f. Surface properties

Surface properties are essential in influencing the efficacy of nanofibers, especially in biomedical and filtration applications. Elevated porosity, substantial surface-to-volume ratio, and regulated pore size distribution improve characteristics such as wettability, adsorption, and drug-loading capacity. The porosity of nanofiber mats can vary from 60% to more than 90%, contingent upon production conditions. Surface wettability is often assessed using contact angle measurements; hydrophilic nanofibers have contact angles below 90°, whereas hydrophobic nanofibers above 90°. Surface modification procedures, such plasma treatment, chemical functionalisation, or the application of bioactive coatings, can customise wettability and biocompatibility. Furthermore, nanoscale surface roughness improves cell adhesion, protein adsorption, and drug interaction, rendering nanofibers exceptionally appropriate for tissue engineering and controlled drug delivery systems[16].

## VI. PRODUCTION TECHNIQUES OF NANOFIBERS

a. Electrospinning

Traditional electrospinning necessitates three fundamental components a high-voltage power supply, a syringe pump with a nozzle, and a grounded collector in Fig2. The nozzle is generally a metallic needle with a truncated tip, which aids in the accurate development and observation of the Taylor cone during the procedure. A polymer solution, often formulated with a volatile solvent at a suitable weight-to-volume ratio, is introduced into a syringe and affixed to a syringe pump for regulated flow.

Upon the application of a high voltage to the needle tip, electrostatic forces influence the droplet of polymer solution, resulting in its elongation into a conical configuration referred to as the Taylor cone. When the applied electrostatic force exceeds the droplet's surface tension, a fine, charged jet is expelled from the cone's tip. The jet experiences swift elongation and reduction in thickness as it moves toward the stationary collector, during which the solvent rapidly evaporates. Consequently, cemented nanofibers are deposited onto the collector, creating a continuous fibrous mat[17].

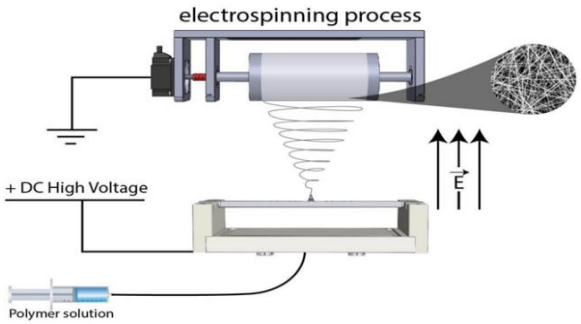


Figure 2. Electrospinning Process with roller collector

1. Merits of Electrospinning

As mentioned earlier, electrospinning is a favourable technique because of several reasons:

- Being a practical and economical approach;
- The setup that isn't time-consuming nor expensive;
- The ability to control many variables such as diameter, length, orientation, and composition to give the desired properties that correspond to the intended use and route of administration[18].

2 Limitations and drawbacks

- Use of organic solvents;
- Broad-spectrum of thickness;
- Casual and irregular orientation;
- Poor mechanical properties;
- Limited control of pore structure[19].

3 Influential Factors

There are a variety of parameters that can be manipulated to obtain a final product possessing certain properties. They can be categorized into two groups: Systemic (solution) parameters and processing parameters as shown in Fig 3[20].

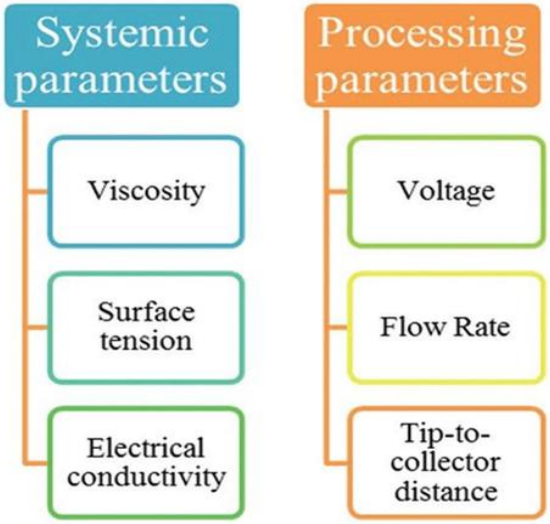


Figure 3. Factors affecting Electrospinning

3.1 Systemic Parameters

They are precisely determined by the polymer's molecular weight and concentration, solvents and additives incorporated. Each parameter has its impact.

1. Viscosity: In systems with low viscosity, the likelihood of electro spraying surpasses that of electrospinning. Conversely, if the viscosity is excessively high, jet ejection becomes challenging.
2. Surface tension: Elevated surface tension exacerbates bending instability, resulting in the formation of rounded or beaded fibres.
3. Conductivity: This property can be modified with the incorporation of ionic salts. High conductivity systems yield finer fibres (reduced diameters). Nonetheless, excessively high conductivity leads to the formation of rounded or beaded fibres, accompanied by an uneven diameter distribution[21].

3.2 Processing Parameters

1. Voltage: At low voltage, surface tension forces dominate, preventing the formation of Taylor's cone; however, excessively high voltages result in the production of round or beaded fibres.
2. Flow rate: It directly influences the diameter of the fibres. A rise in flow rate is thereafter accompanied by an increase in diameter. Nevertheless, it must be meticulously monitored, since an excessively elevated flow rate results in the accumulation of beaded formations on the fibre. This transpires in relation to a brief evaporation duration.
3. The distance from the tip to the collector must be ideal. If the collector is positioned at a short distance, there will be insufficient space for elongation or adequate time for solvent evaporation. Simultaneously, extensive distances render surface tension forces predominant over electric field forces[22].

b. Self-Assembly

Self-assembly is a naturally occurring process wherein diverse biological components, such as nucleic acids and proteins, are organised into a certain configuration in Fig4. This inspired numerous methodologies to use this principle in the synthesis of nanofibers.

This approach relies on the spontaneous arrangement of noncovalently linked molecules via weak intermolecular interactions. Self-assembly, as a bottom-up fabrication technique, relies on the aggregation of small parts[23].

1 Prominent feature of self-assembly

- Smaller diameter nanofibers in comparison to electro spun nanofibers (5–8 nm).
- Short nanofibers can be produced by this technique (1 to several μm)
- Suitable for injection purposes in tissue repair due to similarity within

In Vivo peptides However, this similarity gives rise to some sort of competition with physiological amphiphiles which complicates application[24].

2 Drawbacks and limitations:

- Only a few limited polymers can be involved.
- Poor mechanical strength.
- Undefined pore structure[25].

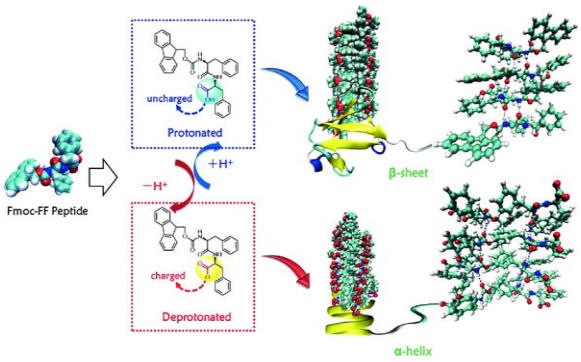


Figure 4. Self-Assembly Process to produce nanofibers

c. Phase Separation

Phase separation occurs when a homogeneous polymer solution is subjected to an appropriate solvent environment, resulting in thermodynamic instability and subsequent division into polymer-rich and solvent-rich phases. The polymer is initially fully dissolved to create a homogeneous single-phase solution in Fig5. This is succeeded by liquid–liquid phase separation, usually initiated by quenching the system, which prompts the emergence of two separate phases. The subsequent essential phase is gelation, which significantly influences the ultimate morphology and porosity of the scaffold. Reduced gelation temperatures facilitate the development of a nanofibrous network structure, while elevated temperatures encourage crystal growth, leading to platelet-like morphologies. Subsequent to gelation, the solvent is withdrawn and eliminated, after which the material undergoes freezing and is subsequently freeze-dried under vacuum conditions to achieve a porous nanofibrous structure[26].

This technology has numerous unique benefits relative to alternative fabrication methods. This process facilitates the generation of nanofibers with diameters generally between 50 and 500 nm and exceptionally high porosity levels (about 98–98.5%), which are challenging to get by techniques such as electrospinning or self-assembly. Furthermore, it facilitates the development of interior macroporous structures and intricate scaffold geometries, rendering it very appropriates for tissue engineering applications. A important characteristic is that augmenting polymer concentration does not markedly influence fibre diameter but rather enhances tensile strength and overall mechanical qualities. Moreover, the procedure is comparatively straightforward and

does not necessitate advanced apparatus, hence augmenting its usefulness and cost-efficiency[27].

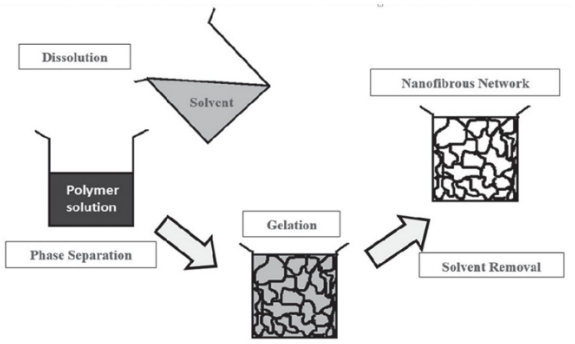


Figure. 5. Process of Nnaofiber formation with the help of phase separation

d. Template Synthesis

Template Synthesis entails the production of nanofibers utilising a predetermined template or mould, generally composed of ceramic substances or specifically engineered polymeric membranes in Fig6. These templates feature consistently dispersed pores of designated sizes that serve as templates for the formation of nanofibers. In the technique, a polymer solution or precursor material is extruded via nanoscale perforations typically utilising applied pressure, such as water or external force leading to the creation of fibres that mirror the shape and dimensions of the template pores [28].

This method is typically utilised for small-scale manufacturing, as it facilitates accurate regulation of fibre diameter and morphology. Nonetheless, its use is constrained by considerations like the intricacy of template preparation, challenges in template removal, and reduced scalability relative to alternative techniques such as electrospinning [29].

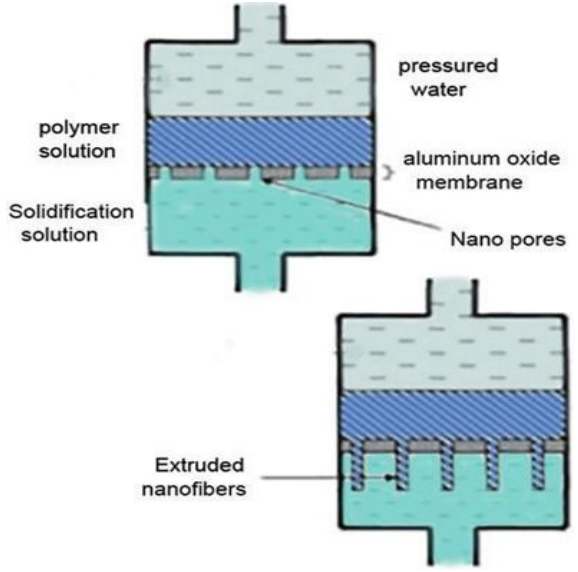


Figure.6. Template synthesis process

In Template Synthesis, nanofibers are produced by extruding a polymer solution through the nanoscale pores of a nanoporous membrane or template. As the polymer traverses these pores, it encounters a coagulating or hardening liquid, resulting in the creation of nanofibers that emulate the shape and dimensions specified by the template structure. Nonetheless, a significant constraint of this approach is the absence of fibre continuity, as it generally yields short fibres with lengths restricted to a few micrometres. The diameter of the nanofibers is directly influenced by the pore size of the template; however, a variety of fibre diameters can be obtained by employing templates with differing pore dimensions [29].

e. Interfacial Polymerization

Interfacial Polymerisation is a manufacturing technique that relies on the interaction between two distinct monomers, each soluble in separate, immiscible phases, commonly aqueous and organic in Fig7. The monomers engage in a polycondensation reaction upon contact with the two phases, resulting in polymer formation specifically at the interface of the emulsion droplets. This localised reaction zone facilitates the regulated growth of nanostructures, such as nanofibers.

A pivotal element influencing this process is homogenous nucleated development, which guarantees consistent fibre creation at the interface. By

keeping the monomers in separate phases, the reaction is restricted, facilitating enhanced control over morphology and structure. This approach provides versatility in material design, enabling the synthesis of diverse polymers through the selection of suitable monomer combinations. The ultimate qualities and quality of the nanofibers are significantly affected by aspects like monomer content, reactivity, the characteristics of functional groups, and interface stability. Effective regulation of these parameters is crucial for attaining uniform and high-quality nanofibers [30].

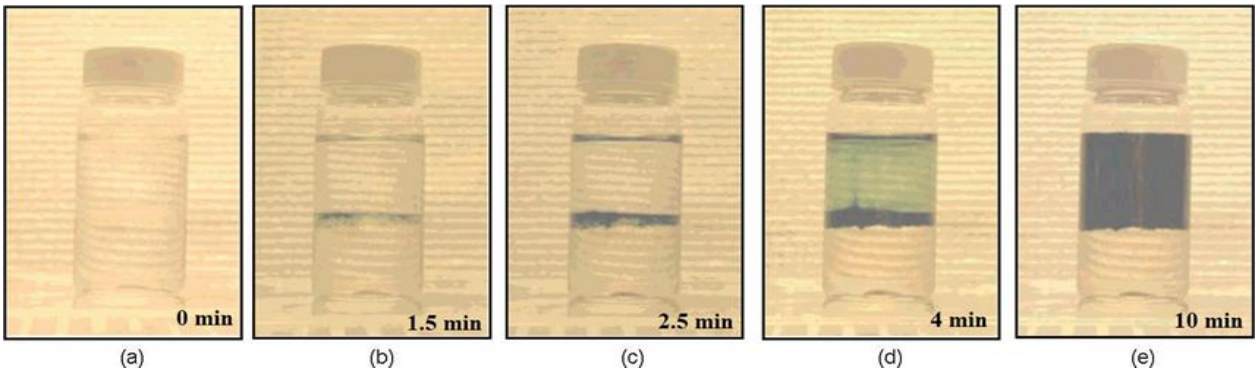


Figure.7. Snapshots showing interfacial polymerization of aniline in a water/chloroform system. From a to e the reaction times are 0, 1.5, 2.5, 4, and 10 min, respectively

## VII CHARACTERIZATION AND EVALUATION OF NANOFIBERS

a. Scanning Electron Microscopy

Microscopic imaging techniques are commonly employed to examine fibre diameters, alignment, porous structures, fibre morphology, and orientation in Fig8. Scanning electron microscopy (SEM) enables the acquisition of high-resolution pictures of scaffold surfaces, facilitating the assessment of surface attributes like as roughness, porosity, and smoothness. To acquire a high-resolution image from scaffolds, samples must exhibit conductivity; thus, sputtering a thin layer of a conductive metal, such as gold or titanium, is a prevalent alteration for nonconductive samples. Scanning Electron Microscopy (SEM) is the predominant characterization technique because to its accessibility and user-friendliness. Porosity, pore width, and pore length on the surface can be quantified, aiding in the comprehension of nanofiber structure [31].

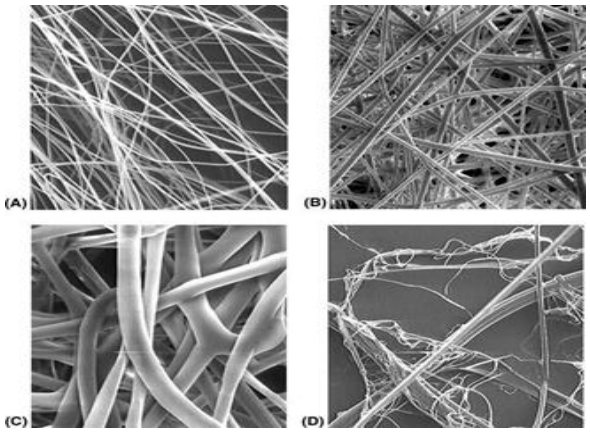


Figure .8. Sample SEMs of various types of GRAS polymer nanofibers produced by electrospinning. (A) Cellulose acetate, (B) PVAc, (C) polyethylene oxide, and (D) Kollidon SR

b. Transmission Electron Microscopy (TEM)

The transmission electron microscope (TEM) is regarded as a fundamental characterization tool due to its capacity to assess the internal structure of samples in Fig9. The pore architecture of the scaffolds is observable in the photos captured by TEM. Like SEM imaging, TEM also produces two-dimensional (2D) images of nanofibers and holes [32].

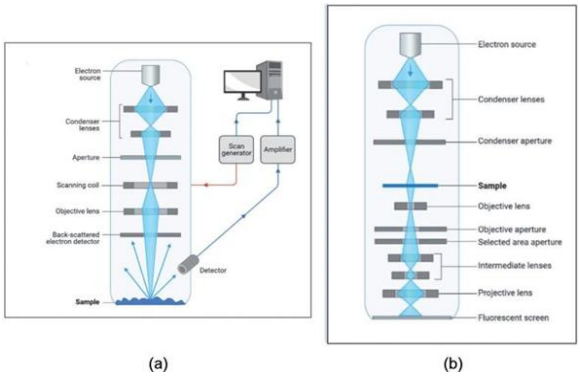


Figure 9. (a) Schematic image of the scanning electron microscope, and (b) schematic image of the transmission electron microscope

c. Atomic Force Microscopy (Afm)

The atomic force microscopy (AFM) technique is mostly used for the evaluation of surface topography in Fig10. The analytical capabilities of AFM are limited to the uppermost atomic layer of a sample because its operation is based on the interactions with the electron clouds of atoms at the surface. This technique also gives information about morphology, surface roughness, fiber orientation, and particle/grain distribution from the surface of the samples[33].

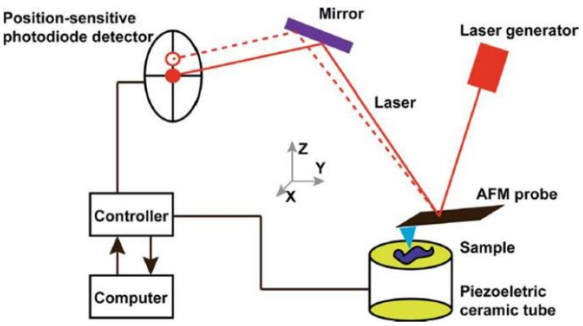


Figure .10. Atomic Force Microscopy setup

d. X-Ray diffraction (xrd)

It is a non-destructive characterisation technique applicable to a diverse array of materials, including minerals, metals, semiconductors, ceramics, and polymers in Fig11. This approach is mostly utilised to assess the structural characteristics of samples, including phase formation, crystallite size, lattice strain, phase composition, and crystal structure. The wavelength of X-rays (0.5–50 Å) approximates the interatomic distances in solids, making them optimal for investigating atomic arrangements within crystal structures [34].

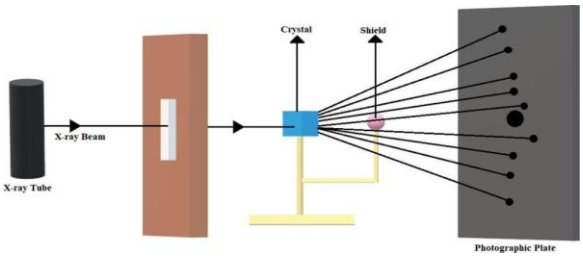


Figure .11. Working principle of X-ray diffraction

e. Thermogravimetric Analysis (TGA)

Thermal methods can be examined under two categories:

(a) Differential thermal analysis and

(b) Thermogravimetric analysis (TGA)

The differential analysis relies on variations in heat content, quantified as a function of rising temperature in Fig12. Conversely, thermogravimetric analysis relies on weight variations recorded as a function of ascending temperature. The TGA technique employs uniform heating to disintegrate all organic materials at elevated temperatures, ultimately providing insights into the sample's composition. The mass reduction of the sample is documented primarily by elevating the temperature at a steady rate. A mass versus temperature or time plot is generated to assess alterations in the physical and chemical properties of the sample. The acquired data elucidate the thermal stability of the residual sample, dehydration, pyrolysis, solid/gas interactions, and other related phenomena[35].

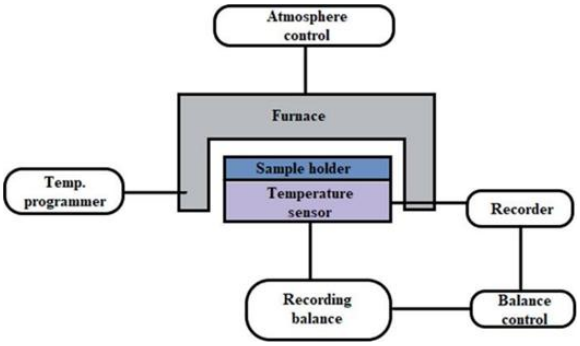


Figure .12. Thermogravimetric analysis diagram

f. X-ray photoelectron spectroscopy (XPS)

It is an efficient characterization technique, as it offers chemical information on the surface of materials, including both elemental and molecular composition in Fig13. It may also differentiate the chemical states of the same element to determine their depth distribution within a thickness range of 5 to 10 nm [36].

g. Fourier's transform infrared spectroscopy (FTIR)
Fourier transform infrared spectroscopy (FTIR) is a method employed to get the infrared spectrum of emission or absorption from solids, liquids, or gases. This technique identifies organic, inorganic, and polymeric compounds by employing infrared light to analyse samples. The standard FTIR configuration consists of a source, sample cell, detector, amplifier, A/D converter, and computer [37].

h. Raman spectroscopy (RS)
This technique is employed to assess vibrational and rotational frequency modes in physical and chemical systems. The magnitude of Raman scattering is contingent upon the variation in polarizability. RS is appropriate for the qualitative and quantitative assessment of organic, inorganic, and biological systems. The acquired spectrum enables the identification of unknown materials, differentiation of materials, assessment of crystallinity, and quantification of material amounts [38].

i. Tensile testing of nanofiber scaffolds
The predominant characterization method for nanofibrous scaffolds is tensile testing or nano-tensile testing. The theory involves securing the scaffold to the grips of the tensile testing in Fig 13 equipment on both sides and thereafter applying a continual pulling force until rupture ensues. The results provide data regarding the stress-strain values, modulus, and strength of the scaffolds [39].

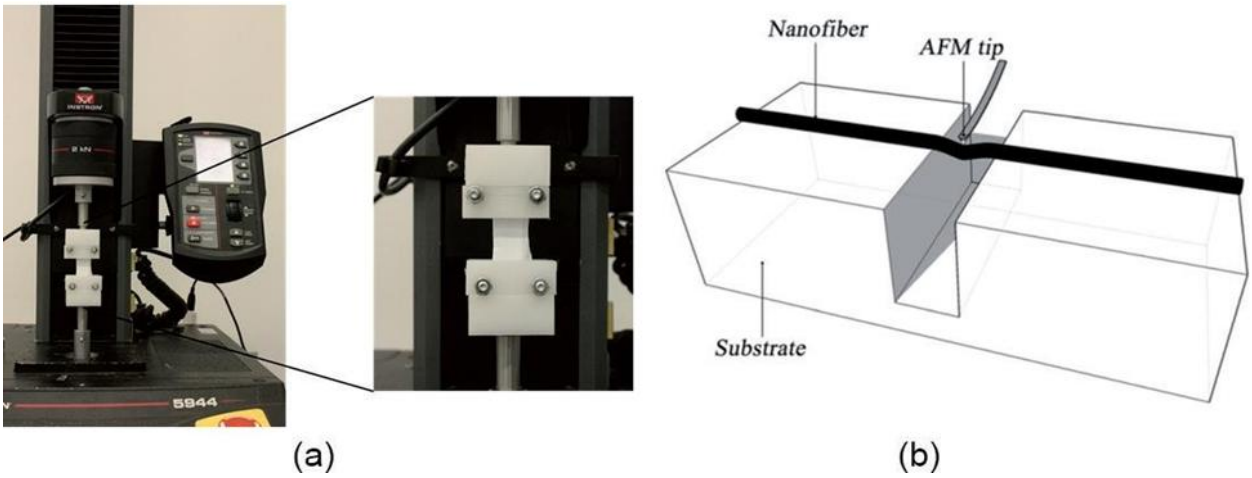


Figure 13. (a) Tensile testing of nanofiber scaffolds, and (b) Nanoscale bending test schematic

## VIII APPLICATION OF NANOFIBERS IN NANOMEDICINE

Nanofibers significantly influence Nanomedicine in Table 1 owing to their nanoscale dimensions, extensive surface area, and adjustable characteristics. Their capacity to facilitate regulated medication delivery, replicate the extracellular matrix in tissue engineering, and improve cosmetic formulations renders them exceptionally significant in biomedical and therapeutic applications [40].

Table 1Applications of Nanofibers in Nanomedicine

| Section | Subcategory | Key Concept / Description | Techniques / Examples | Advantages / Outcomes | Reference |
|---|---|---|---|---|---|
| Drug Delivery | | Nanofibers act as carriers for localized and controlled drug delivery | Electrospun fibers, scaffolds | Sustained release, reduced burst effect, targeted therapy | [41] |
| Loading Techniques | Blending | Drug mixed with polymer solution and electrospun | Homogeneous drug-polymer system | Simple, uniform drug distribution | [42] |

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| | Surface Modification (Physical Adsorption) | Drug adsorbed onto fiber surface via weak interactions | Electrostatic, hydrogen bonding, Van der Waals | Easy loading but burst release possible | [43] |
| | Nanoparticle Assembly | Drug-loaded nanoparticles attached to nanofibers | Hierarchical structures | Enhanced surface area, sustained release | [44] |
| | Layer-by-Layer Assembly | Multilayer coating using polyelectrolytes | DNA, heparin delivery | Controlled and sustained release | [45] |
| | Chemical Immobilization | Covalent bonding of drug to fiber surface | Ringsdorf model | Improved stability, targeting, solubility | [46] |
| | Coaxial Electrospinning | Core-shell fibers protect drug | Coaxial Electrospinning | Protects sensitive drugs, sustained release | [47] |
| | Emulsion Electrospinning | Drug emulsified with polymer | Core-shell or uniform fibers | No need for common solvent, maintains bioactivity | [48] |
| Delivery Systems | Wound Dressing | Nanofibers mimic ECM and support healing | Antimicrobial-loaded fibers | Hemostasis, moisture control, gas exchange, faster healing | [49] |
| | Transdermal Delivery | Drug delivery through skin | Nanofiber patches | Controlled, prolonged release, reduced burst effect | [50] |
| | Cancer Therapy | Implantable nanofibers at tumor site | Paclitaxel, HCPT, GTP-loaded fibers | Localized therapy, reduced toxicity, sustained release | [51] |
| | Gene & Growth Factor Delivery | Delivery of DNA, proteins, growth factors | Viral/non-viral vectors | Enhanced gene expression, low toxicity | [52] |
| Tissue Engineering | General Concept | Nanofibers act as scaffolds mimicking ECM | Cell seeding on nanofiber scaffold | Promotes adhesion, proliferation, differentiation | [53] |
| | Scaffold Requirements | Porosity, biodegradability, mechanical strength | Electrospun scaffolds | Tissue regeneration and integration | [54] |
| | Applications | Various tissues | Bone, cartilage, skin, neural, cardiovascular | Biomimetic structure, improved regeneration | [55] |
| Nanocosmetics | Skin Delivery Systems | Nanofibers deliver cosmetic agents | Vitamin A, C, E loaded fibers | Improved skin absorption and effectiveness | [56] |
| | Materials Used | Polymers + skin agents | Polyvinyl alcohol, glycerin, collagen | Enhanced skin hydration and repair | [57] |
| | Applications | Skin wellness | Anti-aging, moisturizing, protection | Controlled release, better penetration | [58] |

## IX CONCLUSION

Nanofibers have garnered substantial international scientific interest owing to their diverse uses in medicine and healthcare. Their distinctive characteristics render them exceptionally efficient for drug delivery, encompassing site-specific targeting and controlled release, in addition to uses in cancer therapy, periodontal regeneration, and the administration of poorly water-soluble medicines. Ongoing discoveries indicate that nanofibers possess significant potential to enhance healthcare results and public health globally.

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