

Recent Trends in Electrospun Nanofibers for Drug Delivery Systems in Asia

Nurvidian Khasanah^{1,2*}, Sutriyo¹, Fatimah¹, Errol Rakhmad Noordam², Iin Hardiyati², Lyliana Endang Setianingsih³, Afif Wahyudi Hidayat^{3,5}, Pedro Anugerah Aswan^{1,4}, Ignasius Agyo Palmado², Nuzul Gyanata Adiwisatra² and Masita Sari Dewi²

1. Master Program in Pharmaceutical Sciences, Faculty of Pharmacy, Universitas Indonesia, Depok, West Java, 16424, Indonesia,
2. Department of Pharmacy, Faculty of Health Sciences, Universitas Medika Suherman, Bekasi, West Java, 17530, Indonesia
3. Bachelor's Program in Health Administration, Universitas Medika Suherman, Bekasi, West Java, 17530, Indonesia
4. Department of Pharmaceutics and Pharmaceutical Technology, Har-Kausyar Institute of Health Sciences (STIKes Har-Kausyar), Indragiri Hulu, Riau, 29351 Indonesia
5. Doctoral Program in Public Health, Universitas Negeri Semarang, Semarang, 50229, Indonesia

Article Info

Submitted: 09-03-2026

Revised: 15-04-2026

Accepted: 15-04-2026

*Corresponding author
Nurvidian Khasanah

Email:
nurvidian@medikasuherna
n.ac.id

ABSTRACT

Electrospun nanofibers have gained increasing attention as an advanced platform for drug delivery due to their high surface-area-to-volume ratio, tunable porosity, and ability to incorporate a wide range of therapeutic agents. These structural properties enable precise control over drug loading and release kinetics, making electrospun nanofibers a promising alternative to conventional delivery systems such as liposomes, hydrogels, micelles, and polymeric nanoparticles. This review provides a comprehensive overview of electrospinning fundamentals, polymer-solvent interactions, and key processing parameters influencing nanofiber morphology and performance. Various drug encapsulation strategies, including blend, coaxial, and emulsion electrospinning, are discussed, along with their advantages and limitations in achieving controlled and stimuli-responsive drug release. A narrative literature search covering the period from 2015 to 2025 identified 214 studies, of which 137 met the eligibility criteria and were included in this review. The findings reveal significant research progress across several Asian countries, particularly China, Japan, South Korea, India, and Malaysia, where electrospun nanofibers are actively explored for applications in cancer therapy, wound healing, topical drug delivery, and tissue engineering. The integration of natural bioactive compounds, implantable nanofiber systems, and stimuli-responsive architectures further highlights the rapid innovation occurring in this region. Despite these advancements, several challenges remain, including high production costs, limitations in large-scale manufacturing, solvent toxicity, environmental concerns, and the lack of standardized regulatory frameworks. For successful commercial translation, it is important to address these issues through improved fabrication technologies, modular electrospinning systems, solvent recycling strategies, and harmonized quality standards. Overall, electrospun nanofibers represent a rapidly evolving and highly adaptable platform with strong potential to advance future drug delivery strategies, particularly within Asia's growing pharmaceutical and biomedical landscape.

Keywords: Electrospun nanofibers, Drug delivery systems, Electrospinning, Stimuli-responsive release, Nanofiber drug delivery

INTRODUCTION

The Emergence of Electrospun Nanofiber in Drug Delivery Systems

In recent years, nanofibers (fine fibers with diameters of less than 100 nm) have attracted considerable attention in the biomedical field, especially as innovative drug delivery systems (DDS) (Williams G, 2018). One of the most promising techniques for producing nanofibers is electrospinning, a method that utilizes an electric field to attract polymer solutions to form nanoscale continuous fibers (Mohammadzadehmoghadam et al., 2016). This process is performed with a simple apparatus consisting of a pump, needle, high-voltage source, and collector. Through Taylor cone formation, this technique produces fibers with high efficiency, good scalability, and broad relevance in medical applications (Mitchell, 2015).

Over the past decade, Asia has emerged as one of the most active regions in nanofiber-based drug delivery research, driven by rapid growth in the pharmaceutical and biomedical sectors, increased research funding, and strong technological advancement across countries such as China, Japan, South Korea, India, and Malaysia (Ferreira Nascimento et al., 2015). The region also faces a high burden of chronic diseases including cancer, diabetes, and infectious diseases prompting the need for advanced and cost-effective therapeutic delivery systems. Moreover, many Asian laboratories have developed specialized electrospinning facilities and frequently integrate natural bioactive compounds derived from locally abundant medicinal resources, leading to a distinctive research landscape compared to Western countries (Ferreira Nascimento et al., 2015). These factors collectively justify the focused examination of electrospun nanofiber innovations within Asia in this review.

Development of Nanofiber Application as a Drug Delivery System

Electrospun nanofibers have evolved into versatile DDS platforms capable of supporting various drug administration routes, including transdermal, buccal, sublingual, vaginal, ocular, and oral delivery (Alamer et al., 2024; Dou et al., 2025; Kamali et al., 2022; Kariznavi et al., 2024; Pandit et al., 2023; Tuğcu-Demiröz et al., 2021; Vedanayagam et al., 2024; Wsoo et al., 2021). Their high surface-area-to-volume ratio and porous structure facilitate efficient drug loading and controlled release, while also reducing systemic side effects often associated with conventional

therapies. Recent studies have demonstrated that electrospun nanofibers can encapsulate a wide range of therapeutic agents, from small molecules such as antibiotics and anticancer drugs to larger biomolecules including proteins and DNA (Mei et al., 2024; Meng et al., 2024; Wang et al., 2024; Yuan et al., 2024). These capabilities make electrospun nanofibers a promising platform for improving the delivery of poorly soluble drugs with low bioavailability (Gültekin et al., 2024).

Advantages of Electrospun Nanofiber Over Conventional DDS Systems

Controlled and Sustained Drug Release Kinetics

Compared with conventional drug delivery systems, electrospun nanofibers offer several advantages. Their polymer matrix structure enables controlled and sustained drug release over extended periods, as commonly observed in electrospun systems utilizing biocompatible polymers such as PLA or PCL. This sustained-release behavior is supported by several studies. For example, Hashem et al. (2022) developed electrospun nanofibers loaded with venlafaxine (VEN) and reported a biphasic release profile characterized by an initial burst of approximately 30% in the first 0.5 h, followed by a prolonged release reaching 80% over 96 h. Importantly, the nanofiber matrix reduced the burst effect and provided more controlled diffusion compared to pure VEN solution, demonstrating how the elongated diffusion pathway within the polymer matrix contributes to more sustained release. Furthermore, Fosca et al. (2022) showed that matrix-based delivery systems often exhibit diffusion-controlled release profiles, frequently following the Higuchi model. Their findings highlight the role of solid polymeric or inorganic matrices in modulating drug transport and achieving sustained release kinetics, although the study focused on calcium phosphate cements rather than electrospun fibers (Hashem et al., 2022; Fosca et al., 2022). Electrospun nanofibers also exhibit high drug-loading capacity, as demonstrated by Chou and Woodrow (2017), who incorporated tenofovir (TFV) into polycaprolactone (PCL)/poly(lactic-co-glycolic acid) (PLGA) nanofibers at concentrations up to 40 wt% without compromising the mechanical properties of the fibers. Notably, the nanofiber system maintained consistent Young's modulus and tensile strength across a wide range of drug loadings (0–40 wt%), indicating strong drug-polymer interactions and structural stability. In

addition, controlled drug release behavior was observed, with near zero-order release achieved at specific compositions (e.g., 15 wt% TFV in PCL/PLGA 20/80), highlighting the capability of electrospun nanofibers to sustain drug release while maintaining mechanical integrity (Chou & Woodrow, 2017). In addition, their mechanical and chemical properties can be easily tailored through polymer selection, fiber orientation, and surface modification, allowing precise control over degradation rate and drug release profiles (Williams G, 2018). These characteristics, combined with improved adhesion and permeability, contribute to enhanced bioavailability and more effective drug targeting compared to several conventional DDS platforms.

METHODS

Search Strategy

This narrative review was conducted by systematically collecting and synthesizing scientific literature related to electrospun nanofibers and their applications in drug delivery systems. A comprehensive search was performed in PubMed, Scopus, ScienceDirect, Google Scholar, and SpringerLink, covering publications from 1971 to 2025. The keywords used included *electrospinning*, *electrospun nanofiber*, *drug delivery system*, *nanofiber drug release*, *polymer nanofiber*, *coaxial electrospinning*, *blend electrospinning*, *core-shell nanofiber*, *stimuli-responsive nanofiber*, *biomedical nanofiber*, and *nanofiber drug delivery in Asia*. Manual screening of reference lists was also performed to ensure comprehensive coverage. The initial search yielded 214 records.

Study Selection

All retrieved articles were screened based on title, abstract, and full-text evaluation to determine relevance to electrospinning-based drug delivery systems. After removing duplicates and applying eligibility criteria, 137 studies were included in the final analysis. The selection process focused on research conducted in Asian countries to highlight regional developments in nanofiber-based drug delivery.

Inclusion Criteria

Studies were included if they reported primary experimental data related to electrospun nanofibers for drug delivery. Eligible studies included *in vitro*, *in vivo*, preclinical, or early clinical investigations examining electrospinning techniques, polymer-solvent systems, drug

encapsulation strategies, release behavior, and biomedical or pharmaceutical applications. Only English-language publications affiliated with institutions in Asia were considered. Although the primary literature range was from 1971 to 2025, earlier foundational studies were reviewed but not included in the final dataset.

Exclusion Criteria

Non-primary sources such as review articles, book chapters, editorials, commentaries, and conference abstracts were excluded. Studies unrelated to drug delivery (e.g., filtration, environmental remediation, textiles, or energy materials), those using non-electrospinning fabrication methods, articles without accessible full text, and publications not written in English were also excluded.

Data Extraction and Synthesis

Key information from each included study such as polymer composition, electrospinning technique, drug loading strategy, release kinetics, biomedical application, and country of origin was extracted and organized thematically. The findings were synthesized qualitatively across major themes including fabrication principles, polymer drug interactions, nanofiber architectures, and regional innovations in Asia. As a narrative review, no statistical meta-analysis was performed; conclusions were drawn through qualitative synthesis and critical interpretation of the collected literature.

RESULTS AND DISCUSSION

Basic Principles of Electrospun Nanofiber

Electrospinning is a technique that utilizes high-voltage electric fields to produce nano- to micrometer-sized fine fibers from a polymer solution or melt. The basic principle of this process involves electrostatic forces that push the polymer solution out of the needle tip (spinneret) towards the collector, forming a continuous thin fiber. The solution used in electrospinning can be a pure polymer solution, emulsion, suspension, or a solution to which an active substance has been added (Mitchell, 2015; Williams, 2018).

When a high voltage is applied to the tip of the solution droplet in the spinneret, an accumulation of electrostatic charges overcomes the surface tension, forming a cone-like structure called a *Taylor Cone*. Once formed, the charge continues to push the liquid out in the form of a jet, which will undergo elongation and solvent

evaporation and then settle as fibers on the collector (Figure 1). If the process parameters are not optimal, this phenomenon can turn into *electrospraying*, producing particles instead of fibers (Williams, 2018).

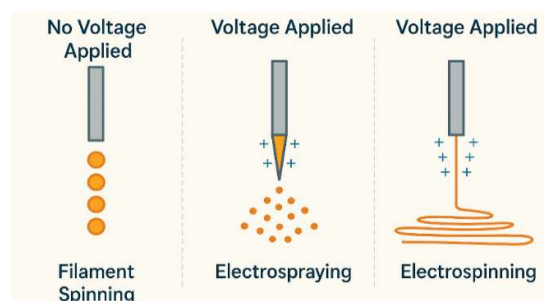


Figure 1. Illustration of the Taylor Cone shape adapted from Williams (2018).

Equipment in the Electrospinning Process

An electrospinning system consists of several main components, including a high-voltage source (power supply), syringe pump, spinneret (usually a metal needle), and collector (Figure 2). The power supply selection should consider stability and voltage range, with voltages up to 25 kV generally sufficient for laboratory-scale applications. Syringe pumps constantly and precisely regulate the solution's flow rate (Mitchell, 2015).

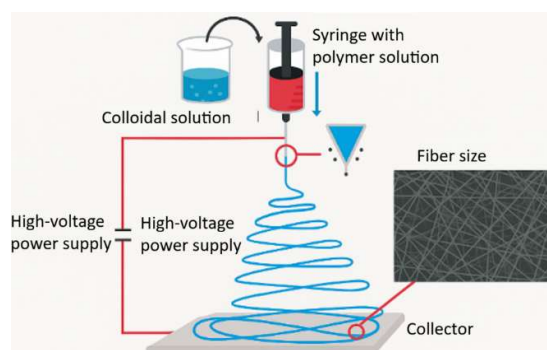


Figure 2. Illustration of electrospinning equipment adapted from Mitchell (2015)

In monoaxial electrospinning, the polymer solution is passed through a single needle to produce homogeneous fibers. The collector can be either a flat metal plate or a rotating cylinder, each affecting fiber orientation. Environmental factors such as temperature and humidity are also

important to control as they affect the yield and reproducibility of the process (Williams G, 2018).

Factors Affecting the Electrospinning Process

The success of electrospinning is greatly influenced by three main groups of parameters, namely solution parameters, process parameters, and environmental parameters (Mohammadzadehmoghadam et al., 2016).

Solution Parameters

Molecular Weight and Chain Structure of Polymers

The molecular weight of the polymer is inversely related to the *critical electrospinning* (ce) value required to produce nanofibers. Generally, polymer molecules have long chains that can consist of many crosslinks. This characteristic depends on the chemical structure of the polymer and its synthesis method. Linear polymers with molecular weights above 50,000 g/mol tend to be more effective in electrospinning, requiring lower values for fiber formation compared to branched polymers having low molecular weights, even if both are dissolved in the same solvent (Mohammadi et al., 2018).

Viscosity

The viscosity of a solution is affected by the polymer's molecular weight and the solvent's characteristics. Therefore, the viscosity of the solution can be adjusted by changing the polymer concentration or the type of solvent. For the electrospinning process, the minimum viscosity required is a solution with a polymer concentration higher than the *critical electrospinning* value (ce). Meanwhile, medium viscosity can produce bead-like fibers, indicating that the product is in between electrospraying and electrospinning results (Williams, 2018).

If the solution's viscosity is too high, it may cause the polymer to solidify during the electrospinning process, potentially leading to clogging. The ideal viscosity range to produce good fibers depends on the composition of the polymer and the solvent used. This viscosity range is specific to each type of polymer and solvent system applied (Mohammadi et al., 2018).

Surface Tension

Surface tension interacts with the viscosity of the polymer solution to counteract the electrical attraction force during the electrospinning process. To initiate this process, surface tension must be overcome by the repulsive force between charges in the polymer solution (Williams et al., 2018). The higher the surface tension, the greater the force

against jet elongation, thus increasing the likelihood of defective fibers. Most solvents used in electrospinning have a relatively low to medium surface tension (20-45 mN/m at 20°C). Surfactants can be added to reduce surface tension, but these surfactants can remain in the fiber product, which may be undesirable (Mitchell, 2015).

Dielectric Constant

Electrospinning solutions with a high dielectric constant (ϵ value between 30 and 20°C) can distribute the jet surface charge more evenly. This simplifies the spinning process and can produce fibers with smaller diameters (Mohammadzadehmoghadam et al., 2016).

Solvent Selection

The selected solvent must meet several criteria. In addition to providing proper electrical conductivity, viscosity, and surface tension, the polymer and functional components must also dissolve or disperse at the required concentration (Williams et al., 2018). In addition, solvents with high volatility are generally preferred because they evaporate quickly. However, too-volatile solvents can dry the jet at the needle tip, while less-volatile solvents cause the nanofiber to form beads in the collector. When using dual solvents, such as tetrahydrofuran (THF) and dimethylformamide (DMF), in nanofiber manufacturing, the difference in evaporation speed between the two solvents creates a porous structure in the nanofiber. The more volatile THF will quickly disappear from the solution, while the less volatile DMF stays longer, causing phase separation and forming pores in the fibers (Haider et al., 2018).

Evidence from previous studies strongly supports the influence of these parameters on electrospinning behavior. For example, Shenoy et al. (2005) demonstrated that PVDF with Mw 180 kDa could be electrospun at concentrations as low as 7.5% w/w in acetone, while up to 30% w/w was required in DMF, illustrating the interplay between molecular weight and solvent properties. Solution viscosity has similarly been shown to dictate fiber morphology, with Doshi and Reneker (1995) and Baumgarten (1971) reporting optimal viscosity windows for successful fiber formation. In addition, surface tension and dielectric constant play critical roles in jet stability and charge distribution; lower surface tension improves fiber uniformity, while solvents with dielectric constants above 30 facilitate the formation of finer fibers. Process and environmental factors also contribute significantly. Morota et al. (2004) reported that high conductivity (>0.5 S/m) disrupts jet stability, while

Vrieze et al. (2009) and Pelipenko et al. (2013) showed that increasing humidity from 20% to 40% reduces fiber diameter, but excessive humidity (>60%) leads to fused fibers. These findings collectively validate how solution, solvent, and environmental conditions critically determine the success of the electrospinning process.

Process Parameters

Voltage

Using a voltage that exceeds the threshold to initiate jet formation can increase instability and lengthen the fiber jet. However, it can also reduce the fiber formation time as it exits the spinneret and moves towards the collector. If the stress is too high and the flow rate is sufficient to support the increased mass transfer rate, some jets may form *Taylor cones* (Williams et al., 2018).

Flow Rate

Higher flow rates usually result in thicker fibers at a given stress and time, as more mass is moved per unit of time. However, this can also lead to defects in the fiber, such as beading or wrinkling, if the solvent does not have enough time to fully evaporate before reaching the collector. Conversely, at flow rates lower than the optimal range, the electrospinning process can become intermittent as the cone at the nozzle tip becomes depleted or even enters the needle, reducing the flow rate and increasing the time required to produce the product (Mitchell, 2015).

Needle Diameter and Distance to Collector

The most commonly used spinnerets are made of metal and generally consist of needles with small holes to produce narrow fibers. Single-hole needles for monolithic electrospinning of fibers usually have a diameter of less than 2 mm. Narrower holes may reduce the fiber diameter and prevent the formation of *beads* but may also increase the risk of clogging. The distance between the spinneret and the collector should be greater because a larger distance provides more time for fiber elongation, resulting in a narrower fiber. However, too much distance can extend the spinning time, resulting in instability and producing fibers with larger diameters and defects (Mohammadzadehmoghadam et al., 2016).

Previous studies have also demonstrated how process parameters directly determine electrospinning performance. Variations in applied voltage can alter jet stability and fiber uniformity. For example, Vrieze et al. (2009) reported that increasing voltage may either decrease or increase fiber diameter depending on the

system, and excessively high voltages can induce multiple jets that generate polydisperse fibers. Similarly, flow rate affects fiber morphology. Nagy et al. (2015) demonstrated that increasing the flow rate from 20 mL/h in single-needle electrospinning to 1,500 mL/h in high-speed corona spinning increased productivity 75-fold, but also resulted in more bead-on-string defects due to insufficient solvent evaporation. The distance between the spinneret and collector also influences fiber formation; Kidoaki et al. (2006) observed a steady increase in fiber diameter when the distance was expanded from 10 to 30 cm, reflecting changes in electric field strength and jet flight time. Collectively, these findings confirm that applied voltage, flow rate, and spinneret–collector distance must be optimized within specific ranges to achieve stable jet formation and uniform nanofibers.

Environmental Parameters

Humidity

Depending on the type of solvent used, increasing the humidity from 20% to 40% can reduce the diameter of the fiber produced. This is due to the rate of solvent evaporation, which is related to the difference between the solvent vapor pressure and the surrounding vapor pressure. Increasing humidity makes the solvent's evaporation rate slower, providing more time for the fiber to elongate (Williams et al., 2018).

Temperature

Higher temperatures have two distinct impacts on the electrospinning process. On the one hand, higher temperatures provide more energy to the molecules in the solution, increasing the electrical conductivity and reducing the viscosity and surface tension of the solution. This facilitates the formation of finer fibers and improves polymer chain alignment, which in turn improves the fiber's mechanical properties. On the other hand, higher temperatures also accelerate the solvent evaporation rate and reduce the time available for fiber elongation before the solidification process occurs (Mitchell, 2015).

Materials

Polymers are the main components in the electrospinning process because of their long chain structure, which allows intermolecular entanglement to occur, an important prerequisite in the formation of nanofibers. Based on their sources and characteristics, polymers used in electrospinning can be classified into three major groups: synthetic polymers, natural polymers, and blends of both.

Polymers

Synthetic Polymers

Synthetic polymers are widely used in electrospinning because they have advantages in process stability, mechanical strength, and controllable degradation rate. Some commonly used examples include polyesters such as PLA, PAN, PGA, and PLGA; vinyl polymers such as PVA and PVP; and polyamides and polyurethanes (Chou & Woodrow, 2017; Eskitoros-Togay et al., 2023; W. Zhang et al., 2019).

Natural Polymers

Natural polymers such as collagen, gelatin, chitosan, alginate, silk fibroin, and cellulose derivatives attract attention due to their high biocompatibility and similarity to natural extracellular matrices (Xu et al., 2025). However, limitations such as low solubility and process sensitivity make their use in electrospinning more challenging (Abdulhussain et al., 2023).

Small Molecules

Small molecules can be directly electrospun into fibers when the entanglement of the chain is significant enough to stabilize the electric jet and suppress the Rayleigh instability. The solution-phase spinning ability of small molecules is influenced by their structure and concentration and the choice of solvent type. Small molecules reported to be frequently used include amphiphiles and cyclodextrin derivatives. Lecithin was first reported to be able to be used as a material for electrospinning. Lecithin has *self-assembly* properties or can form its micelles in non-aqueous solutions at concentrations above the critical micelle concentration (Xue et al., 2019).

Polymer Blends

Polymer blending strategies are a practical approach to combining the advantages of both synthetic and natural polymers. For example, the synthesis of blends between polymers with high mechanical strength and those with bioactive properties can produce fibers with more balanced performance for medical and pharmaceutical applications (Haider et al., 2018b; Ru et al., 2025).

Colloidal Particles

Colloids consisting of a dispersed and continuous phase have also been used for electrospinning when they have sufficient entanglement between their particles to maintain the jet as a continuous structure. Colloidal particles must be of a specific size and crosslinked between their particles to obtain a stable electrospinning process, with viscosity as an important parameter in determining the diameter of the resulting nanofibers.

Table I. Polymers and Solvent Systems Used in Electrospun Drug Delivery with Examples of Loaded Drugs

Polymer	Solvent	Active Ingredient	Ref
Cellulose acetate	Acetone/ dimethylacetamide (2:1)	Naproxen, indomethacin, ibuprofen, sulindac, curcumin, vitamin A, and vitamin E.	(Kailasa et al., 2021)
Poly(ϵ -caprolactone)	Dichloromethane/ methanol (7:3)	Heparin, resveratrol, gentamicin	(Williams, 2018)
Polyvinyl alcohol	Deionized water	Ketoprofen, sodium salicylate, diclofenac, naproxen, and indomethacin.	(Li et al., 2024)
Poly(lactic-co-glycolic-acid)	Dichloromethane/ dimethylformamide	Paclitaxel and cefoxitin sodium	(Xue et al., 2019)
Polyurethane	Dimethylformamide	Itraconazole and ketanserin	(Williams, 2018)
Poly(L-lactic-acid)	Chloroform	Tetracycline HCl	(Williams, 2018)
Blend of polyethylene oxide and poly(ϵ -caprolactone)	Chloroform	Lysozyme	(Tahir et al., 2023a)
Blend of poly(acrylic acid) and poly(allylamine)	Deionized water	Methylene blue	(Tahir et al., 2023a)

Colloidal particles in electrospinning are generated through hydrolysis and condensation of metal alkoxides or metal salts. Examples of colloidal particles used include silica solutions made using tetraethyl orthosilicate (TEOS), distilled water, ethanol, and HCl at 80°C for 30 minutes (Tahir et al., 2023; Xue et al., 2019).

Composites

Composites are usually made by adding sol-gel precursors or nanoscale components into a polymer solution. This method has been extensively explored and can be used for electrospinning. In the case of sol-gel precursors, premature sol-gel reactions in the stock solution must be avoided. Instead, hydrolysis, condensation, and gelation should be initiated within the jet as it comes into contact with the surrounding air. Thus, a continuous network of inorganic phases will be formed in the polymer matrix, forming nanofibers made of polymer-inorganic composites. For example, PVP containing titanium tetraisopropoxide $Ti(OiPr)_4$ using TiO_2 as a precursor was dissolved in alcohol to obtain a spinnable solution (Table I).

Solvent Systems and Solution Modification

The success of the electrospinning process largely depends on the selection of a suitable solvent. The solvent should be able to dissolve the polymer thoroughly, have moderate volatility, and have adequate electrical conductivity (Mitchell, 2015; Williams, 2018). Commonly used solvents include water, alcohol (ethanol, methanol), DMF,

DMAc, THF, chloroform, DCM, and HFIP (Jahani et al., 2025; Kourde-Hanafi et al., 2017).

Solution modification with adding additives is also commonly done to improve fiber characteristics. For example, salts can increase solution conductivity (Khadka et al., 2024), surfactants decrease surface tension (Harahap et al., 2025), plasticizers add flexibility (Zhao et al., 2024), crosslinking agents stabilize fiber structure (Bahtiyar et al., 2024), and nanoparticles provide additional functions such as antimicrobial activity or increased mechanical strength (Özgün Öztürk et al., 2024).

Special Material Configuration

Melt Electrospinning

This variation uses polymer melts instead of solutions, thus eliminating potential toxicity stemming from solvents or residues left in the final product (Tavakoli et al., 2025). The main advantage of this approach is that it produces an entirely solvent-free final product, making it particularly suitable for applications that demand high purity.

Composite Nanofiber

Various inorganic materials, such as metal nanoparticles, carbon nanotubes, ceramic particles, and graphene, can be incorporated into polymer solutions. This can form nanofiber composites with enhanced or new characteristics, such as electrical conductivity, mechanical strength, or response to external fields (Chen et al., 2024; Deng et al., 2024; Mohamed et al., 2025; Wu et al., 2025).

Nanofiber Hydrogel

Electrospinning hydrogels can create nanofiber structures suitable for tissue engineering applications. The resulting structures have optimized fiber dimensions to enhance cellular interactions and adhesion (Najafi et al., 2023).

The selection of the right material determines the performance of the nanofiber produced, both from physical, chemical, and biological aspects, especially in drug delivery applications (Williams, 2018).

Ideal Characteristics of Nanofiber for Drug Delivery

Nanofibers possess several structural characteristics that make them highly suitable for drug delivery applications. Their high surface area-to-volume ratio enhances drug release and bioavailability, particularly for water-soluble compounds (Xu et al., 2025). The porous and interconnected fiber structure facilitates efficient drug diffusion and controlled release, which can be adjusted through electrospinning parameters (Flaig et al., 2024). Drugs can be incorporated by dissolving or dispersing them in the polymer solution prior to electrospinning, enabling uniform distribution within the fiber matrix and compatibility with various drug types (Kamalpour et al., 2025). Additionally, drug release kinetics can be regulated through polymer composition, fiber architecture, and processing conditions, allowing sustained or stimuli-responsive release (Alzahrani et al., 2025). The flexible structure of nanofibers also enables good conformity to irregular tissue surfaces, making them suitable for topical delivery and soft biomedical implants (Wsoo et al., 2021; Xiao et al., 2020).

Drug Encapsulation Strategy

Various strategies have been developed to incorporate therapeutic agents into electrospun nanofibers. The most common method is solution or blend electrospinning, where drugs are dissolved or dispersed in the polymer solution prior to fiber formation, resulting in molecularly distributed or domain-based drug incorporation within the fiber matrix (Mitchell, 2015; Williams G., 2018). Emulsion electrospinning is used when drugs are incompatible with the polymer solvent, allowing encapsulation within droplets of a two-phase emulsion before fiber formation (Zhang et al., 2025). More advanced control can be achieved through coaxial electrospinning, which produces core-shell fibers enabling precise drug localization and controlled release behavior (Xie et al., 2025). In addition, surface functionalization can be applied

after fiber formation through physical adsorption or chemical conjugation to improve drug release efficiency and targeting specificity (Xu et al., 2025).

Comparison with Other Drug Delivery Systems Micro/nanoparticles

Although the particles can be administered injectively, electrospun nanofibers offer better release control, higher drug loading capacity, and a lower risk of burst release (Fosca et al., 2022; Li et al., 2023; Pourtalebi et al., 2020; Williams, 2018).

Hydrogel

Both hydrogels and nanofibers have good biocompatibility; however, nanofibers generally exhibit higher mechanical strength and a more predictable degradation profile (Nazemoroaia et al., 2025; Wlodarczyk et al., 2022). Hydrogel-nanofiber hybrid systems have also been developed to combine the advantages of both (Miranda et al., 2020).

Solid implants

Electrospun materials have higher flexibility, larger surface area, and porosity, which can lead to cellular infiltration and lower immune response (Babadi et al., 2022).

Liposomes

Liposomes are excellent for delivering hydrophobic drugs and targeting specific tissues, but often suffer from stability issues and rapid elimination from the body (Liu et al., 2023; Lu & ten Hagen, 2020). In contrast, electrospun nanofibers offer better physical stability and long-term release profiles (Alzahrani et al., 2025).

Development and Applications of Electrospun Nanofibers in Asia: Case Studies in Japan, China, South Korea, India, and Malaysia

Electrospun nanofibers have become a significant focus of material development due to their particular surface characteristics, customizable morphology, and application flexibility (Williams G, 2018). Asia is becoming a center of innovation in this field, with increasing scientific contributions from India, China, and Japan, particularly in the context of electrospinning technology and its applications (StatNano, 2021).

Clinical Applications of Electrospun Nanofiber in Asia Wound Healing and Anti-Inflammatory Delivery

Nanofibers containing nonsteroidal anti-inflammatory drugs (NSAIDs), such as ibuprofen

and diclofenac, have been shown to reduce systemic toxicity and possess the ability to release drugs locally and sustainably (Hsiung et al., 2022). This is particularly effective in the treatment of chronic wounds and inflammation. In India and China, antibacterial nanofibers containing silver nanoparticles, triclosan, or chitosan are widely used in wound dressings to prevent infection and promote healing (Lan et al., 2021; Zhou et al., 2021).

Cancer Therapy

Nanofibers loaded with chemotherapeutics, such as doxorubicin or a combination of paclitaxel with magnetic nanoparticles, can be used for local cancer therapy and hyperthermia therapy (Faraji Dizaji et al., 2020; Radmansouri et al., 2018). This technology reduces side effects on healthy tissues and increases the effectiveness of drug delivery directly to the tumor site. China has developed stimuli-responsive nanofibers for programmable drug release, improving therapeutic precision (Zhou et al., 2025).

Tissue Engineering and Regenerative Medicine

Japan is leading the way in developing nanofibers for bone and cartilage tissue engineering, using biodegradable materials and carriers of growth factors such as VEGF (Gao et al., 2024; Rana et al., 2017). These nanofibers serve as scaffolds capable of gradually delivering stem cells or biomolecules, accelerating tissue regeneration (Rana et al., 2017).

Countries with Leading Electrospun Nanofiber Development Center

China

China is one of the leading contributors to electrospun nanofiber research in Asia. Studies in China mainly focus on cancer therapy, wound healing, and transdermal drug delivery systems. For instance, polymeric nanofibers such as PLA and PLGA have been widely explored for the delivery of chemotherapeutic agents including doxorubicin and paclitaxel, enabling controlled drug release and targeted therapy (Faraji et al., 2020; Radmansouri et al., 2018). In addition, collagen- and silk fibroin-based nanofibers have been developed to accelerate wound healing through the delivery of growth factors and antimicrobial agents (Arumugam et al., 2024; Fang et al., 2024). Several studies also investigate NSAID-loaded nanofibers for transdermal delivery to reduce systemic side effects (Chao et al., 2023) (Table II).

India

India has shown rapid development in electrospun nanofiber-based drug delivery

research, particularly in wound healing and controlled drug release systems. Various polymer systems such as PCL, chitosan, PVA, and gelatin have been investigated to fabricate nanofibers loaded with antibiotics and anti-inflammatory drugs (Kalangadan et al., 2023; Panda et al., 2022). These systems demonstrate promising antibacterial activity, enhanced drug release control, and improved therapeutic efficiency (Table II).

Japan

Japan focuses on advanced biomedical and functional nanofiber applications, including tissue engineering scaffolds, drug delivery systems, and flexible electronic devices. Biodegradable polymers such as PLA and PLGA have been widely used for cartilage regeneration and tissue engineering due to their favorable mechanical properties and controlled degradation behavior (Rana et al., 2017). In addition, Japan has developed nanofiber-based piezoelectric sensors and optically functional nanomaterials, highlighting the interdisciplinary nature of nanofiber research (Xiong et al., 2024) (Table II).

South Korea

South Korea has demonstrated significant progress in electrospun nanofiber research for drug delivery systems and advanced biomedical technologies. Several studies focus on developing functional nanofibers with improved physicochemical and responsive properties. For example, pullulan-based nanofiber films containing tetracycline-cyclodextrin inclusion complexes have been investigated for fast-dissolving oral drug delivery with enhanced antibacterial activity (Hsiung et al., 2022). In addition, temperature-responsive nanofibers based on ethyl cellulose modified with biocompatible fatty acids have been explored to enable controlled drug release triggered by body temperature (Wildy & Lu, 2023). Beyond pharmaceutical applications, Korean researchers have also developed ultrathin nanofiber-based electronic patches using cellulose acetate coated with conductive polymers such as polyaniline, highlighting the integration of nanofibers into wearable biomedical devices (Ji et al., 2024) (Table II).

Malaysia

Malaysia has contributed to the advancement of electrospun nanofiber technology primarily through material optimization and the development of functional nanofiber systems for biomedical and sensing applications.

Table II. The following table presents research on electrospun nanofiber for various drug delivery applications in Asia

No.	Country	Title	Polymers	Results	Ref
1.	China	Electrospun Dimensional Nanofibrous Structure via Probe Arrays Inducing	Three-Poly(Ethylene Oxide) Nanofibers (PEO) with Mw = 300,000 g/mol	The study successfully developed three-dimensional nanofiber structures using an electrospinning method with probe arrays that affect the electric field. Adding ethanol to the solvent increases evaporation and decreases the dielectric constant, thereby increasing the diameter of the nanofiber and supporting the formation of 3D electrospun structures.	(Liu et al., 2018)
2.	China	Ibuprofen-Loaded Nanoparticle-Polyacrylonitrile Nanofibers for Dual-Stimulus Sustained Release of Drugs	ZnO Polyacrylonitrile (PAN)	The development of PAN-based nanofibers loaded with ZnO nanoparticles and ibuprofen resulted in a controlled-release drug delivery system responsive to two stimuli, increasing the effectiveness and duration of sustained drug release.	(Chao et al., 2023)
3.	China	Development and Characterization of Alcohol/Polyvinyl Acetate Composite Nanofiber as Wound Dressing Matrix with Controlled Drug Release	Polyvinyl Alcohol (PVA) and Polyvinyl Acetate (PVAc)	The electrospinning method successfully prepared PVA/PVAc composite nanofiber, showing potential as a wound dressing with controlled drug release ability and physical properties suitable for medical applications.	(Rahmani et al., 2021)
4.	China	Doxorubicin hydrochloride - Loaded electrospun cobalt ferrite nanofibers for combined chemotherapy and hyperthermia treatment of melanoma cancer	Chitosan	Chitosan/cobalt ferrite/titanium oxide composite nanofiber was successfully prepared with doxorubicin (DOX) encapsulation efficiency >95%. These nanofibers showed better synergistic antitumor effects on B16F10 melanoma cells when combined with chemotherapy and hyperthermia therapy (HPT), with cell death reaching 78% after 3 days of treatment.	(Radmansouri et al., 2018)
5.	China	Synthesis of zeolites and metal-organic nanofibers for drug delivery	PLGA (polylactic-co-glycolic acid) and chitosan	Incorporating PLGA and chitosan with zeolites and MOFs improves the mechanical strength, biocompatibility, and controlled delivery of anticancer drugs, overcoming the problem of burst drug release in pure chitosan.	(Faraji et al., 2020)
6.	India	Investigation of alcohol-gellan nanofiber as scaffolds.	Poly(vinyl alcohol) (PVA) gum-based and Gellan Gum	PVA-gellan gum-based nanofibers were successfully fabricated and showed potential as scaffolds for tissue engineering. Their physical and chemical characteristics support biomedical applications.	(Aadil et al., 2019)

Table II. (Continue) The following table presents research on electrospun nanofiber for various drug delivery applications in Asia

No.	Country	Title	Polymers	Results	Ref
7.	India	Curcumin-loaded polycaprolactone-polyvinyl alcohol-silk fibroin-based nanofibrous mats for wound healing applications.	Polycaprolactone (PCL), Polyvinyl Alcohol (PVA), and Silk Fibroin	PCL-PVA-silk fibroin-based nanofiber loaded with curcumin shows potential as an active bandage material for wound healing with good morphological properties and controlled drug release, and it supports cell proliferation and adhesion.	(Agarwal et al., 2021)
8.	India	Silver nanoparticles loaded triple-layered acetate-based nanofibrous mats for antibacterial wound dressing applications.	Polyvinyl alcohol (PVA), Cellulose acetate (CA), Polycaprolactone (PCL)	Through the addition of silver nanoparticles, a triple-layer nanofiber composed of PVA, CA, and PCL was successfully fabricated with good thermal stability and effective antibacterial properties. The multilayer structure enhances the interaction between polymers, thus improving thermal stability and potential application as an antibacterial wound dressing.	(Dugam et al., 2024)
9.	India	Repurposing ivermectin and ciprofloxacin in nanofibers for enhanced antimicrobial activity	Poly(ϵ -caprolactone) (PCL), Polyvinyl alcohol (PVA), and chitosan are the main polymers in nanofiber.	Nanofiber containing ivermectin and ciprofloxacin showed good antibacterial activity against <i>E. coli</i> and <i>S. aureus</i> and improved drug delivery effectiveness and antibacterial ability compared to over-the-counter drugs.	(Kalangadan et al., 2023)
10.	India	Synergistic induction of programmed cell death in breast cancer cell lines	Poly(lactic acid) (PLA) and other biocompatible polymers for scaffolds and nanoparticles	Using PLA-based nanofibers and surface modification of nanoparticles enhances the effectiveness of drug delivery and synergistically induces programmed cell death in breast cancer cells.	(Jaisankar et al., 2025)
11.	Japan	Nanofiber composites in cartilage tissue engineering	Poly(glycolic acid) (PGA), Poly(lactic acid) (PLA), Poly(lactic-co-glycolic acid) (PLGA), and copolymer combinations such as PLA-PEG	Using nanofiber-based scaffolds of biodegradable polymers such as PLGA and PLA supports cartilage tissue reconstruction with good mechanical stability, controlled degradation, and positive cellular response, making it suitable for cartilage tissue engineering applications.	(Rana et al., 2017)
12.	Japan	Core-shell nanomembrane with sequential immune and vascular functions	PLCL (Poly(L-lactide-co- ϵ -caprolactone)), Gelatin (Gel), as well as combinations with KGN (Cartogenin) and Curcumin (Cur) in shell nanomembranes.	Nanomembranes with a core-shell structure were successfully fabricated and showed good mechanical properties, controlled degradation, and the ability to gradually release KGN and Cur to support tissue regeneration through immune modulation and vascularization.	(Gao et al., 2024)

Table II. (Continue) The following table presents research on electrospun nanofiber for various drug delivery applications in Asia

No.	Country	Title	Polymers	Results	Ref
13.	Japan	Flexible Piezoelectric Sensor Based on Two-Dimensional Topological	Poly(vinylidene fluoride) (PVDF)	This research developed a PVDF-based flexible piezoelectric sensor with an electrospun nanofiber structure that is highly efficient for flexible sensor applications and mechanical energy collection.	(Xiong et al., 2024)
14.	Japan	Electrospun nanofiber exhibit high total transparency and scattering	SLIPS Poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP)	SLIPS nanofiber exhibits high total transparency (93.2%), high scattering (50%), and low sliding angle ($\leq 10^\circ$), with a nonwoven nanofiber structure that can control scattering.	(Abe et al., 2016)
15.	South Korea	Electrospun nanofiber-supported composite membrane	Polyacrylonitrile (PAN) as nanofiber support and polyamide as thin-film composite layer.	Electrospun nanofiber-based thin composite membranes exhibit high gas and water separation performance. They have a controlled pore structure and improved selectivity and permeability compared to conventional membranes.	(Byun et al., 2024)
16.	South Korea	Antibacterial nanofibers of pullulan tetracycline-inclusion cyclodextrin complexes for fast-integrating oral films	Pullulan	Successfully fabricated pullulan-based antibacterial nanofibers containing tetracycline-cyclodextrin inclusion complexes with fast-dissolving properties for fast-integrating oral film applications.	(Hsiung et al., 2022)
17.	South Korea	A fully nanofiber-based ultrathin electronic patch for self-powered multifunctional on-skin applications	Polyaniline (PANI) coated on cellulose and acetate nanofibers	The study developed nanofiber-based ultrathin electronic patches that are flexible, resistant to mechanical deformation, biocompatible, and can be used as flexible electrodes for medical applications and wearable electronics. PANI shows good electrical properties and does not cause skin irritation.	(Ji et al., 2024)
18.	South Korea	Exploring temperature-responsive drug delivery with biocompatible fatty acids phase change materials in ethyl cellulose nanofibers	Ethylcellulose	The study developed ethyl cellulose-based nanofiber containing biocompatible fatty acids as phase change material for temperature-responsive drug delivery. This nanofiber shows potential as a drug delivery system with release control triggered by temperature changes.	(Wildy & Lu, 2023)
19.	South Korea	Exploring antibacterial ethyl cinnamate cyclodextrin inclusion complexes	Cyclodextrin (including hydroxypropyl- β -cyclodextrin and β -cyclodextrin) in the form of inclusion complex and nanofibers.	The formation of the inclusion complex between ethyl cinnamate and cyclodextrin improves water solubility, thermal stability, antibacterial activity, and potential application in drug delivery systems and active ingredients with better antimicrobial properties.	(Siva et al., 2025)
20.	Malaysia	Effects of concentration on the synthesis of polyvinylidene fluoride solution on the (PVDF)	Polyvinylidene fluoride (PVDF)	Increasing the PVDF concentration from 14 wt% to 18 wt% produced more uniform nanofibers with better morphology and diameter.	(Al-Dhahebi et al., 2023)

Table II. (Continue) The following table presents research on electrospun nanofiber for various drug delivery applications in Asia

No.	Country	Title	Polymers	Results	Ref
21.	Malaysia	Effects of nanofiber immobilization of bacteria	Polyethersulfone, Poly(vinylidene fluoride), Cellulose acetate, Polysulfone	Electrospun nanofibers enhance bacterial immobilization, increasing stability and biocatalyst activity for applications such as xyloitol production. PVDF nanofibers with a positive charge, small diameter, and beaded structure were most effective as immobilization carriers for recombinant E. coli bacteria. The nanofibers' morphology and physicochemical properties affect biocatalysts' immobilization efficiency and performance.	(Mohamad Sukri et al., 2024)
22.	Malaysia	A novel electrospinning design for preparing of high alignment β -phase PVDF nanofibers for high-performance piezoelectric nanogenerators	centrifugal PVDF (Polyvinylidene fluoride)	The study developed a novel centrifugal electrospinning design capable of producing PVDF nanofibers with high orientation and dominant β phase, improving piezoelectric performance for nanogenerator applications.	(Alqallab & Hjumali, 2024)
23.	Malaysia	Ultrasensitive aptasensor using electrospun polyvinylidene fluoride	Polyvinylidene fluoride MXene (PVDF)	An ultrasensitive aptasensor based on PVDF nanofiber membrane doped with MXene was developed, showing improved sensitivity and detection performance of the biosensor.	(Al-Dhahebi et al., 2022)
24.	Malaysia	Vitamin D3-loaded electrospun cellulose acetate polycaprolactone nanofibers for biomedical applications	Cellulose acetate polycaprolactone	A combined cellulose acetate and polycaprolactone nanofiber was successfully prepared by electrospinning. It shows mechanical characteristics and a controlled release of vitamin D3, and it has potential for biomedical applications such as drug delivery and tissue scaffolds.	(Wsoo et al., 2021)

Several studies have focused on improving nanofiber morphology and structural properties to enhance performance in various applications. For instance, optimization of polyvinylidene fluoride (PVDF) solution concentration has been shown to produce nanofibers with improved uniformity and reduced fiber diameter (Al-Dhahebi et al., 2023). Research conducted in Malaysia has also explored nanofibers as immobilization matrices for microbial biocatalysts, demonstrating enhanced stability and efficiency in biotechnological processes such as xylitol production (Mohamad Sukri et al., 2024). In addition, PVDF-based nanofibers incorporating advanced materials such as MXene have been developed for highly sensitive biosensing platforms, highlighting the growing potential of nanofibers in biomedical diagnostics (Al-Dhahebi et al., 2022) (Table II).

Overall, research on electrospun nanofibers in the Asian context is dominated by China and India, while Japan and South Korea focus more on advanced functional materials and biomedical devices. Malaysia contributes primarily to material optimization and biosensing applications. These regional trends highlight the growing interdisciplinary nature of nanofiber research across Asia.

Recent research on electrospun nanofiber types in Asia

Innovation of Electrostatic Fabrication and Manipulation Techniques in China and South Korea

Recent studies have demonstrated how electrical parameters and electrode design directly enhance electrospinning performance. Y. H. Wu et al. (2025) showed that optimizing electrostatic repulsion through a *polymer-coated spinneret* (1 mm nozzle diameter) significantly improved fiber alignment by stabilizing the electrostatic field and reducing energy dissipation. Using PVP-ethanol solutions, voltage adjustments from 5 to 10 kV progressively produced straighter nanofibers with more uniform diameters, confirming that stronger repulsive forces increase jet stability and alignment.

Research in Korea on a multi-focus electrospinning system utilizing ring-shaped auxiliary electrodes demonstrated how engineered electrode geometry can precisely control deposition. By reducing the potential difference V_{NE} from 9.5 kV to 3.5 kV, the deposition diameter decreased from 9.83 μm to 2.30 μm , while maintaining stable jet confinement. The system achieved up to 95.88% material collection

efficiency far higher than conventional setups ($\approx 62.94\%$), highlighting how voltage modulation and electrode configuration can drastically improve control and productivity in fiber fabrication (Lee et al., 2025).

Development of Three-Dimensional Nanofiber Structure using Probe Array Induction Technique in China and Taiwan

Several studies conducted in Asia have also demonstrated how material properties and electrostatic design innovations improve electrospinning performance. For instance, Y. Liu et al. (2018) developed a probe-array induction system capable of generating 3D electrospun architectures, representing a significant advancement over traditional 2D deposition. Using PEO (Mw 300,000 g/mol) dissolved in a 1:1 deionized water ethanol system, the researchers simultaneously tuned evaporation rate and dielectric environment, enabling stable jet stacking and controlled 3D structural growth.

Complementing this, Hsu et al. (2024) integrated electrospinning with 3D printed PCL scaffolds to fabricate functional small joint implants. Their system used PLGA (800–840 mg) dissolved in HFIP (3–5 mL) to produce drug loaded and sheath core nanofibers capable of sustaining the release of teicoplanin, ceftazidime, and ketorolac for 19–30 days. The resulting hybrid structure demonstrated excellent mechanical endurance, with the PCL joints withstanding 10,000 load cycles, highlighting how optimized solution formulation and device design directly enhance functional outcomes.

The probe array induction technique used in the study enables the spatial deposition of fibers with high precision, resulting in complex three-dimensional structures. These structures show significant improvements in mechanical properties and surface area, making them potential candidates for a variety of advanced applications, including tissue engineering and drug delivery systems.

Integration of Electrospun Nanofiber in Flexible Piezoelectric Sensors in Japan and China

Recent advances have also demonstrated the potential of electrospun nanofibers in flexible electronics applications. For instance, Xiong et al. (2024) developed dopamine-modified PVDF electrospun nanofibers that exhibited enhanced piezoelectric response and mechanical flexibility, enabling stable signal generation under repeated deformation and improving sensitivity for applications such as body motion and health monitoring sensors.

Table III. Companies Manufacturing Laboratory-Scale Electrospinning Equipment in Asia

Company	Country	Tool Type	Brand	How to Order	Source
Inovenso	Turkey	Lab & Industrial	NE100, NE200, NE300, etc.	Direct & distributor	(Inovenso, 2026))
MECC Co. Ltd	Japan	Lab & Semi-Industrial	Nanon series	Direct	(MECC Co., Ltd, 2025)
Foshan Nanofiberlabs	China	Customizable Lab/Industrial	Biomedical grade	Direct	(Foshan Nanofiberlabs, n.d)

Complementing this, Chen et al. (2024) designed a multilayer flexible piezoelectric sensor based on electrospun P(VDF-TrFE)/ZnO nanofibers, achieving a significant increase in sensitivity from 2.82 mV/kPa to 8.30 mV/kPa, while maintaining stable performance over 10,000 loading cycles. These findings highlight how material modification and structural engineering in electrospun nanofibers can synergistically enhance sensitivity, durability, and functional performance in next-generation flexible sensing devices.

Development of Electrospun Nanofiber Systems with Advanced Optical Properties in Japan and Turkiye

Recent developments also highlight the expanding role of electrospun nanofibers in optical and diagnostic technologies. In Japan, Abe et al. (2016) engineered *slippery liquid-infused porous surfaces (SLIPS)* using electrospun PVDF-HFP nanofibers, achieving an unusual combination of high light scattering ($\approx 50\%$) and excellent total transmission (93.2%), together with a low sliding angle ($\leq 10^\circ$) that provides self-cleaning performance. These properties were enabled by precise regulation of nanofiber layer density, allowing selective manipulation of light pathways. Complementing these optical advances, Us et al. (2025) demonstrated the diagnostic utility of electrospun nanofibers by developing PS:PEG (5:5) substrates optimized under 9–11 kV, 0.9–1.1 mL/h, and 14–16 cm spinning conditions. The resulting membranes exhibited enhanced hydrophilicity (contact angle 82.26° vs. $140\text{--}160^\circ$ for pure PS), a high swelling ratio (891%), and a BET surface area of $4.228\text{ m}^2/\text{g}$, enabling sensitive colorimetric detection of U87-MG glioblastoma cells across a wide linear range ($10^1\text{--}10^6$ cells/mL) using AuNP-aptamer bioconjugates. Together, these studies demonstrate how electrospun nanofiber architectures can be engineered to simultaneously control optical behavior and enhance biosensing precision

Company Manufacturing Laboratory-Scale Electrospun Nanofiber Equipment in Asia Types of Electrospun Nanofiber Technologies for Drug Delivery Blending Electrospinning

Using polymer blends in the spinning process can improve the balance between drug-loaded nanofibers' mechanical and physicochemical properties. In addition, it can also effectively improve the formulation design for drug release, where the release rate can be manipulated by adjusting the proportion of polymer in the blended solution (Williams, 2018). The electrospinning blending method achieves drug encapsulation in one step because the drug is dissolved or dispersed in the polymer solution. The interaction between the polymer solution and the drug is affected by the physicochemical properties of the polymer; so, the polymer selected largely determines the efficiency in drug encapsulation, drug dispersion into the fiber, and drug release rate (Mitchell, 2015). The researchers also emphasized that when using this method, it is important to pay attention to the balance of the hydrophilicity of the drug and the polymer. With the electrospinning blending method, single-phase fibers are obtained. However, this method cannot be used to produce fibers with core and shell structures; other methods, such as coaxial or emulsion electrospinning, can be employed (Cornejo Bravo et al., 2016).

Coaxial Electrospinning

The main objective of coaxial electrospinning is to obtain fibers with a core-shell structure. This technique can be used to obtain fibers with specific drugs encapsulated inside the fiber core, leading to sustained and controlled drug release. This type of fiber presents a high surface area and three-dimensional network. Based on reports of several coaxial electrospinning studies, proteins, growth factors, antibiotics, and other biological agents have been successfully loaded into coaxial fibers for drug delivery

(Williams, 2018). One of the main advantages of this technique is that the core-shell structure protects the loaded compounds and drug bioactivity.

The advantage of the coaxial electrospinning method is that it can improve the functionality of biomolecules by loading them into the inner jet while the polymer solution is in the outer jet, protecting the biomolecules. The polymer shell helps avoid direct contact between the biomolecule and the external environment in this technique. The core-shell system enhances sustained drug release and can also retain the ability of unstable biological agents

Emulsion Electrospinning

Emulsion electrospinning is a flexible and potential technique for encapsulating multiple drugs into nanofibers. It is also one of the most important methods to prepare core-shell electrospun nanofibers cost-effectively and efficiently. In emulsion electrospinning, the oil phase consists of the drug emulsion or aqueous protein solution dispersed within the continuous aqueous phase. In this case, it is a polymer solution, which is then followed by the electrospinning process (Cornejo Bravo et al., 2016).

Bubble Electrospinning

Bubble electrospinning is an electrospinning technique that uses air bubbles to initiate the spinning process of nanofiber fibers. This method introduces air bubbles into the polymer solution, creating an unstable state that can form nanofiber fibers when a high voltage is applied. This technique was first introduced in 2007 and is known for its ability to increase the mass production of nanofiber fibers.

The process begins by creating bubbles within the polymer solution. When a high electric voltage is applied, the electric field causes deformation on the bubble surface, forming "Taylor cones" from which nanofiber fibers are extruded (Mamun & Sabantina, 2023). This method differs from conventional needle-based electrospinning in that it does not require needles, thereby reducing clogging issues and enabling large-scale production.

Roller Electrospinning

Roller electrospinning is a flexible method for producing continuous nanofiber webs. The process involves applying an external electric field to a polymer solution or melt to produce continuous polymer fibers with diameters in the sub-micron range. In roller electrospinning systems, nanofiber fibers are produced by exciting the polymer solution using an electric force generated by a high voltage. This method offers

advantages over needle electrospinning, particularly in terms of higher throughput and the continuous production of nanofibers.

One of the main advantages of roller electrospinning is its ability to continuously produce nanofibers with diameters in the nanometer range, depending on the polymer type and processing conditions. Potential applications of nanofibers produced by roller electrospinning include filtration, tissue engineering, wound dressings, and sound-absorbing materials. The parameters affecting the roller electrospinning system can be divided into independent parameters (such as voltage, the distance between the roller and collector, and the nature of the polymer solution) and dependent parameters (such as fiber diameter and fiber morphology). Research has also shown that parameters such as solution conductivity can affect the length of the polymer jet during the electrospinning process (Yalcinkaya et al., 2013).

Porous Hollow Tube Electrospinning

Electrospinning by a porous hollow tube is one of the needleless electrospinning techniques that uses a limited feed process. This technique uses a tube with porous walls to increase the electrospinning process's productivity. The polymer solution is pushed through the pores of the cylindrical tube filled with the polymer solution, which causes droplets to form on its outer surface. The polymer solution inside the tube is pressurized with enough air to force the polymer to flow through the pre-drilled holes. When the solution is electrically charged, each hole produces a jet, and these jets form from the droplets and eventually form multiple fibers (Alghoraibi & Alomari, 2018).

Melt Blowing Electrospinning

The melt-blowing electrospinning method combines melt-blowing and electrospinning processes to produce polymer fibers. In this method, the polymer is melted and extruded through multiple nozzles simultaneously. Afterward, the resulting polymer jet is drawn using a high-speed hot air stream, which causes the diameter of the jet to decrease dramatically. Fine fibers with random orientation are then deposited on the collector surface to form a nonwoven web.

This method has several advantages, such as producing fibers with minimal diameters and high productivity. However, it also has some limitations, such as the limited types of polymers that can be used and the potential for thermal degradation (Alghoraibi & Alomari, 2018).

Based on the drug delivery mechanism Controlled Release Mechanism in Electrospun Nanofiber Systems

One of the main approaches to using electrospun nanofibers for drug delivery is the *controlled release system*. This system is designed to constantly keep the drug concentration within therapeutic limits over a period of time, which can significantly improve treatment effectiveness, reduce dosing frequency, lower the risk of side effects, and improve patient adherence to therapy (Hasan Aneem et al., 2024).

The advantages of electrospun nanofibers in controlled release lie in their distinctive fiber structure and their customizability based on polymer material properties and drug characteristics (Hong et al., 2023). Some important factors that affect the drug release pattern from nanofiber include:

Morphology and fiber diameter.

The smaller the diameter of the nanofiber, the larger its surface area relative to volume, which tends to accelerate drug release (Khalid et al., 2025).

Fiber porosity level.

High porosity can increase the diffusion of drug molecules, thus accelerating the release (Khalid et al., 2025).

Interaction between drug and polymer matrix.

Intense physical or chemical interactions between the drug molecules and the polymer will slow the drug release, resulting in a slower and sustained release profile (Nezamoleslami et al., 2023).

Polymer degradation rate.

In biodegradable polymers, drug release occurs along with matrix degradation, contributing to the release mechanism (Nezamoleslami et al., 2023).

The relationship between material structure and drug release function is key in the design of nanofiber-based delivery systems (Hong et al., 2023). The arrangement of drug molecules within the polymer matrix directly affects the release kinetics, which can help develop specifically tailored release profiles for various therapeutic needs (Hasan Aneem et al., 2024). Thus, electrospun nanofibers offer a flexible and efficient platform for developing precision drug delivery systems.

Release System Responsive to Stimuli

Stimulus-responsive electrospun nanofibers are among the latest innovations in drug delivery systems. These systems are designed to release

therapeutic agents in response to internal environmental signals (such as pH or temperature) or external stimuli (such as light or magnetic fields) (Sakhaee et al., 2025). This response-based release mechanism can release specific and on-demand drugs, thereby increasing therapeutic effectiveness while reducing unwanted systemic toxicity.

pH-Responsive system

The pH-responsive electrospun nanofiber utilizes the difference in acidity (pH) levels in different biological environments (Hu et al., 2025). For example, the tumor microenvironment is generally more acidic than that of normal tissues. At the same time, the gastrointestinal tract exhibits a pH gradient, ranging from acidic conditions in the stomach to alkaline conditions in the intestine (Sakhaee et al., 2025). This difference can be utilized to direct drug release specifically at the target site.

One example of the application of this system is the use of polyvinyl alcohol (PVA) and polyacrylic acid (PAA) based nanofibers developed to encapsulate bromothymol blue (BTB) and the antibiotic ciprofloxacin (Arafat et al., 2021). These systems exhibit significantly different drug release profiles at acidic, neutral, and alkaline pH conditions, making them highly potential for targeted drug delivery to specific tissues or organs with typical pH (Arafat et al., 2021; Khan & Saneja, 2025).

Temperature Responsive System

Temperature-responsive nanofibers use thermosensitive polymers capable of undergoing structural or conformational changes at certain temperatures. These changes then trigger drug release from the nanofiber matrix (Wei et al., 2023). Such systems can be designed to respond to normal body temperature (approximately 37° C) or locally elevated temperature through the administration of an external thermal stimulus (e.g., heat therapy) (Dou et al., 2025).

Applications of this system can control more precise release, especially in conditions that require drug release only when the temperature reaches a certain threshold (Huang et al., 2024). Thus, this system is very suitable for localized therapy, such as cancer or inflammation treatments, where the local temperature can indicate or trigger the desired drug release (Wildy & Lu, 2023).

Light Responsive System

Nanofibers containing photosensitive molecules can release drugs when exposed to specific wavelengths of light (e.g., UV or near-

infrared light), providing precise spatial and temporal control (Wei et al., 2023).

Magnetic Field Responsive Nanofiber

Integrating magnetic nanoparticles into the nanofiber matrix allows drug release to be controlled through exposure to an external magnetic field that can activate drug release at the targeted site non-invasively (Navaei et al., 2025).

Ultrasonic Wave Responsive System

Ultrasonic waves can trigger drug release from nanofibers by increasing the local temperature or physically disrupting the fiber structure (Khadka et al., 2025).

Nanofiber Responsive to Reactive Oxygen Species (ROS)

These systems are designed to degrade and release drugs in environments with high levels of ROS, such as in tissues undergoing inflammation or tumors, thus providing selective drug release against pathological conditions (D. Fang et al., 2023). Nanofibers, with this response to external stimulus, offer unprecedented control over the timing and location of drug release due to nanofibers' high specific surface area and pore structure, which facilitate rapid response to changes in the surrounding environment (Zou et al., 2023).

Targeted Drug Delivery System

Targeted drug delivery systems using electrospun nanofibers aim to concentrate therapeutic agents at specific pathological sites, maximizing local efficacy while minimizing systemic toxicity (Çeliközlü, 2025). This strategy is particularly important in oncology, where selective drug deposition within tumor tissues can significantly reduce damage to healthy cells. Recent evidence supports this approach; for example, Li et al. (2025) developed a multimodal electrospun nanofiber membrane incorporating paclitaxel and GSNO within a Cu-based HKUST-1/PLEA matrix (PTX/GSNO@HKUST-1/PLEA), which responded to elevated intratumoral GSH by triggering $\text{Cu}^{2+} \rightarrow \text{Cu}^+$ conversion, catalytic NO release, and Fenton-like reactive oxygen species generation. In a murine model of advanced gastric cancer with peritoneal metastasis, this targeted system suppressed tumor growth, reduced ascites formation, alleviated cancer cachexia, and achieved a dramatic reduction in tumor burden approximately 10% of that observed in the untreated control group ultimately prolonging survival. These findings demonstrate how

engineered electrospun nanofibers can achieve site-specific activation and markedly enhance intraperitoneal chemotherapy outcomes.

Approaches used in directed delivery systems include

Surface Functionalization with Targeting Ligands

The surface of the nanofiber can be modified with targeting molecules (such as antibodies, peptides, or aptamers) that have specific affinity to receptors overexpressed on target cells (C. Li et al., 2024).

Use of Magnetic Nanoparticles

Magnetic nanoparticles incorporated into nanofibers can direct drug delivery using an external magnetic field, thereby improving the accuracy of the release site (Navaei et al., 2025).

Response to Target Microenvironment

Nanofibers can also respond to specific microenvironment conditions, such as low pH in tumors or specific enzymes, to ensure drug release only occurs at the target site (Hu et al., 2025; Su et al., 2022).

This system's ability to precisely target specific locations opens up great opportunities for more effective and safe therapies. It can be adapted for a variety of chronic and acute disease conditions.

Challenges and Future Prospects

Constraints in the development of electrospun nanofiber in Asia (production cost, industrial scale, regulation)

The development of electrospun nanofibers in Asia continues to face several technical and structural limitations. Production cost remains a central challenge, predominantly due to the high investment needed for electrospinning equipment, the use of toxic organic solvents, and energy-intensive post-processing steps. These factors significantly increase the cost per unit of product, limiting the transition of nanofiber technology from research laboratories to industrial settings (Keirouz et al., 2023).

Scaling up production also presents notable constraints. Although multi-nozzle and needleless electrospinning systems can improve throughput, maintaining fiber uniformity, reducing bead formation, and ensuring consistent drug loading efficiency at large volume manufacturing remain significant barriers (Qin et al., 2022).

Furthermore, regulatory challenges related to environmental safety, solvent toxicity, and the absence of standardized quality benchmarks complicate commercial translation and product certification (Keirouz et al., 2023). For example, several Asian countries have begun establishing regulatory frameworks relevant to nanofiber-based products. In China, the food and drug regulatory system through instruments such as the Food Act (1979), the Food Sanitation Law (1982), the revised Measures for the Administration of New Food Additives (2010), and the Food Safety Law (2015) specifies safety limits for solvent residues and additive approval pathways. Japan, through the Ministry of Health, Labour and Welfare (MHLW), provides regulatory guidance for nanostructured food materials, including requirements for toxicological assessment and material characterization. These regional regulations operate alongside broader international guidelines, such as FDA's permitted daily solvent exposure limits (0.5–38.8 mg/day), EFSA's risk assessment frameworks, and FSANZ's Food Standards Code, collectively highlighting the ongoing need for harmonized standards tailored to electrospun nanofiber technologies (Leidy & Maria Ximena, 2019). These issues are interdependent and must be addressed simultaneously to advance the industrialization and commercialization of electrospun nanofiber-based drug delivery systems in Asia.

Potential solutions to increase adoption of this technology

Several strategies have been proposed to ease the transition of electrospinning technology from laboratory research into industrial-scale manufacturing. Increasing production throughput through multi-nozzle and multi-jet electrospinning systems has shown promising results, with some platforms achieving outputs of 12–15 m²/h using up to 1200 nozzles (Lee et al., 2025; Zheng et al., 2020), (Ma & Hsiao, 2018). The adoption of centrifugal electrospinning, which integrates centrifugal and electrostatic driving forces, offers another pathway for large-scale production with improved fiber uniformity (Alatawi, 2025).

To reduce production costs, the development of continuous modular electrospinning lines has been suggested to lower both initial investment and operational expenses (Luo et al., 2024; Ojagh & Bakhshi, 2025). Additionally, optimized post-processing techniques such as solvent extraction using supercritical fluids or controlled freeze-

drying can improve fiber quality and reduce material waste (Celem & Tarakci, 2025).

Environmental sustainability can be improved through solvent recycling systems, which reduce the ecological burden associated with toxic organic solvents (Özgün Öztürk et al., 2024). Furthermore, aligning nanofiber fabrication with evolving regulatory requirements such as producing environmentally friendly, multifunctional, and fully characterized nanofiber systems will facilitate smoother commercialization pathways (Lee et al., 2025; Özgün Öztürk et al., 2024; Zheng et al., 2020).

Future research trends in Asia in the field of drug delivery using electrospun nanofibers

Research across Asia is rapidly expanding toward application-oriented innovation in electrospun nanofiber-based drug delivery systems. Nanofibers offer a unique advantage due to their high surface area-to-volume ratio, tunable porosity, and capability to encapsulate a wide range of bioactive molecules, including antimicrobial, anti-inflammatory, anticancer, and natural therapeutic agents (Mei et al., 2024; Meng et al., 2024), (Alzahrani et al., 2025; Flaig et al., 2024; Kamalpour et al., 2025; Wsoo et al., 2021; Xiao et al., 2020; Xu et al., 2025).

A growing trend is the development of implantable nanofiber-based delivery systems, enabling localized and sustained drug release while minimizing systemic toxicity, highly relevant for cancer therapy and postoperative care (Wsoo et al., 2021), (Xiao et al., 2020).

Research directions in Asia are expected to focus on several strategic areas that support the advancement and practical implementation of electrospun nanofiber-based drug delivery systems. One key direction involves enhancing local therapeutic relevance, particularly through the encapsulation of natural compounds and bioactive substances traditionally used in Asian medicine. Another important trend is the development of stimuli-responsive nanofibers, which enable controlled drug release triggered by environmental factors such as pH changes, temperature variations, enzymatic activity, or external electric fields. In addition, considerable attention is being directed toward production-scale optimization, aiming to establish stable and high-throughput electrospinning processes that can support large-scale industrial manufacturing. Furthermore, future research is expected to increasingly adopt interdisciplinary approaches, integrating pharmaceutical sciences,

biotechnology, and materials engineering to design more innovative, effective, and clinically translatable nanofiber-based drug delivery systems.

Despite significant progress, broader adoption in the Asian pharmaceutical industry will require clinical validation, economic feasibility studies, and regulatory harmonization. Strengthening regional collaboration and documenting successful translation of nanofiber-based technologies into commercial and clinical settings will play a crucial role in accelerating technological uptake

CONCLUSION

Electrospun nanofibers represent a powerful and versatile platform for modern drug delivery systems. Their intrinsic advantages—such as high surface area, interconnected porosity, and customizable structural and chemical properties enable improved drug loading efficiency, controlled release kinetics, and compatibility with a wide range of active substances. Variations in electrospinning techniques, including blend, coaxial, and emulsion methods, further expand the potential of nanofibers to encapsulate sensitive or complex therapeutic agents.

Recent advancements in Asian countries, particularly China, Japan, South Korea, India, and Malaysia, underscore the region's growing leadership in nanofiber-based therapeutics for applications such as cancer therapy, wound healing, and regenerative medicine. Continued innovation in polymer design, nanofiber architecture, and stimuli-responsive systems enhances the clinical relevance and technological maturity of this platform.

Overall, electrospun nanofibers offer a transformative approach to targeted, precise, and efficient drug delivery. The successful translation of this technology into clinical and industrial applications will depend on sustained multidisciplinary collaboration, investment in large-scale production infrastructure, and alignment with evolving regulatory frameworks. With strategic development, electrospun nanofibers are poised to become a key driver in the future landscape of pharmaceutical drug delivery in Asia and beyond.

ACKNOWLEDGMENTS

The author would like to express sincere appreciation to (author information removed for blind review) for their invaluable guidance and continuous support during the preparation of this

review article. The author also acknowledges Universitas Indonesia for providing academic support that facilitated the completion of this work.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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