Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc
ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 4, 2025
DOI (Journal): 10.37591/JoPC
Research JoPC

Electrospun Nanofibers for Biomedical and Pharmacological Applications

Prashant B. Patel[1], Shete A. S.[2,*], S. S. Sable[3], Vandana Sharma[4]

Abstract

In biological and pharmaceutical sectors, nanofibers which have unique properties including a lot of surface area, tunable porosity, and high mechanical strength are very fascinating and may be made flexibly and effectively by electrospinning. More and more in biosensors, tissue engineering, drug delivery, wound healing, and medication delivery are these electrospun nanofibers being used. They may fundamentally alter the way healthcare is administered. Advanced medical applications benefit from fibres' ability to be changed in thickness, orientation, and surface qualities. They can replicate the extracellular matrix and enable cells to interact and proliferate; hence they are ideal for use as scaffolding in tissue restoration. Because medications may be placed either within the fibres or on the surface for regulated and long-lasting release, electrospun nanofibers are a possible method for the pharmaceutical sector to provide pharmaceuticals. This approach decreases adverse effects, increases the bioavailability of medications, and improves their therapeutic efficacy. Additionally possible with electrospun nanofibers is the simultaneous release of many drugs. This qualifies them for combination therapy addressing cancer, disorders, and chronic conditions. Because they better retain moisture in and have higher mechanical characteristics that aid in wound healing, electrospun nanofibers are also employed in wound treatments. Including bioactive elements like as growth factors and antimicrobial peptides into the fibres helps the tissue repair more quickly and prevents the occurrence of infections

Keywords: Electrospinning, nanofibers, biomedical applications, drug delivery, tissue engineering

INTRODUCTION

Electrospinning is a well-known way to make nanofibers that have special qualities like a lot of surface area, holes, and flexibility, which makes them perfect for many biological and pharmaceutical uses. Nanofibers, which are usually between 1 and 1000 nanometres across, are much better than regular microscale fibres because they are stronger, have a higher surface area-to-volume ratio, and have a lot of holes in them. Electrospun nanofibers are very useful in fields like tissue engineering, drug delivery, wound healing, and biosensing, where fine control over the structure and function of materials is very important. Electrospinning pulls a polymer solution or melt into a fibre using a high-voltage electric field. The fibre stiffens when the liquid dries out. Based on the working circumstances, this simple approach may produce continuous fibres with diameters ranging from nanometres to micrometres. The porosity, mechanical strength, and surface qualities of the electrospun nanofibers may be adjusted to suit a particular need. Changing variables like the proportion of the solution, the voltage, and the kind of collecting employed can help one to also adjust their form and structure [1].

***Author for Correspondence**
Shete A. S

[1]Professor, Department of Instrumentation Engineering, Dr. D.Y. Patil Institute of Technology, Pimpri, Pune, Maharashtra, India
[2]Professor and Head, Department of Pharmaceutics, Krishna Vishwa Vidyapeeth (Deemed to be University), Krishna Institute of Pharmacy, Karad, Maharashtra, India
[3]Associate Professor, Department of Chemical Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India
[4]Associate Professor, Arya College of Pharmacy, Jaipur, Rajasthan, India

Received Date: March 20, 2025
Accepted Date: May 21, 2025
Published Date: June 05, 2025

Citation: Prashant B. Patel, Shete A. S, S. S. Sable, Vandana Sharma. Electrospun Nanofibers for Biomedical and Pharmacological Applications. Journal of Polymer & Composites. 2025; 13(Special Issue 4): S375–S387p.

This allows scientists to create nanofibers with ideal properties for certain biological and medicinal purposes. One of the most fascinating applications for electrospun nanofibers is tissue engineering. Electrospun fibres resemble the natural extracellular matrix (ECM) in several respects including surface area and pores. This makes them suitable for cells' growth, differentiation, and connection to each other. By altering the make-up and surface characteristics of these fibres, researchers can enable the proliferation of many kinds of cells. This makes them valuable for restoring skin, bone, cartilage, and nerve tissue.

By providing cells the mechanical support, biological signals, and physical framework they require to develop and rebuild tissues, electrospun nanofiber supports have been shown to help tissues grow again. Furthermore added to the fibres might be growth elements, cytokines, or other bioactive compounds to assist in body healing and tissue development once again. In tissue engineering as well as in drug delivery systems, electrospun nanofibers offer great possibilities. Over the conventional methods of medicine, being able to include beneficial compounds such medications, peptides, and proteins into electrospun threads offers several advantages [2]. By releasing healing substances in a regulated manner, nanofiber frameworks may reduce adverse effects, make medications more bioavailable, and help to limit the frequency of medication needed. Furthermore, electrospun fibres may be designed to release medications over extended times, therefore enabling regulated and long-lasting drug administration. Those with long-term diseases requiring long-term care may notably benefit from this [3]. Regarding cancer, electrospun nanofibers may be sent directly to the tumour to deliver chemotherapy medications, therefore reducing side effects affecting the entire body and increasing the efficacy of treatment. Figure 1 illustrates many applications of electrospun nanofibers in industry, environment, and medicine.

Using electrospun nanofibers to aid in wound healing is another vital area of study. Electrospun wound bandages are excellent for treating both fresh and chronic wounds as they include a unique combination of features. Their big pores allow air and water to pass through them easily, which maintains the surroundings suitable for healing of wounds. Mechanical characteristics of nanofibers promote construction; they may also include bioactive compounds such antibacterial agents, growth factors, or stem cells, therefore accelerating the healing process even more [4]. Faster healing of wounds, prevention of infections, and encouragement of tissue regeneration have been proven using nanofibers electrospun from electricity. For advanced wound treatment, this makes them a perfect fit. Because they have a huge surface area and may have certain biomolecules bonded to their surface [5], electrospun nanofibers are also under investigation for use in biosensing. These fibres allow you to create sensors capable of detecting many biomolecules, toxins, and environmental contaminants. The sensors will possess selective and sensitive qualities. Flexible and with a lot of surface area, electrospun nanofibers may be used to create very sensitive sensors capable of detecting extremely minute levels of target molecules. This qualifies them for medicinal usage [20-24].

BACKGROUND WORK

Originally developed in the 1930s, electrospinning has grown in popularity as a method of producing nanofibers as it can produce fibres with diameters typically between 50 nm and 1 μm. Under the electrospinning process, a polymer solution or melt is subjected to a high-voltage electric field. This generates a charged jet that becomes longer and stronger as it approaches towards a gathering. This results in continuous nanofibers that may be collected in many directions matches, sheets, or fibres aligned in rows. Over time, electrospinning has evolved and now it is considered as one of the most adaptable and scalable methods to create nanofibers with particular properties for a broad spectrum of purposes. People began to focus more in late 1990s and early 2000s on how electrospun nanofibers may be used in life sciences and medicine [6]. Because they resemble the extracellular matrix (ECM) present in biological tissues, researchers started investigating employing electrospun fibres as tissue engineering templates. Comparable to the structure of the ECM, electrospun nanofibers have a highly porous and flexible framework. Cells may therefore readily interact, proliferate, and differentiate. Electrospun nanofibers have so attracted a lot of attention for application in producing skin, bone, cartilage, neurones, and blood vessels. Because electrospun nanofibers can retain medications and release them gradually, they were originally investigated in the field of pharmacology for applications in drug transportation [7]. Working better by altering the composition, thickness, and surface properties of the fibre, scientists have developed nanofiber-based drug transport systems. These systems provide pharmaceuticals better stability, bioavailability, and potency. Controlled release electrospun nanofibers have enabled fresh approaches to treat cancer, infections, and chronic disorders. They do this by delivering drugs over a long period of time with few side effects. Adding bioactive chemicals like growth factors, antimicrobials, and peptides to electrospun fibres has also led to the creation of materials that can heal wounds in more than one way. Table 1 highlights important results, obstacles, and background work for different uses. These fibres not only support the wound physically, but they also help the tissue grow back and stop infections.

ELECTROSPINNING PROCESS

Overview of Electrospinning Mechanism

A high-voltage electric field is applied to a polymer solution or melt in the electrospinning process, which is a flexible way to make nanofibers. A polymer solution is put into a tube that is linked to a needle or spinneret to start the process. When a strong voltage is put on the needle and a grounded collection, an electric field forms around it. This field makes the polymer solution break through its surface tension and form a charged jet. Since this jet is being pulled towards the collector, it gets longer. It quickly solidifies as the liquid evaporates, making nanofibers [11]. Three forces act on the polymer fluid during the electrospinning process. These are the electric field, surface tension, and viscous forces. At first, the polymer solution forms a droplet at the tip of the needle. As the voltage rises, the electrostatic force beats the surface tension to form a Taylor cone. When the cone hits a certain point, the polymer solution is released as a fine jet. The charges pushing against each other cause the jet to stretch and thin. The polymer turns into nanofibers as the liquid disappears, and these fibres are then gathered on a platform [12]. Changing different parts of the electrospinning setup can change the size, structure, and qualities of the electrospun nanofibers. This makes the method very flexible and useful for many situations.

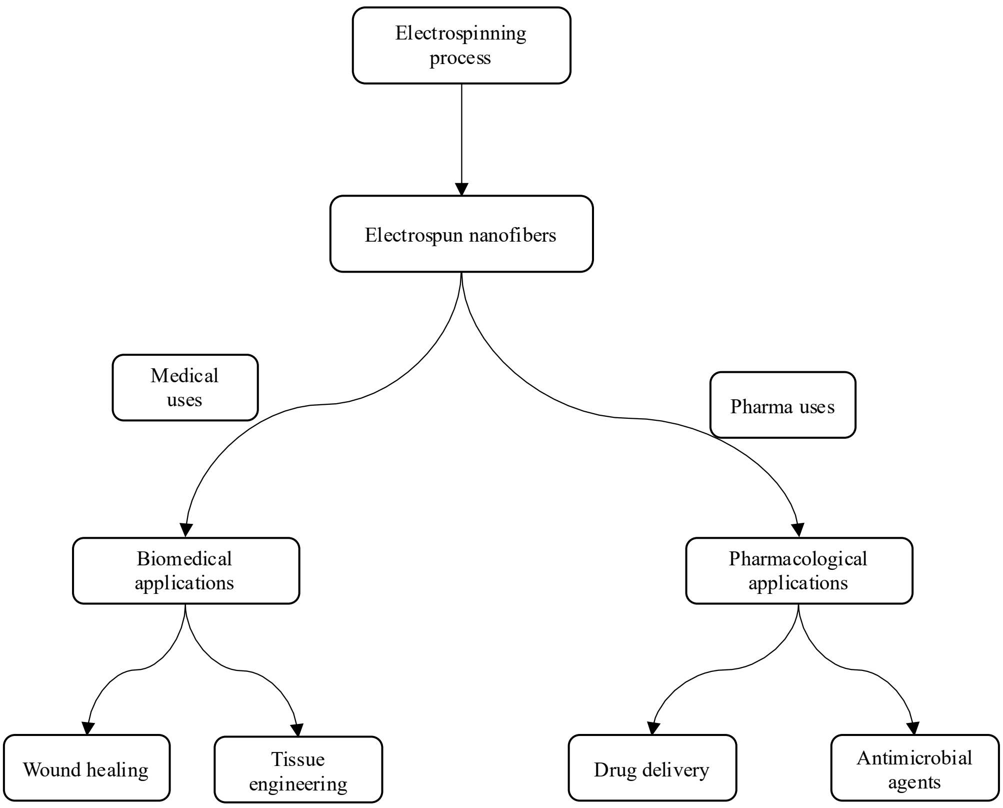

Figure 1. Illustrating electrospun nanofibers applications.

Table 1. Summary of Background work.

Application	Key findings	Challenges	Scope
Tissue Engineering	Electrospun scaffolds mimic ECM, promoting cell attachment and growth.	Scalability and uniformity of fiber formation.	Potential for regenerative medicine and personalized therapies.
Wound Healing	Nanofiber dressings enhance wound healing and reduce infection.	Material degradation and limited antimicrobial properties.	Widely applicable in chronic and acute wounds, enhancing recovery.
Drug Delivery Systems	Controlled drug release from nanofibers increases bioavailability and reduces side effects.	Achieving desired release profiles for a variety of drugs.	Promising for chronic disease treatments and localized drug delivery.
Bone Regeneration [8]	Electrospun nanofibers accelerate bone tissue regeneration and mineralization.	Maintaining mechanical strength and porosity for long-term use.	Could significantly improve clinical outcomes in orthopedic applications.
Skin Regeneration	Nanofibers promote skin regeneration by providing a scaffold for cell proliferation.	Optimizing nanofiber properties for various skin types.	Suitable for wound care, burn injuries, and cosmetic surgeries.
Cancer Treatment	Nanofibers deliver chemotherapy agents directly to tumor sites, improving efficacy.	Toxicity and difficulty in precisely controlling drug release.	Could provide more targeted and less toxic chemotherapy options.
Gene Delivery	Gene delivery via nanofibers shows potential in targeted gene therapy and DNA vaccination.	Ensuring efficient gene transfer and minimizing immune response.	Shows great potential for gene therapy and DNA vaccines.
Antibacterial Dressings [9]	Antimicrobial electrospunfibers show improved wound healing and infection prevention.	Ensuring the stability and effectiveness of antimicrobial agents in fibers.	Useful in preventing infections in wounds, burns, and surgical sites.
Vascular Tissue Engineering	Electrospun nanofibers promote endothelial cell growth, essential for vascular tissue regeneration.	Ensuring proper alignment and growth of endothelial cells.	Vital for developing functional blood vessels for tissue regeneration.
Wound Infection Control	Nanofibers incorporated with antibiotics prevent wound infections and promote healing.	Effectively preventing microbial infections while promoting healing.	Has potential for use in various wound types, reducing infection risk.
Bone Tissue Engineering	Polymeric nanofiber scaffolds enhance osteogenic differentiation for bone tissue engineering.	Achieving optimal mechanical and biological properties for bone regeneration.	Shows promise in developing advanced bone implants and prostheses.
Drug Loading and Release [10]	Nanofiber-based systems enable sustained release of anticancer drugs and growth factors.	Controlling the release rate of multiple drugs from nanofiber-based systems.	Can be utilized for personalized cancer treatments and combination therapies.
Cellular Behavior Modulation	Electrospunfibers modulate cellular behavior and support tissue development by mimicking ECM properties.	Fine-tuning fiber composition to optimize cellular responses.	Can be optimized for different tissue types, improving therapeutic efficacy.

Materials Used for Electrospinning

Usually, polymer melts or solutions are used for electrospinning. These materials need to have certain qualities in order for the process to work. The polymers can be man-made or natural, and they are chosen based on how well they can melt or make a solution that can be woven into small fibres. Poly(lactic acid) (PLA), polycaprolactone (PCL), polyvinyl alcohol (PVA), and polyurethane (PU) are all common man-made polymers used in electrospinning. A lot of people also use natural polymers like collagen, silk fibroin, and chitin because they are biocompatible and biodegradable and can be used in medicinal settings [13]. The electrospinning process is much influenced by the molecular weight, quantity, and solvation capacity of the chosen polymer; therefore these factors define its importance.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

For stable nanofibers, for example, polymers with low molecular weight or those that dissolve poorly may not be feasible. Conversely, greater molecular weight polymers could provide fibres with superior mechanical properties but may need more time or power to manufacture. One may also include compound materials into the electrospinning fluid. Among them are bioactive substances, nanoparticles, and polymer blends [14]. This may enhance the characteristics of the nanofibers for certain applications like tissue engineering or medication delivery.

Parameters Affecting Nanofiber Properties (E.G., Solvent Type, Voltage, Distance)

Changing many stages of the electrospinning process helps to optimise the characteristics of electrospung nanofibers. Among the most crucial factors influencing the form, structure, and purpose of nanofibers are solvent type, voltage, and the distance between the needle and collection.

- *Type of fluid:* The type of fluid used to dissolve the polymer has a big effect on the electrospinning process and the qualities of the fibre that is made. The solvent needs to be able to break down the polymer enough to make a solid solution, but it also needs to evaporate quickly enough to let fibres form. A good solvent will let smooth jets form, while a bad solvent might lead to problems like beads forming or fibre sizes that aren't all the same [15]. The instability and absorption rate of the solvent can also change the shape of the fibres and the speed at which they are formed.
- One of the most crucial elements influencing the electrospinning process is the employed voltage. The electric force increases with rising voltage. This renders the polymer jet thin and dispersed. Apart from the voltage, the formation of fibres depends much on the formation of the Taylor cone at the needle tip. On the other hand, if the voltage is too high the jet may become unstable and instead of continuous threads dips will develop. Therefore, the voltage must be precisely adjusted to get the desired fibre size and uniformity. The distance between the collector and the needle is the fibre composition is largely influenced by the "tip-to--collector distance," or the distance between the needle and the collection. Given their less stretching, the fibres may be thicker if the distance is shorter. Longer distances mean that the fibres will strain more and shrink [16]. The optimal distance depends on the voltage applied as well as the viscosity and surface tension of the solution. Making the nanofibers operate in certain ways depends on adjusting this number to modify the thickness, orientation, and density of the fibre.

BIOMEDICAL APPLICATIONS OF ELECTROSPUN NANOFIBERS

Tissue Engineering and Scaffolds

Because they can replicate the extracellular matrix (ECM), which is crucial for enabling cells to stay together, develop, and differentiate, electrospun nanofibers have attracted a lot of interest in tissue engineering. Scaffolds are required in tissue engineering to provide cells shape and facilitate their waste and nutrient sharing. Perfect for this are electrospun nanofiber scaffolds as they are robust, have plenty of surface area, and allow their porosity to be altered. The flexible construction of electrospun scaffolds is somewhat comparable to that of the natural ECM. Cells find it simple to adhere to and expand in this regard. Both man-made and natural materials may be used to create nanofiber scaffolding, so their characteristics can be altered to suit the tissue that has to be healed. Natural polymers such as collagen and fibrin enable cells to interact and carry bioactive actions [17]. Synthetic polymers simplify manufacturing and increase stability; examples of these include poly (lactic acid) (PLA) and polycaprolactone (PCL). Furthermore added to the surface of electrospun nanofibers are bioactive compounds like peptides, cytokines, and growth factors, thereby enhancing cell reactivity and tissue healing even more. Many diverse tissues including skin, bone, cartilage, and nerve cells can regenerate again using these scaffolds with additional purposes. The fact that electrospun nanofibers for tissue engineering promote blood vessel development in the tissue is among its finest features. Blood vessels-like formations may develop from the connected and porous nature of the fibres. Bigger tissues' survival and development depend on this.

Drug Delivery Systems

Electrospun nanofibers have become a possible method to release medications in a regulated manner as they may store many pharmaceuticals and bioactive compounds. Perfect for adding and releasing healing ingredients, electrospun fibres contain a lot of surface area and may be manufactured to have varying degrees of porosity. Depending on the kind of medicine and the desired release profile, nanofibers may retain medications in many different ways. These cover covalent bonding, physical packing, and electrostatic interaction. The ability of electrospun nanofiber-based drug delivery systems to release medications gradually and slowly over extended periods of time is among its finest features [18]. The release kinetics can be changed to fit the needs of different treatment uses by changing the polymer makeup, fibre diameter, and drug loading. Electrospun nanofibers can be used to send anti-cancer drugs, medicines, or anti-inflammatory drugs directly to the site of the disease. This reduces side effects in the body and makes therapy more effective. Nanofibers electrospun can also be made to carry more than one drug at the same time, which makes them good for combo treatments. Especially helpful for treating cancer, where several drugs with various ways of working may be needed to provide better results.

Wound Healing and Regeneration

Because they have a high surface area, a lot of holes, and good mechanical qualities, electrospun nanofibers have shown a lot of promise in helping wounds heal and grow back. Making workable wound coverings depends on this. Not often do conventional wound coverings provide the correct environment for healing. Conversely, electrospun nanofiber-based dressings are very excellent in helping wounds heal as they may provide greater gas exchange, muscle support, and moisture retention. Many microscopic pores in electrospun nanofibers allow oxygen and nutrients to reach the wound site readily. This makes it a perfect habitat for cells to migrate around and flourish [19]. Like the natural ECM, the flexible framework also enables cells to stay together and tissues to regenerate. By adding bioactive compounds like antibiotic peptides, growth factors, or stem cells to the electrospun fibres, these therapies may hasten the mending process, reduce the danger of infection, and increase tissue regeneration. Antimicrobial properties are rather crucial in cases of chronic wounds like diabetic sores or burn wounds, when infection is a major concern. Additionally customisable to your requirements are electrospun nanofiber treatments. The fibre width, polymer content, and surface characteristics of the dressing allow one to get the highest dynamic strength, medication release, and moisture retention. For example, whilst dressings with larger fibre diameters may provide the wound site greater muscle support, dressings with lower fibre diameters provide cells more sites to attach to and proliferate from. By promoting cell migration, angiogenesis, and collagen generation, including medicinal compounds within the nanofibers may also help the body recover and create fresh tissue.

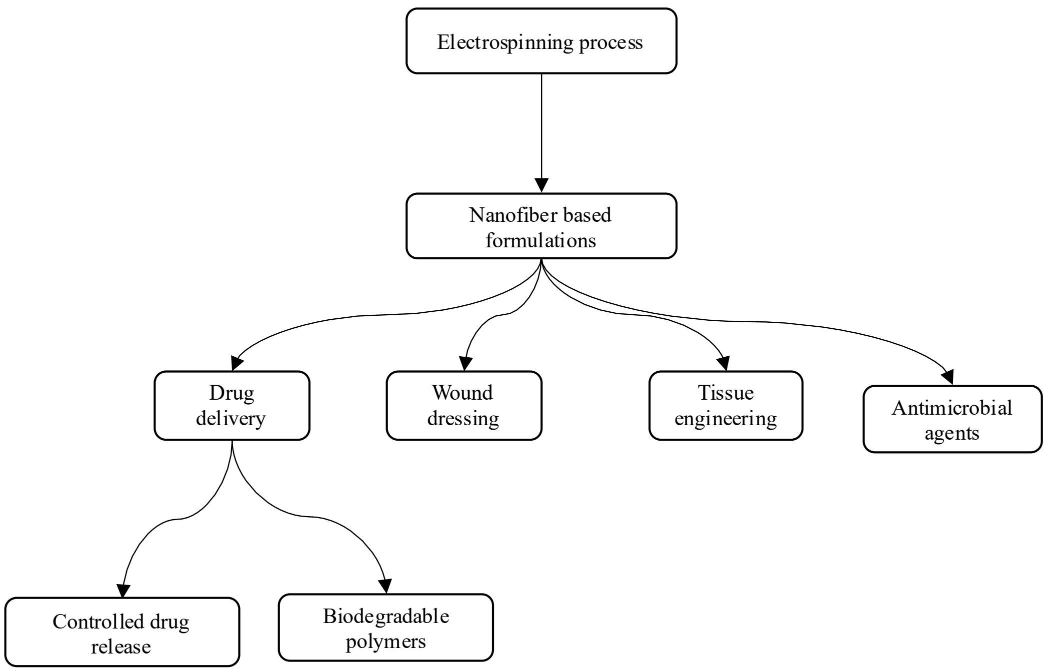

Figure 2. Illustrating nanofiber-based pharmaceutical formulations.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

PHARMACOLOGICAL APPLICATIONS OF ELECTROSPUN NANOFIBERS

Controlled Drug Release Systems

Among the most significant applications of electrospun nanofibers in pharmacology are controlled drug release systems. Because of their huge surface area, customisable porosity, and structural flexibility, electrospun nanofibers are excellent for encasing and releasing therapeutic substances in a controlled and sustained manner. By altering the polymer matrix, fibre thickness, and drug loading, researchers may create nanofiber-based systems releasing medications over extended times. Drugs so do not have to be administered as often as Those with long-term conditions like cancer, diabetes, and high blood pressure should particularly benefit from this as long-term medication adherence is very crucial. Physically enclosing several types of pharmaceuticals, including hydrophobic and hydrophilic compounds, proteins, peptides, and nucleic acids, electrospun nanofibers may They might do this in many ways: they can follow the medications, encasing them, or create covalent connections with them. Changing the polymer composition or adding other components, such as bonding agents or detergues, which alter how fast the fibre breaks down or dissolves, will affect how rapidly pharmaceuticals are released from nanofiber matrices. Often utilised to create nanofibers that break down over time and release the medicine within them in a regulated manner are biodegradable polymers such as poly(lactic acid) (PLA) or polycaprolactone (PCL).

Nanofiber-Based Pharmaceutical Formulations

Better in many respects than prior formulations, electrospun nanofibers have become a possible method to create novel medical formulations. Among the many medical applications for nanofiber systems are drug delivery, wound healing, tissue development, and pharmacological synthesis. Special qualities of electrospun nanofibers include many of holes, a tiny fibre diameter, and a great surface area. These characteristics let medications be more bioavailable, released more slowly, and loaded more effectively. Figure 2 illustrates how pharmaceuticals are delivered and their release is under control using nanofiber-based treatments.

For several medical purposes, this makes them valuable. Different kinds of medications may be produced from the many materials—man-made and natural—that can be utilised to create nanofibers. Active pharmaceutical ingredients (APIs) may be included into solid liquids or amorphous dispersions, for instance, using electrospun nanofibers. Drugs that don't dissolve readily find it much simpler to dissolve and dissolve faster. This is particularly useful for lipophilic medications that do not readily dissolve in the body. Furthermore flexible electrospinning allows bioactive compounds like peptides, proteins, enzymes, and nucleic acids to be included to nanofiber-based products. This makes a great variety of medical applications feasible. Devices releasing medications via the skin may also be created using nanofiber-based medicine formulations. Because electrospun threads are so tiny and contain so much surface area, medicines may readily pass over the skin. One alternative to using medications orally or via injection is this one. Furthermore, one may create electrospun nanofibers to release medications under control. Consequently, medications are released gradually over time, so dosages are not as necessary to be taken as regularly. This approach not only helps patients continue through with their therapy but also increases its efficacy by maintaining body medication levels stable.

Biocompatibility and Toxicity Evaluation

Before they may be used in biological and medicinal environments, electrospun nanofibers have to be completely examined for biocompatibility and probable toxicity. Biocompatibility is the ability of a substance to perform as it should without damaging the body. With their tiny size and great surface area, electrospun nanofibers may interact with tissues and cells in unusual ways. Their cytotoxicity, inflammation, and overall safety need to so be carefully examined. The substance the biocompatible electrospun nanofibers are composed of mostly affects their biocompatibility. Because they resemble the extracellular matrix of the body, natural polymers such collagen, chitosan, and alginate are biocompatible. This implies they might be used for wound healing and tissue engineering among other purposes. Often used for electrospinning are synthetic polymers such poly(lactic-co-glycolic acid) (PLGA) and polycaprolactone (PCL). Nevertheless, their biocompatibility must be investigated case-by-case as it relies on the breakdown products they generate and any existing chemicals. Toxicology studies are very crucial if one wants to completely grasp the probable risks of electrospun nanofibers entering the body. Cytotoxicity is often tested for in vitro research including cell survival tests (e.g., MTT, LDH). Conversely, in vivo investigations in animal models might provide a more whole picture of the material's safety. These investigations may identify any negative consequences such as swelling, an overactive immune system, or organ damage that can arise from using electrospun nanofibers.

CHALLENGES AND LIMITATIONS

Scalability and Production Challenges

Although electrospinning has been shown to be a helpful technique for producing nanofibers, its large-scale use may be challenging. On a small scale, the technique can generate carefully regulated quality nanofibers. On an industrial level, nevertheless, it is rather difficult to make this successful. Usually performed in batches, the electrospinning technique limits production and makes it difficult to produce a lot of low-cost nanofibers. Additionally difficult to maintain the appropriate processing parameters (such as voltage, flow rate, and humidity) over large regions when attempting to scale up might influence the regularity and consistency of the nanofibers. The fact that electrospun nanofibers must be constantly gathered presents another challenge. On a small scale, the fibres often aggregate on a flat surface or a spinning drum. But when the production needs to go up, bigger, better collectors need to be made so that the fibres are spread out evenly. Large-scale production is also hard because of the high cost of raw materials, the need to precisely control external factors like temperature and humidity, and the use of a lot of energy. Because of these problems, scientists are working on making electrospinning systems that work better so they can make more nanofibers while keeping their quality and regularity. Different approaches, like needleless electrospinning and multi-nozzle sets, are also being looked into to make output more flexible and lower prices. Even though there are problems, electrospun nanofibers are still a hopeful technology. In the future, it should be easier to make a lot of them because process engineering is getting better all the time.

Material Limitations and Biocompatibility

Nanofiber-based medicinal uses depend on the materials that are used for electrospinning working well. Electrospun nanofibers can be made from a lot of different manufactured and natural polymers, but there are some material limits that need to be thought about. It is very hard because plastics don't always dissolve in the liquid that is used. To make an electrospinning-safe steady solution, polymers must be able to dissolve in a solvent. However, some polymers, especially natural ones, may not dissolve well in common solvents. This limits the kinds of materials that can be electrospun and can make it harder to make nanofibers that work in certain ways. Another challenge is obtaining desired mechanical properties of electrospun nanofibers. Although electrospun nanofibers are very flexible and have a lot of surface area, their mechanical strength may not be sufficient for certain applications, particularly those involving long-term or weight-bearing usage like bone tissue engineering. Scientists are creating hybrid materials that are, combinations of many polymers or add nanoparticles to nanofibers to increase their strength to solve this dilemma. Especially for therapeutic applications, biocompatibility is another crucial consideration when selecting materials for electrospinning. Natural polymers are biocompatible by nature include collagen, chitosan, and fibrin. Conversely, synthetic polymers such as poly(lactic acid) (PLA) and polycaprolactone (PCL) could require their surfaces altered or functionalised to ensure they are biocompatible.

Regulatory and Safety Concerns

Safety and regulatory concerns have made it difficult for electrospun nanofibers to be extensively employed in clinical settings while their use in biological and pharmaceutical environments is increasing. Although nanomaterials are employed in medicine, their tiny size and great surface area might lead to unknown biological effects that must be carefully considered for safety. Strict policies in place by regulatory authorities such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) guarantee that pharmaceuticals and medical equipment are safe and functional. When it comes to nanoparticles, these guidelines are not always apparent, however, and regulating institutions are still evolving to handle the special issues nanotechnology raises. Because they are so tiny, nanofibers can cross past biological barriers and interact with cells in ways that more bulk materials cannot. Among the primary safety concerns are these ones. Should it enter your lungs, skin, or vital systems, it might have negative consequences like inflammation, cell death, or immunological reactions. Comprehensive safety investigations both in vitro and in vivo will help us to determine any hazards associated with electrospun nanofibers. Before being utilised in a medical environment, a drug has to be meticulously examined for long-term safety, biodegradability, sterilisation, and toxicity. Particularly those produced from man-made polymers, the breakdown products of electrospun nanofibers must be safe for the body to manage and non-lethal. Furthermore, sterilising electrospun nanofibers is rather crucial to prevent their contamination or infection, particularly in cases of wound healing or medicine carrying. More and more effort is being done to standardise the testing techniques for nanoparticles and provide clear guidelines for their use in medications and medical equipment in order to manage these legal concerns. As additional data on the safety, efficacy, and biocompatibility of electrospun nanofibers is acquired, regulatory agencies are probably going to modify their guidelines regarding them. This will facilitate acceptance of these materials for therapeutic usage.

RESULT AND DISCUSSION

Electrospun fibres' large surface area and adjustable features made them a great place for cells to connect and grow, which is why they are useful for tissue regrowth. Nanofibers that were loaded with drugs also had controlled release patterns, which improved the stability and absorption of the drugs. Adding bioactive molecules made the treatments work even better, especially when it came to fixing wounds, where nanofiber bandages sped up the process and cut down on infection. Even though electrospinning has many benefits, it still faces problems like scalability, material limits, and legal hurdles. These problems need to be fixed so that electrospinning methods and materials can be used in more clinical settings.

Table 2 shows the results of testing electrospun nanofibers for tissue engineering with four different types of polymers. The tests focused on important factors like fibre thickness, porosity, cell survival, mechanical strength, and biodegradation rate. Figure 3 shows how different types of polymers relate in terms of their qualities, focussing on changes in their structure and performance.

The fibre width is a key factor in how well the structure can replicate the natural extracellular matrix (ECM). Polymer Type A makes fibres that are 350 nm in diameter, which may help cells stick together better than Polymer Type B's fibres, which are 450 nm in diameter.

Porosity affects the flow of nutrients and gases. Figure 4 looks at how polymer properties vary by type and shows how these properties have changed over time and under different situations. Polymer Type A has the most porosity (85%), which makes it a great choice for improving cell growth. Polymer Type B, on the other hand, has 78% less air holes and a more compact structure that might be better for load-bearing uses. Cell viability shows how well the scaffold can help cells grow. Polymer Type B had the best viability (92%), which means it is most compatible with cells.

Table 2. Tissue Engineering Evaluation:

Parameter	Polymer type A	Polymer type B	Polymer type C	Polymer type D
Fiber Diameter (nm)	350	450	420	380
Porosity (%)	85	78	80	82
Cell Viability (%)	90	92	88	91
Mechanical Strength (MPa)	5.2	4.8	6	5.5
Biodegradation Rate (days)	45	50	40	43

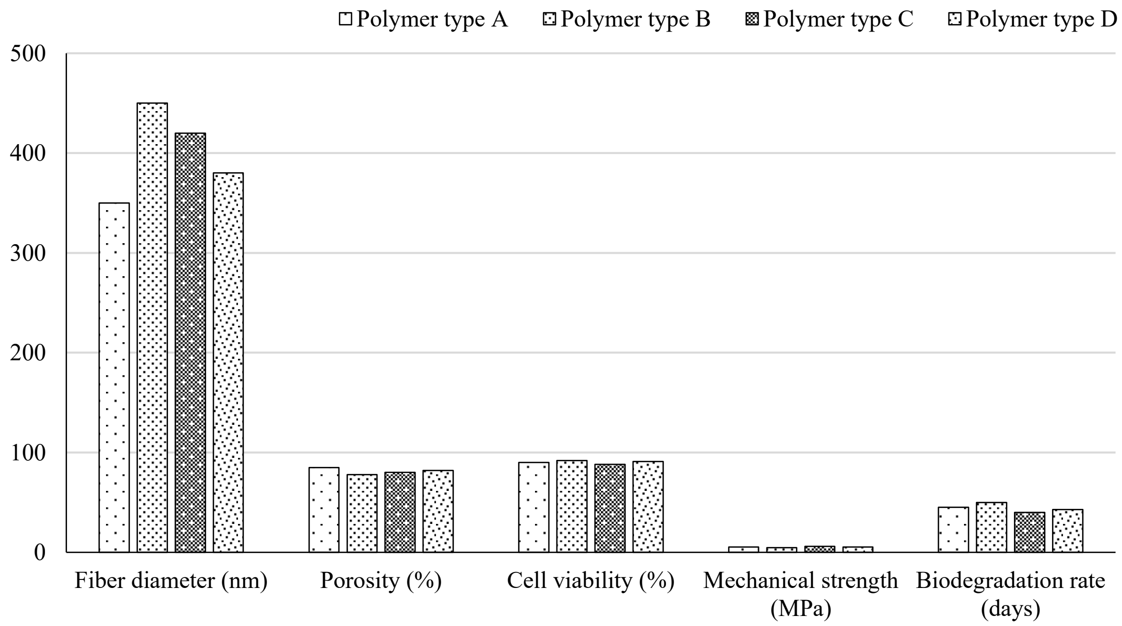

Figure 3. Comparison of polymer properties across different types.

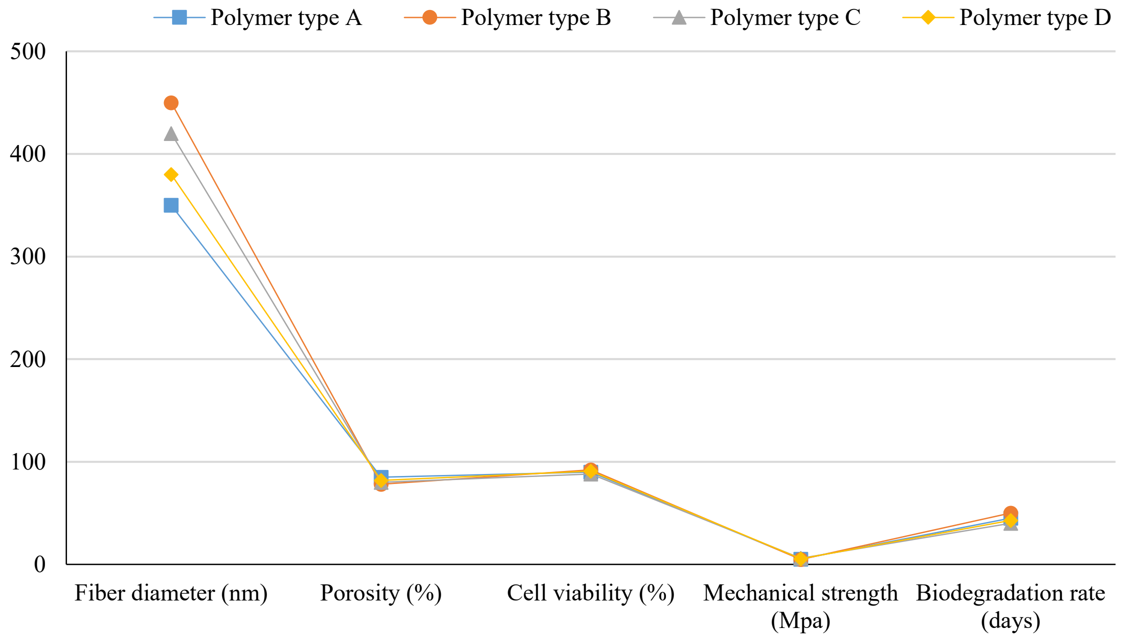

Figure 4. Trend analysis of polymer properties across types.

Table 3. Drug Delivery Evaluation.

Parameter	**Polymer type A**	**Polymer type B**	**Polymer type C**	**Polymer type D**
Initial Drug Load (%)	15	18	12	14
Release Rate (%)	60	65	55	62
Sustained Release Duration (hours)	48	45	50	47
Cumulative Release (%)	85	88	80	83

Journal of Polymer & Composites
Volume 13, Special Issue 4
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Table 3 shows the results of testing four different types of polymers on electrospun nanofibers for drug transport. The tests looked at things like initial drug load, release rate, steady release length, and total release. Figure 5 shows how different types of polymers affect the rate at which drugs are released.

The starting drug load is a little different for each type of polymer. Polymer Type B has the biggest load (18%), which means it can carry more drug. Polymer Type C has the lowest load (12%), which could make it useful for uses that need a smaller drug amount. Another important factor is the release rate. Figure 6 shows how much of the drug is released over time using different polymers.

Polymer Type B has the fastest release rate (65%), closely followed by Polymer Type D at 62%. Polymer Type C releases drugs the slowlyst (55%), which suggests it might work better for managed, slower drug delivery. The steady release duration is pretty much the same for all four polymers. Polymer Type C has the longest duration (50 hours), making it perfect for long-term medicinal uses. The cumulative release shows how much of the drug is released over time. Polymer Type B has the biggest cumulative release (88%), which means that the drug is delivered more completely.

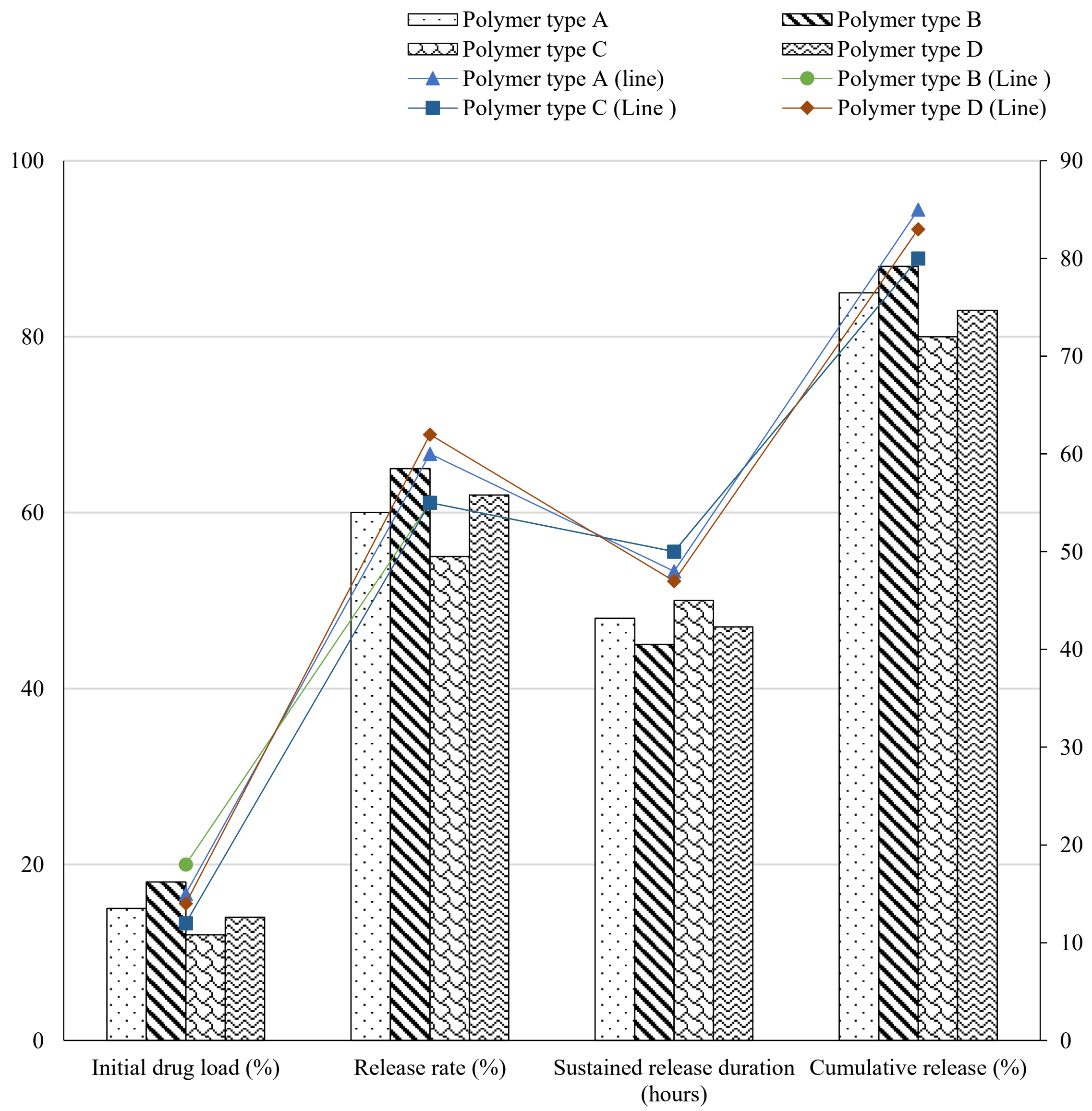

Figure 5. Drug release profile of different polymer types.

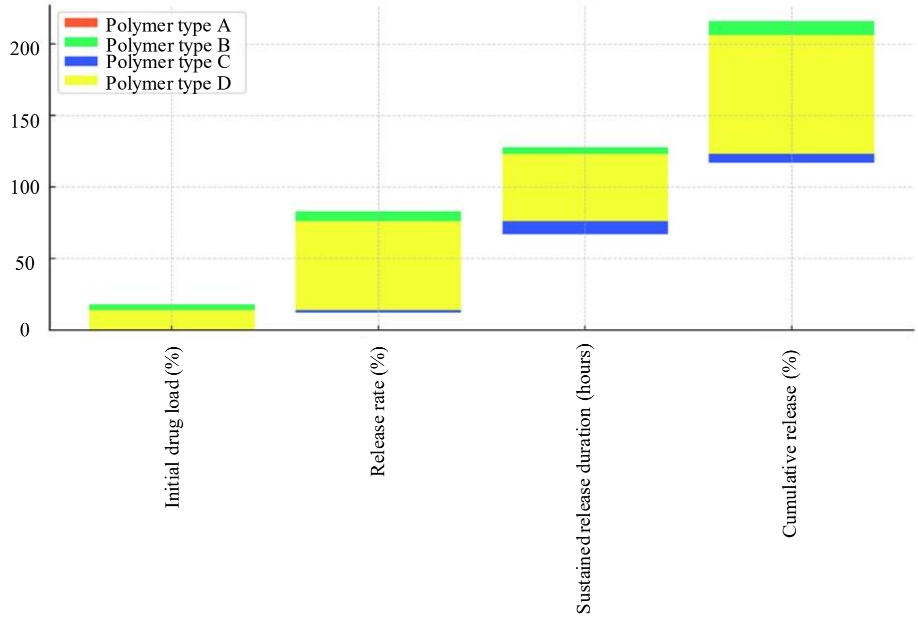

Figure 6. Cumulative drug release analysis across polymers.

CONCLUSION

Electrically spun nanofibers are a new and exciting technology that has a lot of uses in medicine and pharmacology. Because they have a lot of surface area, adjustable porosity, and different fibre shapes, they are perfect for use in tissue engineering, controlled drug delivery, and wound healing. Electrospun nanofiber supports create a natural setting for cell growth and division, which makes it possible for tissues like skin, bone, and cartilage to grow back. They can also contain drugs and bioactive molecules, which lets them be released slowly and steadily. This increases the bioavailability of medications and enhances the outcomes of therapy. By adding antibacterial agents or growth factors, electrospun nanofiber bandages help the wound heal quicker, reduce the risk of infection, and promote tissue regeneration, hence surpassing conventional methods of healing wounds. Furthermore, electrospun nanofibers may be tuned to respond to certain outside variables, such as temperature or pH. This makes it possible to send drugs precisely to the right place, which is especially useful for treating cancer and chronic diseases. Even though electrospun nanofibers have amazing qualities, there are still some problems that need to be fixed before they can be widely used in clinical settings. Scalability is still a big problem because the electrospinning methods we have now are mostly good for small-scale production. To make electrospun nanofibers a business reality, we need to find ways to make them quickly, cheaply, and on a big scale. To get around material limits like solubility and mechanical strength, mixed materials need to be used or polymers need to be functionalised for certain uses.

REFERENCES

1. Niemczyk-Soczynska, B.; Zaszczyńska, A.; Zabielski, K.; Sajkiewicz, P. Hydrogel, electrospun and composite materials for bone/cartilage and neural tissue engineering. Materials 2021, 14, 6899.
2. Luraghi, A.; Peri, F.; Moroni, L. Electrospinning for drug delivery applications: A review. J. Control. Release 2021, 334, 463–484.
3. Dubashynskaya, N.V.; Skorik, Y.A. Patches as polymeric systems for improved delivery of topical corticosteroids: Advances and future perspectives. Int. J. Mol. Sci. 2022, 23, 12980.
4. Lata Wanjari, D. P. Bisen, Raunak Kumar Tamrakar. (2015). Photoluminescence behaviour of Cu doped ZnS Nanoparticles synthesized by wet chemical route method. Advance Physics Letter, 2(3), 12-15
5. Rajeev Singh. (2015). A Review of Applications of Polymer Electrets. Advance Physics Letter, 2(3), 16-20

6. Broadwin, M.; Imarhia, F.; Oh, A.; Stone, C.R.; Sellke, F.W.; Bhowmick, S.; Abid, M.R. Exploring electrospun scaffold innovations in cardiovascular therapy: A review of electrospinning in cardiovascular disease. Bioengineering 2024, 11, 218.
7. Berdimurodov, E.; Dagdag, O.; Berdimuradov, K.; Wan Nik, W.M.N.; Eliboev, I.; Ashirov, M.; Niyozkulov, S.; Demir, M.; Yodgorov, C.; Aliev, N. Green electrospun nanofibers for biomedicine and biotechnology. Technologies 2023, 11, 150.
8. Rather, A.H.; Khan, R.S.; Wani, T.U.; Beigh, M.A.; Sheikh, F.A. Overview on immobilization of enzymes on synthetic polymeric nanofibers fabricated by electrospinning. Biotechnol. Bioeng. 2022, 119, 9–33.
9. Omer, S.; Forgach, L.; Zelko, R.; Sebe, I. Scale-up of electrospinning: Market overview of products and devices for pharmaceutical and biomedical purposes. Pharmaceutics 2021, 13, 286.
10. Shi, S.; Si, Y.; Han, Y.; Wu, T.; Iqbal, M.I.; Fei, B.; Li, R.K.Y.; Hu, J.; Qu, J. Recent progress in protective membranes fabricated via electrospinning: Advanced materials, biomimetic structures, and functional applications. Adv. Mater. 2022, 34, 2107938.
11. Mao, Y.; Shen, W.; Wu, S.; Ge, X.; Ao, F.; Ning, Y.; Luo, Y.; Liu, Z. Electrospun polymers: Using devices to enhance their potential for biomedical applications. React. Funct. Polym. 2023, 186, 105568.
12. Li, Y.; Zhu, J.; Cheng, H.; Li, G.; Cho, H.; Jiang, M.; Gao, Q.; Zhang, X. Developments of advanced electrospinning techniques: A critical review. Adv. Mater. Technol. 2021, 6, 2100410.
13. Wu, S.; Dong, T.; Li, Y.; Sun, M.; Qi, Y.; Liu, J.; Kuss, M.A.; Chen, S.; Duan, B. State-of-the-art review of advanced electrospun nanofiber yarn-based textiles for biomedical applications. Appl. Mater. Today 2022, 27, 101473.
14. Li, Y.; Wang, J.; Wang, Y.; Cui, W. Advanced electrospun hydrogel fibers for wound healing. Compos. Part B Eng. 2021, 223, 109101.
15. Petrova, V.A.; Poshina, D.N.; Golovkin, A.S.; Mishanin, A.I.; Zhuravskii, S.G.; Yukina, G.Y.; Naumenko, M.Y.; Sukhorukova, E.G.; Savin, N.A.; Erofeev, A.S.; et al. Electrospun composites of chitosan with cerium oxide nanoparticles for wound healing applications: Characterization and biocompatibility evaluation in vitro and in vivo. Polymers 2024, 16, 1787.
16. Petrova, V.A.; Golovkin, A.S.; Mishanin, A.I.; Romanov, D.P.; Chernyakov, D.D.; Poshina, D.N.; Skorik, Y.A. Cytocompatibility of bilayer scaffolds electrospun from chitosan/alginate-chitin nanowhiskers. Biomedicines 2020, 8, 305.
17. Yang, D.L.; Faraz, F.; Wang, J.X.; Radacsi, N. Combination of 3D printing and electrospinning techniques for biofabrication. Adv. Mater. Technol. 2022, 7, 2101309.
18. Dilamian, M.; Joghataei, M.; Ashrafi, Z.; Bohr, C.; Mathur, S.; Maleki, H. From 1D electrospun nanofibers to advanced multifunctional fibrous 3D aerogels. Appl. Mater. Today 2021, 22, 100964.
19. Rahmati, M.; Mills, D.K.; Urbanska, A.M.; Saeb, M.R.; Venugopal, J.R.; Ramakrishna, S.; Mozafari, M. Electrospinning for tissue engineering applications. Prog. Mater. Sci. 2021, 117, 100721.
20. Palaniappan, M., Palanisamy, S., Khan, R. *et al.* Synthesis and suitability characterization of microcrystalline cellulose from *Citrus* x *sinensis* sweet orange peel fruit waste-based biomass for polymer composite applications. *J Polym Res* 31, 105 (2024). https://doi.org/10.1007/s10965-024-03946-0
21. Palanisamy, S.; Mayandi, K.; Palaniappan, M.; Alavudeen, A.; Rajini, N.; Vannucchi de Camargo, F.; Santulli, C. Mechanical Properties of Phormium Tenax Reinforced Natural Rubber Composites. *Fibers* 2021, *9*, 11. https://doi.org/10.3390/fib9020011
22. Karuppiah, G.; Kuttalam, K.C.; Palaniappan, M.; Santulli, C.; Palanisamy, S. Multiobjective Optimization of Fabrication Parameters of Jute Fiber/Polyester Composites with Egg Shell Powder and Nanoclay Filler. *Molecules* 2020, *25*, 5579. https://doi.org/10.3390/molecules25235579
23. Palanisamy, S.; Kalimuthu, M.; Santulli, C.; Palaniappan, M.; Nagarajan, R.; Fragassa, C. Tailoring Epoxy Composites with *Acacia caesia* Bark Fibers: Evaluating the Effects of Fiber Amount and Length on Material Characteristics. *Fibers* 2023, *11*, 63. https://doi.org/10.3390/fib11070063
24. Sumesh, K. R., Palanisamy, S., Khan, T., Ajithram, A., and Ahmed, O. S. (2024). "Mechanical, morphological and wear resistance of natural fiber / glass fiber-based polymer composites," *BioResources* 19(2), 3271-3289.

