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REVIEW ARTICLE

Advances in Electrospun Polymer-Based Nanofibers for Wound Healing: A Narrative Review

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ABSTRACT

Polymer-based nanofibers produced using electrospinning techniques have become a significant innovation in drug delivery systems, particularly in wound healing. The nanofiber structure, which resembles the extracellular matrix (ECM), provides an advantage in supporting tissue regeneration and drug release control, making it an effective solution for the treatment of acute and chronic wounds. The aim of this review is to analyze recent advancements in the use of polymer-based nanofibers for drug delivery in wound healing therapy. The method used is a systematic approach with modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Relevant literature was extracted from the ScienceDirect database using the keywords "polymers", "nanofiber", "electrospinning" and "wound healing", with the publication period limited to 2016–2025. From the search results that yielded 5,750 articles, a strict selection process narrowed them down to 21 relevant articles for analysis. The analysis results show that polymer-based nanofibers such as polyvinyl alcohol (PVA), polycaprolactone (PCL), and poly(n-vinylpyrrolidone) (PVP) demonstrate outstanding abilities in delivering antibacterial drugs, enhancing wound healing efficiency, and combating infections, especially in chronic wounds. Nanofiber technology also provides innovative solutions in mitigating bacterial resistance. In conclusion, polymer-based nanofibers open significant opportunities in the pharmaceutical field and wound healing therapy with more precise and effective drug release control.

Keywords: Drug delivery, electrospinning, nanofibers, tissue regeneration, wound healing

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Introduction

Wound healing is a complex biological process that unfolds in four main stages: hemostasis, inflammation, proliferation, and tissue remodeling. The primary goal of this process is to restore the structure and function of damaged skin [1]. However, certain conditions such as chronic wounds resulting from diabetes or bacterial infections can disrupt these stages, hindering the healing process and increasing the risk of serious complications. The prevalence of chronic wounds continues to rise with the aging population and the increasing incidence of metabolic diseases like diabetes, presenting a significant challenge in clinical care [2], [3], [4]. Innovations in nanotechnology have offered promising solutions for accelerating wound healing, notably through the development of polymer-based nanofibers. These nanofibers possess unique properties that mimic the extracellular matrix (ECM), providing an environment that supports cell migration, proliferation, and tissue regeneration [5]. Electrospinning technology, the primary method for producing nanofibers, allows precise control over material properties, including fiber diameter, porosity, and surface area, all of which are critical for wound healing applications [6].

Polymer materials such as polycaprolactone (PCL), polyethylene oxide (PEO), collagen, and zein are commonly used in the fabrication of nanofibers due to their biocompatibility and favorable biodegradability. For instance, the combination of PCL and PEO has demonstrated the ability to enhance cell adhesion and proliferation by reducing the hydrophobic properties of PCL while also providing controlled drug release to support chronic wound therapy [4], [7]. Meanwhile, the development of core-shell nanofiber designs, such as those using combinations of PCL and zein, offers advantages in mechanical stability and water resistance, which are crucial for durable and effective wound dressings [4]. Furthermore, Eudragit-based nanofiber systems have been developed to respond to pH changes, enabling drug release tailored to the wound environment. In chronic wounds, which typically exhibit an alkaline pH, this technology can enhance antibacterial efficacy against pathogens such as Staphylococcus aureus and Escherichia coli. The incorporation of natural substances like thymol and farnesol with standard antiseptics such as chlorhexidine has also shown synergistic effects in combating bacterial biofilms that often impede wound healing [2], [3], [8].

State-of-the-art advancements in this field include the integration of technologies such as supercritical impregnation, which allows for the encapsulation of drugs within nanofibers without compromising their structural integrity. This technology enables the production of multifunctional wound dressings that not only protect the wound but also actively promote healing through controlled and sustained drug release [8]. Additionally, stimulus-responsive innovations, such as light or pH-triggered drug release, open the door to more sophisticated and personalized therapeutic applications [9]. However, despite the great potential of these technologies, challenges remain. Large-scale, consistent, and reproducible production of nanofibers, broader clinical testing, and the high cost of production are key obstacles that need to be addressed. Additionally, some synthetic polymers exhibit potential long-term toxicity, warranting more extensive safety evaluations regarding their use [5], [6].

This narrative review aims to explore the recent developments in the use of polymer-based nanofibers for wound healing. The primary focus is on material innovations, drug release mechanisms, and the challenges and opportunities in the development of this technology. By integrating findings from various studies, this review seeks to provide an in-depth understanding of the potential and limitations of nanofiber technology as a more effective and innovative solution for wound therapy.

Methods

The methodology for writing this narrative review follows a systematic approach based on the modified PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Literature search was conducted in the ScienceDirect database using keywords such as "polymers", "nanofiber", "electrospinning", and "wound healing," covering the publication period from 2016 to 2025. The search targeted research articles that are available in open access format and focused on the pharmaceutical field, particularly drug delivery systems relevant to wound healing. From an initial search that yielded 5,750 articles, a selection process was carried out by filtering for research articles, resulting in 2,277 articles. After restricting the selection to only open access articles, 409 relevant articles remained. The final selection, based on their relevance to pharmaceutical applications, particularly drug delivery systems and wound healing technologies, included 21 core articles for analysis. Potential applications in biomedical engineering, nursing care, and related healthcare fields are also acknowledged for further exploration.

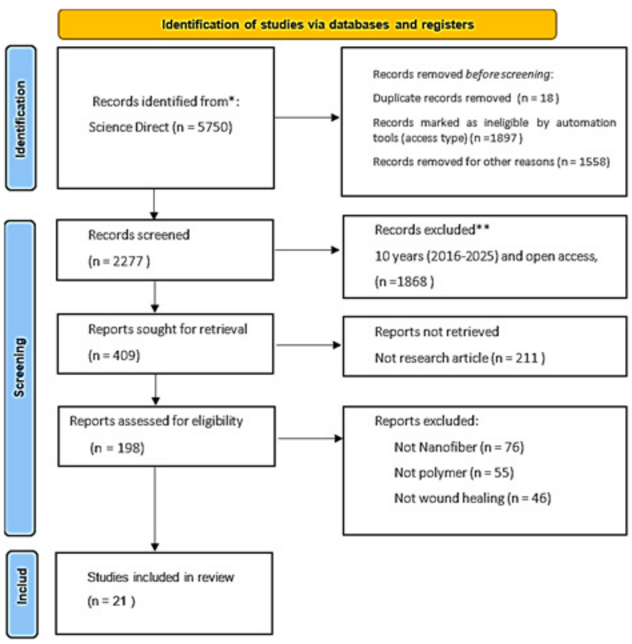

Figure 1. Review strategy scheme

Data extracted from the selected articles included the types of polymers used, electrospinning techniques, processing parameters, drug release mechanisms, biological applications such as antimicrobial activity and wound healing efficiency, as well as challenges and future prospects. The findings from this literature were synthesized qualitatively to present a detailed overview of recent advancements in polymer-based nanofiber technology, focusing on its applications in wound healing, including material properties, and fabrication techniques. The results of this process are summarized in a PRISMA flow diagram, illustrating the number of articles at each selection stage, as shown in **Figure 1**.

Results and Discussion

Introduction to Polymer Materials for Nanofibers

Polymer materials have become a key element in the development of nanofibers produced through electrospinning techniques. Both natural and synthetic polymers possess unique properties such as biocompatibility, biodegradability, and the ability to be physically and chemically modified, making them ideal choices for wound healing applications [4], [10]. Natural polymers, such as collagen, zein, and chitosan, are frequently used due to their bioactive properties that support tissue regeneration and cell migration. Collagen, as a major component of the extracellular matrix, mimics the natural biological environment, supporting fibroblast migration and accelerating epithelialization [6], [11]. Zein, a corn-derived protein, is utilized in core-shell nanofiber designs to enhance mechanical stability and water resistance, making it ideal for wound dressing applications [4]. Chitosan, with its inherent antibacterial properties, provides strong antimicrobial protection and accelerates wound healing [12].

Polymer combinations also enable the design of nanofibers with additional properties suitable for various medical applications. For example, the core-shell design based on zein and PCL allows for controlled drug release, providing sustained therapeutic effects while enhancing the mechanical stability of the nanofibers [4]. Additionally, pH-responsive Eudragit-based polymers offer further advantages for chronic wound therapy by responding to the changing pH conditions typical of infected wounds [13]. Meanwhile, synthetic polymers such as PCL and PEO offer greater flexibility in controlling material properties. PCL is known for its mechanical strength and slow biodegradation, making it ideal for sustained drug release applications [7]. However, the hydrophobic nature of PCL often limits cell adhesion and proliferation, which is why it is commonly combined with collagen, a hydrophilic polymer, to create an optimal binary polymer system [14]. With innovations in the combination of natural and synthetic polymers, nanofibers now have multifunctional capabilities, including drug release, tissue regeneration, and antibacterial activity. Further development of these materials will enable the optimization of their properties to support more effective wound healing applications in clinical settings. **Table 1** presents examples of polymer materials frequently used in the development of electrospun nanofibers for wound healing applications.

Table 1. Examples of polymer materials for nanofibers in wound healing

Polymer	Origin	Key Properties	References
Collagen	Natural	Biocompatible, supports cell migration, mimics ECM	[15]
Zein	Natural	High mechanical stability, sustained drug release	[4]
Chitosan	Natural	Antibacterial, supports tissue regeneration, accelerates wound healing	[12]
PCL	Synthetic	Slow biodegradability, high mechanical strength	[7]
Polyethylene oxide (PEO)	Synthetic	Hydrophilic, enhances bioadhesion and polymer degradation in combination	[7]

Polymer-based nanofibers offer remarkable breakthroughs in the medical field, particularly for wound healing. Their main advantage lies in the ability to integrate the unique properties of both natural and synthetic polymers into a cohesive solution. Collagen, for instance, exemplifies how biological inspiration can be harnessed to create materials that naturally support tissue regeneration. This reflects technological advancements moving us closer to "biocompatible" biomaterials. However, the greatest challenge arises from the diversity of materials themselves. Zein, known for its mechanical stability, and chitosan, valued for its antibacterial properties, are promising natural materials that require further optimization for clinical applications. Similarly, PCL, despite its mechanical strength, benefits from combinations with materials like PEO to enhance its hydrophobicity and bioadhesive properties. The success of such combinations shows that a multidisciplinary approach is key in the development of medical materials.

The use of pH-responsive Eudragit opens new possibilities for treating complex chronic wounds. This demonstrates that modern technology can create intelligent materials that adapt to a patient's specific conditions, offering hope for personalized therapies. Overall, polymer-based nanofibers not only promise better medical solutions but also pave the way for the development of more adaptive, efficient material-based technologies that support holistic healing. The combination of material innovation and clinical approaches serves as a cornerstone for a brighter future in the medical field.

Electrospinning Technology and Process Parameters

Electrospinning is a primary technique for the fabrication of polymer-based nanofibers, particularly for wound healing applications. This process utilizes a high-voltage electric field to draw a polymer solution from the tip of a needle towards a collector with an opposite charge, thereby forming nanoscale fibers with customizable structures. Electrospinning technology offers exceptional flexibility in controlling the physical and chemical properties of nanofibers through the manipulation of parameters such as voltage, distance between the needle and collector, solution viscosity, and flow rate of the solution [3], [7], [8]. At the core of the electrospinning process is the formation of the Taylor cone, where the electric field overcomes the surface tension of the polymer solution, resulting in a jet of fibers directed toward the collector. During this journey, the solvent evaporates, leaving behind solid fibers deposited on the collector. This process enables the creation of nanofibers with various morphologies, including continuous, porous, and core-shell designs, depending on the specific needs of the application, such as drug release or tissue regeneration support [4], [16].

Advancements in electrospinning technology have introduced methods such as coaxial spinning and supercritical impregnation. Coaxial spinning enables the production of nanofibers with a core-shell structure, where the core and shell layers can possess distinct materials and functionalities. For example, the combination of zein and PCL using this technique has been shown to enhance mechanical stability, water resistance, and controlled drug release over time [2], [11], [17]. On the other hand, supercritical impregnation is a technique for encapsulating drugs within nanofibers without compromising their structural integrity, allowing for controlled drug release to enhance the effectiveness of wound healing therapies [5], [9], [15].

The success of electrospinning is highly dependent on the precise adjustment of process parameters. Voltage, solution flow rate, and the distance between the needle and collector are key parameters that influence the morphology, diameter, and mechanical properties of the nanofibers. For instance, increasing the voltage results in smaller diameter fibers due to the stronger electrostatic force, while higher solution viscosity tends to produce thicker fibers [6], [10], [18]. Innovations in electrospinning continue to drive the development of new methods for producing high-performance nanofibers. Current research is focused on improving production efficiency, achieving more precise fiber structure control, and exploring new materials that can support clinical applications of nanofibers, including tissue regeneration, drug delivery, and antimicrobial activity [8], [19]. **Table 2** presents the key electrospinning parameters and their impact on the resulting nanofiber properties.

Table 2. Key parameters in electrospinning

Parameter	Description	Impact	References
Voltage	Electric field between the needle and collector (10-20 kV)	Fiber diameter, jet stability	[6], [7]
Needle-Collector Distance	Distance between the needle tip and the collector (10-20 cm)	Solvent evaporation time, fiber morphology	[3], [4]
Solution Flow Rate	Volume of solution flowing from the needle (0.5-1 mL/hour)	Fiber diameter, fiber continuity	[8], [15]
Solution Viscosity	Viscosity of the polymer solution (depends on polymer and solvent concentration)	Fiber diameter, droplet formation	[11], [18]
Solvent Composition	Type of solvent (water, DMF, Ethanol, or mixtures)	Effects on jet stability and solvent evaporation	[2], [16]

Table 2 outlines the key parameters in the electrospinning process that influence the formation and quality of nanofibers. Each parameter plays a crucial role in determining the

morphology, size, and stability of the nanofibers, making precise control of these factors essential for successful applications. Voltage is one of the most influential parameters in electrospinning, as a high electric field is required to produce a fiber jet from the polymer solution. Optimal voltage results in small and stable fiber diameters, but excessively high voltage can cause irregular fibers or disrupt the jet flow. The needle-collector distance also affects solvent evaporation time, which ultimately impacts the fiber structure. A distance that is too short may prevent the fibers from solidifying, while too long a distance reduces process efficiency. The solution flow rate controls fiber continuity; too high a flow rate can lead to droplet formation (beads), while too low a rate reduces productivity. Solution viscosity plays a role in determining the consistency of the jet flow and the structure of the resulting fibers. High-viscosity solutions tend to produce thicker fibers but may hinder the jet flow. Finally, solvent composition affects jet stability and solvent evaporation during the process. Selecting the right solvent, such as a mixture of organic solvents and water, is critical for producing uniform fibers. By optimizing these parameters, electrospinning can produce high-quality nanofibers for various applications, including wound healing, tissue regeneration, and drug delivery. **Figure 2** is an image depicting the electrospinning process.

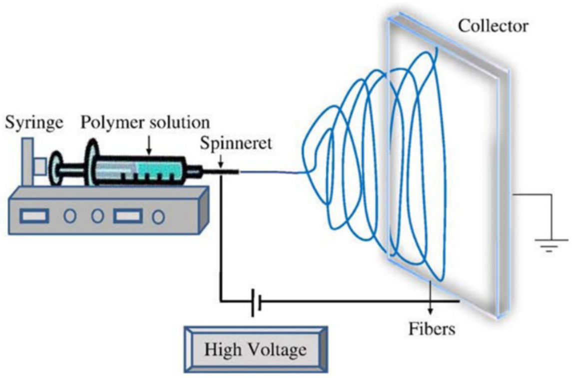

Figure 2. Schematic of electrospinning apparatus [20]

Nanofibers as Drug Delivery Systems

Polymer-based nanofibers produced via electrospinning technology have emerged as a significant innovation in drug delivery systems, particularly for wound healing applications. The structure of these nanofibers, resembling the ECM, offers distinct advantages in supporting gas diffusion, cell migration, and controlled release of bioactive molecules. These characteristics make nanofibers an effective tool for accelerating tissue regeneration and preventing infection in wounds [4]. One of the key benefits of nanofibers is their ability to control drug release. The release profile can be tailored to meet specific therapeutic needs through modifications in polymer material or electrospinning process parameters. For example, polymer-based systems such as Eudragit have been designed to respond to pH changes in the wound environment, particularly in chronic wounds with an alkaline pH. Eudragit-based nanofibers can release antimicrobial drugs, such as chlorhexidine, with high efficiency, providing optimal antimicrobial activity without damaging healthy tissue [2].

The use of combinations of natural and synthetic materials presents significant opportunities in nanofiber-based drug delivery systems. Bioactive molecules such as thymol and farnesol, known for their antibacterial and anti-inflammatory properties, have been successfully incorporated into nanofibers. When combined with synthetic polymers like PCL, these molecules enable more effective sustained drug release compared to conventional methods [3]. Additionally, core-shell nanofiber designs allow for separation of core and shell materials, creating a layered drug release profile that can address bacterial infections while promoting regeneration [21].

Nanofibers also hold great potential in addressing the challenge of bacterial resistance. For example, antibiotics such as ciprofloxacin can be incorporated into nanofibers with homogeneous distribution using the electrospinning technique. Research has shown that ciprofloxacin-loaded nanofibers can efficiently destroy bacterial biofilms while also accelerating wound healing in in vivo models [22]. Beyond antibiotics, antifungal agents, antioxidant molecules, and regenerative enzymes have also been integrated into nanofibers, expanding their therapeutic applications. To produce nanofibers capable of efficiently loading and releasing drugs, the electrospinning process parameters must be finely controlled. Parameters such as voltage, solution viscosity, and flow rate play crucial roles in determining the morphology of the nanofibers and the efficiency of drug release. Higher voltage, for instance, results in fibers with smaller diameters, increasing the surface area and enhancing drug release [6]. These parameters allow for the customization of nanofibers to suit different types of wounds, including chronic wounds, burns, and other skin infections.

Table 3. Examples of nanofiber systems for drug delivery

Polymer Material	Drug Type	Nanofiber Design	Application in Drug Delivery System	References
Zein, PCL	Tetracycline Hydrochloride	Core-shell nanofibers	Topical drug delivery for wound healing with controlled drug release	[4]
PVA, Sodium Alginate	Ciprofloxacin	Electrospun nanofibers	Antibacterial drug delivery for wound care, controlled drug release	[22]
PLA	Levofloxacin	Drug-loaded electrospun fibers	Drug delivery for hernia tissue repair, controlled drug release	[15]
PVA, Hydroxypropyl Methylcellulose (HPMC), PEO	Acyclovir	Electrospun fibers, Core-shell fibers	Antiviral drug delivery for herpes treatment with rapid drug release	[18]
PVP	Silver Nanoparticles	Electrospun nanofibers embedded with AgNPs	Antibacterial drug delivery for wound healing, controlled silver release to prevent infection	[23]
Pectin, PEO	Chloramphenicol (CAM)	Nanofibers with encapsulated liposomes	Antibiotic drug delivery for chronic wounds, controlled drug release with liposomes	[5]

The development of nanofibers for drug delivery systems holds tremendous potential in the medical field, particularly for wound care, infection treatment, and chronic disease therapy. Nanofibers, with their unique properties of high surface area and the ability to control drug release, offer distinct advantages over conventional drug delivery methods. Various polymer types, such as PVA, PCL, and PVP, provide flexibility in designing drug formulations tailored to specific therapeutic needs. One of the most compelling aspects of nanofiber technology is its ability to encapsulate a wide range of drugs, from antibiotics (such as ciprofloxacin and chloramphenicol) to antivirals (such as acyclovir), which can be released in a controlled manner. This enables more effective solutions in preventing infections and accelerating healing, especially for chronic wounds that are difficult to treat. Furthermore, nanofibers encapsulated with liposomes or silver nanoparticles open new possibilities in maximizing treatment efficiency by reducing side effects and improving drug bioavailability. As research continues to evolve, the potential of nanofibers for clinical applications both in topical treatments and more advanced therapies such as cancer or systemic infections is highly promising. Moving forward, the development of drug-loaded nanofibers could revolutionize wound and infection care, paving the way for more precise and efficient drug delivery systems.

Biological Applications of Nanofibers in Wound Healing

Polymer-based nanofibers have demonstrated significant potential in biological applications, particularly in accelerating wound healing. The unique structure of nanofibers, which mimics the ECM, provides an environment that supports tissue regeneration through migration, adhesion, and proliferation of fibroblasts and keratinocytes. Furthermore, nanofibers enable the integration of bioactive molecules such as growth factors, antibacterial agents, and anti-inflammatory compounds, making them a multifunctional solution for both acute and chronic wounds [4]. Nanofibers serve not only as carriers for bioactive molecules but also as scaffolds for new tissue growth, thereby enhancing the healing rate and reducing the risk of infection. One of the primary applications of nanofibers is in supporting tissue regeneration. Polymers such as collagen, a major component of the ECM, are frequently utilized due to their high biocompatibility. Collagen-based nanofibers have been shown to accelerate fibroblast proliferation and enhance epithelialization in burn and chronic wounds. The combination of collagen with materials like chitosan imparts antibacterial properties, which are crucial in addressing infections in wound sites [24]. Chitosan, with its antimicrobial and biocompatible characteristics, is often incorporated into nanofiber formulations to further enhance wound healing efficacy.

Environment-responsive nanofibers offer further advantages for complex wound healing. Systems based on Eudragit, for example, can respond to pH changes in the wound area. In chronic wounds with an alkaline pH, these nanofibers release antimicrobial agents, such as chlorhexidine, with high efficiency, providing optimal therapeutic effects. This approach is particularly important for addressing pathogenic microorganisms that often become resistant in abnormal wound environments [2], [13]. Such responsive systems enable more targeted and condition-specific drug delivery, marking a significant breakthrough in the treatment of complex wounds and difficult-to-treat infections.

Overall, the use of nanofibers in drug delivery systems and wound care presents tremendous promise. With their tunable physical, chemical, and biological properties, nanofibers offer innovative solutions for wound management, reducing infections, and accelerating healing through more controlled and precise therapies. **Table 4** presents examples of biological applications of nanofibers in wound healing

Table 4. Examples of biological applications of nanofibers in wound healing

Nanofiber Material	Primary Function	Biological Outcomes	Application Advantages	References
PCL, Collagen, Gelatin	Scaffold-based wound dressing	Enhances fibroblast adhesion and proliferation, accelerates burn wound healing	High biocompatibility, supports new tissue formation	[24], [25]
Polyvinyl Alcohol (PVA), Sodium Alginate	Antibiotic delivery for chronic wounds	Effective against bacterial biofilms (*Staphylococcus aureus*, *Pseudomonas aeruginosa*), supports skin regeneration	High bioavailability, controlled antibiotic release	[26], [27]
Zein, Polycaprolactone Core-Shell	Controlled drug release for wounds	Controlled release of tetracycline hydrochloride, enhances wound strength	Reduces infection risk, improves water stability	[4]
Poly(N-vinylpyrrolidone) (PVP), Silver Nanoparticles	Antibacterial membrane for acute wounds	High effectiveness against both Gram-positive and Gram-negative bacteria, non-cytotoxic	High stability with controlled antimicrobial release	[23]
Polyvinyl Alcohol (PVA), HPMC-PEO	Antiviral delivery for herpes simplex virus	Higher antiviral activity against HSV compared to commercial formulations (Zovirax® cream)	Fast drug release with high efficacy	[18]
Pectin, Polyethylene Oxide (PEO)	Chronic wound dressing with antibiotics	Controlled release of Chloramphenicol, high biocompatibility, supports angiogenesis	Effective solution for chronic wounds with stable antibiotic release	[5]
PCL, Irgasan, Levofloxacin	Antibiotic-based wound dressing for hernia	Broad antibacterial effect, prevents postoperative infection, supports hernia tissue regeneration	Controlled drug release, improves post-surgery clinical outcomes	[15], [28]
PCL, Gelatin	Scaffold for burn wound regeneration	Accelerates epithelial and collagen regeneration in wounds, improves biocompatibility	Addresses high-degree burns with regenerative stimulation effects	[25]
Polyurethane (PU), Lactoferrin	Wound dressing with bioactive agents	Enhances antimicrobial activity, promotes fibroblast growth at wound sites	High biocompatibility, accelerates chronic wound healing	[8]
Chitosan, Hyaluronic Acid	Regenerative scaffold with antibacterial properties	Additional antibacterial properties, supports fibroblast adhesion and epithelialization in wounds	Optimal combination of regenerative and antibacterial properties	[29]

Table 4 illustrates various nanofiber materials used in wound healing, highlighting their functions, biological outcomes, and advantages. One notable material is PCL and collagen, which serves as a regenerative scaffold-based wound dressing. This combination enhances fibroblast adhesion and proliferation, accelerating the healing process of burn wounds [24]. Its high biocompatibility and ability to support new tissue formation make it an ideal choice for skin regeneration in severe burns.

Additionally, PVA and sodium alginate are used for antibiotic delivery in chronic wounds. This material effectively combats bacterial biofilms, including *Staphylococcus aureus* and *Pseudomonas aeruginosa*, which are commonly found in infected wounds [30]. PVA and sodium alginate offer high bioavailability and can release antibiotics in a controlled manner, ensuring more effective wound healing and preventing recurrent infections. Other applications demonstrate the versatility of nanofibers in wound treatment, including antibacterial functions, controlled drug delivery, and inflammation reduction. Materials like polyurethane (PU) with lactoferrin and chitosan with hyaluronic acid combine antibacterial and regenerative properties, offering excellent potential for accelerating chronic wound healing, improving tissue repair, and preventing infections [8], [29].

Conclusion

The use of nanofibers in medical applications has made significant progress in wound therapy, with key advantages such as biocompatibility, controlled drug release, and enhanced healing efficiency, resulting in improved clinical outcomes for patients.

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