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Review Article

Recent Advances in Chitosan-Based Blended Nanofibers: Fabrication, Structural Characterization and Biomedical Applications

Dr. Samrat Khedkar, Dr. Nitin Mali, Vaibhav Shingade*

Vidya Niketan College of Pharmacy, lakhewadi, Pune, Maharashtra, India 413103

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ABSTRACT

Chitosan-based blended nanofibers have gained significant attention in recent years because of their excellent biocompatibility, biodegradability, mechanical strength, and ability to support tissue regeneration. Blending chitosan with natural or synthetic polymers improves the physical, chemical, and biological properties of nanofibers, making them suitable for various biomedical applications. This review summarizes recent advances in the fabrication methods, structural characterization, and biomedical applications of chitosan-based blended nanofibers. Different fabrication techniques, including electrospinning and chemical crosslinking, are discussed along with characterization methods such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Thermal Analysis, and mechanical property evaluation. The review also highlights the potential applications of these nanofibers in wound healing, drug delivery, tissue engineering, antimicrobial therapy, and regenerative medicine. Overall, chitosan-based blended nanofibers are promising biomaterials for developing advanced healthcare products because of their excellent biological performance, safety, and versatility.

INTRODUCTION

Nanotechnology is an emerging field of science that deals with materials having sizes between 1 and 100 nanometers. Nanomaterials possess unique physical, chemical, and biological properties that differ from their bulk materials due to their extremely small size and large surface area.

These properties have led to their widespread use in medicine, pharmaceuticals, biotechnology,

tissue engineering, and drug delivery. Among different nanomaterials, nanofibers have gained considerable attention because of their high surface area, porous structure, flexibility, and ability to mimic the natural extracellular matrix, making them suitable for various biomedical applications.[1–3]

Nanofibers are ultrafine fibers with diameters in the nanometer range. They provide an excellent

***Corresponding Author:** Vaibhav Shingade

Address: Vidya Niketan College of Pharmacy, lakhewadi, Pune, Maharashtra, India 413103

Email ✉: shingadevaibhav03@gmail.com

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platform for cell attachment, proliferation, and tissue regeneration. Their interconnected porous structure allows efficient nutrient transport and drug release, making them ideal for wound dressings, drug delivery systems, tissue engineering scaffolds, biosensors, and regenerative medicine. Different natural and synthetic polymers have been explored for nanofiber fabrication, among which chitosan has become one of the most extensively studied biopolymers because of its excellent biological properties.[4–6] Chitosan is a naturally occurring polysaccharide obtained by the deacetylation of chitin, which is mainly found in the shells of shrimp, crabs, and other crustaceans. It is biodegradable, biocompatible, non-toxic, and possesses remarkable antimicrobial, antioxidant, and wound-healing properties. Chitosan also exhibits excellent film-forming ability and supports cell adhesion and proliferation. These characteristics have made it an important biomaterial for pharmaceutical and biomedical applications. However, pure chitosan has certain limitations, including poor mechanical strength, limited solubility at neutral pH, and relatively low electrospinnability, which restrict its direct use in nanofiber fabrication.[7–9] To overcome these limitations, chitosan is commonly blended with other natural or synthetic polymers such as polyvinyl alcohol (PVA), polyethylene oxide (PEO), gelatin, collagen, alginate, cellulose, polycaprolactone (PCL), and polylactic acid (PLA). Blending improves the mechanical strength, flexibility, stability, and spinnability of nanofibers while maintaining the excellent biological properties of chitosan. The resulting blended nanofibers exhibit enhanced structural integrity, controlled degradation, and improved drug-loading capacity, making them highly suitable for advanced biomedical applications.[10–12]

Various fabrication methods have been developed for preparing chitosan-based blended nanofibers. Among these, electrospinning is the most commonly used technique because it produces continuous nanofibers with uniform diameter, high porosity, and large surface area. Other fabrication methods include solution casting, phase separation, freeze drying, and chemical crosslinking. The selection of fabrication method depends on the desired physical properties, intended application, and polymer composition. Proper optimization of fabrication parameters is essential to obtain nanofibers with suitable morphology and mechanical performance.[13–15] After fabrication, structural characterization plays an important role in evaluating the quality and performance of nanofibers. Various analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), tensile strength testing, swelling studies, and porosity measurements are widely used to determine the chemical structure, morphology, crystallinity, thermal stability, mechanical strength, and surface characteristics of the fabricated nanofibers. These analyses help ensure the reliability and reproducibility of nanofiber-based formulations.[16–18]

Chitosan-based blended nanofibers have demonstrated remarkable potential in several biomedical applications. They are widely investigated as wound dressings because of their antimicrobial activity, moisture retention ability, and promotion of tissue regeneration. They also serve as effective carriers for controlled drug delivery, allowing sustained release of therapeutic agents while minimizing side effects. Furthermore, these nanofibers are extensively used in tissue engineering, regenerative medicine,



antimicrobial coatings, and biosensor development. Their excellent biocompatibility and biodegradability make them suitable for long-term clinical applications.[19,20] Despite significant progress, challenges such as large-scale production, reproducibility, long-term stability, sterilization, and regulatory approval still need to be addressed. Future research should focus on improving fabrication techniques, developing multifunctional nanofibers, and conducting clinical studies to enhance their therapeutic potential. Overall, chitosan-based blended nanofibers represent a promising class of biomaterials that can contribute significantly to the advancement of modern biomedical and pharmaceutical sciences.

FABRICATION OF CHITOSAN-BASED BLENDED NANOFIBERS

The fabrication of chitosan-based blended nanofibers is an important step in developing advanced biomaterials for pharmaceutical and biomedical applications. Chitosan alone has excellent biological properties but poor mechanical strength and limited electrospinnability. Therefore, it is commonly blended with other natural or synthetic polymers to improve fiber formation, stability, flexibility, and mechanical performance. Common blending polymers include polyvinyl alcohol (PVA), polyethylene oxide (PEO), gelatin, collagen, alginate, polycaprolactone (PCL), and polylactic acid (PLA). These polymer blends produce nanofibers with improved structural integrity and enhanced biological performance.[21–23]

Among various fabrication techniques, electrospinning is the most widely used method for preparing chitosan-based blended nanofibers. In this technique, a polymer solution is loaded into a syringe and exposed to a high-voltage electric field. The electrical force stretches the polymer

solution into very fine fibers that are collected on a grounded collector. Electrospinning produces continuous nanofibers with uniform diameter, high surface area, and interconnected porous structures. Several parameters such as polymer concentration, applied voltage, flow rate, needle-to-collector distance, temperature, and humidity influence the quality and morphology of the nanofibers.[24–26] Chemical crosslinking is another important technique used to improve the stability and mechanical properties of chitosan nanofibers. Crosslinking agents such as glutaraldehyde, genipin, citric acid, and sodium tripolyphosphate are commonly used to strengthen the polymer network. Crosslinked nanofibers show better water resistance, slower degradation, and improved mechanical strength, making them more suitable for long-term biomedical applications.[27,28]

Other fabrication methods, including freeze-drying, solvent casting, phase separation, and self-assembly, are also employed depending on the intended application. Although these techniques may not produce fibers as uniform as electrospinning, they are useful for preparing porous scaffolds and drug delivery systems with controlled structures.[29]

STRUCTURAL CHARACTERIZATION OF CHITOSAN-BASED BLENDED NANOFIBERS

Structural characterization is essential to evaluate the quality, composition, and performance of fabricated nanofibers. It helps researchers understand the chemical interactions, morphology, crystallinity, thermal stability, and mechanical properties of the nanofiber matrix. Proper characterization ensures reproducibility and confirms the suitability of nanofibers for biomedical applications.[30]



- 1. Fourier Transform Infrared Spectroscopy (FTIR)** is widely used to identify functional groups and confirm interactions between chitosan and blending polymers. FTIR spectra provide information about hydrogen bonding, chemical crosslinking, and the successful incorporation of bioactive compounds into the nanofiber matrix.[31]
- 2. Scanning Electron Microscopy (SEM)** is commonly used to observe the surface morphology, fiber diameter, pore structure, and uniformity of nanofibers. SEM images help determine whether smooth, bead-free, and continuous fibers have been successfully produced. Uniform morphology is important for consistent drug release and cell attachment.[32]
- 3. X-ray Diffraction (XRD)** is used to study the crystalline or amorphous nature of nanofibers. Blending chitosan with other polymers often reduces crystallinity, resulting in increased flexibility and improved drug-loading capacity. XRD also helps evaluate changes in polymer structure after fabrication and crosslinking.[33]
- 4. Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA).** DSC measures melting temperature and thermal transitions, while TGA determines thermal stability and decomposition patterns. These techniques help predict the storage stability and processing conditions of nanofibers.[34]

Mechanical properties such as tensile strength, elongation at break, and Young's modulus are important for biomedical applications, especially wound dressings and tissue engineering scaffolds. Strong mechanical properties improve durability during handling and clinical use. Swelling studies,

porosity measurements, and water absorption tests are also performed to evaluate the ability of nanofibers to absorb biological fluids and maintain a moist environment, which promotes wound healing and tissue regeneration.[35]

BIOMEDICAL APPLICATIONS OF CHITOSAN-BASED BLENDED NANOFIBERS

Chitosan-based blended nanofibers have attracted considerable attention because of their excellent biocompatibility, biodegradability, antimicrobial activity, and ability to support cell growth. Their high surface area and porous structure make them suitable for many biomedical applications. These nanofibers can be loaded with drugs, growth factors, plant extracts, or nanoparticles to improve their therapeutic performance.[36,37]

One of the most important applications is wound healing. Chitosan nanofibers maintain a moist environment, absorb wound exudates, prevent microbial infection, and promote faster tissue regeneration. They also support cell adhesion and collagen formation, leading to rapid healing with reduced scar formation. Because of these properties, chitosan-based nanofibers are widely investigated as advanced wound dressing materials.[38,39] Another major application is drug delivery. Chitosan-based blended nanofibers can encapsulate various therapeutic agents and provide controlled and sustained drug release. This improves drug stability, reduces dosing frequency, and minimizes side effects. They have been explored for the delivery of antibiotics, anti-inflammatory drugs, anticancer agents, and herbal extracts. Their ability to release drugs in a controlled manner makes them suitable for localized therapy.[40]

In tissue engineering, chitosan nanofibers act as scaffolds that closely resemble the natural



extracellular matrix. They support cell attachment, proliferation, and differentiation, making them useful for skin, bone, cartilage, nerve, and vascular tissue regeneration. Their porous structure allows efficient transport of oxygen and nutrients, which is essential for new tissue formation.[41] Chitosan-based blended nanofibers also possess excellent antimicrobial activity against various bacteria and fungi. The positively charged amino groups of chitosan interact with negatively charged microbial cell membranes, causing membrane damage and inhibition of microbial growth. This property makes these nanofibers useful in wound dressings, medical textiles, implants, and infection control.[42]

Recently, researchers have incorporated natural products, essential oils, plant extracts, metallic nanoparticles, and bioactive compounds into chitosan nanofibers to further improve their antioxidant, anti-inflammatory, antimicrobial, and regenerative properties. Such multifunctional nanofibers are expected to play an important role in future biomedical and pharmaceutical products.[43]

CURRENT CHALLENGES AND FUTURE PERSPECTIVES

Although chitosan-based blended nanofibers have shown excellent potential, several challenges remain before their widespread clinical application. One major challenge is the large-scale production of nanofibers while maintaining uniform fiber diameter, morphology, and mechanical properties. Small changes during fabrication can affect product quality and therapeutic performance.[44]

Another limitation is the poor long-term stability of some nanofiber formulations. Sterilization methods may alter the physical properties of nanofibers, and therefore suitable sterilization

techniques must be optimized. In addition, batch-to-batch reproducibility remains an important concern for industrial manufacturing.[45] Most research has been limited to laboratory studies and animal models. More preclinical and clinical investigations are required to evaluate long-term safety, biodegradation, toxicity, and therapeutic efficacy in humans. Regulatory guidelines for nanofiber-based medical products also need further development to facilitate commercialization.[46]

Future research should focus on developing multifunctional nanofibers with improved mechanical strength, smart drug-release behavior, and enhanced biological activity. The incorporation of bioactive molecules, nanoparticles, and natural products may lead to advanced wound dressings, targeted drug delivery systems, tissue engineering scaffolds, and regenerative therapies. Artificial intelligence, three-dimensional printing, and advanced electrospinning technologies are also expected to improve nanofiber fabrication and personalized biomedical applications.[47–50] Chitosan-based blended nanofibers represent a highly promising biomaterial for modern healthcare. Continued research and technological advancements are expected to overcome current limitations and support their successful translation into clinical and pharmaceutical applications.

CONCLUSION

Chitosan-based blended nanofibers have emerged as promising biomaterials because of their excellent biocompatibility, biodegradability, antimicrobial activity, and high surface area. Blending chitosan with natural or synthetic polymers improves its mechanical strength, stability, electrospinnability, and overall performance, making these nanofibers suitable for a wide range of biomedical applications.



Electrospinning remains the most widely used fabrication technique due to its ability to produce uniform and highly porous nanofibers that closely resemble the natural extracellular matrix.

Structural characterization techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), and Thermogravimetric Analysis (TGA) play an important role in evaluating the chemical, morphological, thermal, and mechanical properties of fabricated nanofibers. These techniques ensure the quality, stability, and reproducibility of nanofiber-based formulations.

Recent studies have demonstrated the significant potential of chitosan-based blended nanofibers in wound healing, drug delivery, tissue engineering, antimicrobial therapy, and regenerative medicine. Their ability to incorporate drugs, plant extracts, growth factors, and nanoparticles further expands their therapeutic applications. Although challenges such as large-scale production, long-term stability, and clinical translation remain, continuous advancements in nanotechnology and biomaterial engineering are expected to overcome these limitations. Overall, chitosan-based blended nanofibers represent an innovative and sustainable platform for the development of advanced pharmaceutical and biomedical products and are expected to play an increasingly important role in future healthcare and regenerative medicine.

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