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From Fabrication to Application: Electrospun Chitosan/PVA Nanofiber Films for Water and Wastewater Treatment

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Water contamination poses serious risks to ecosystems and human health, prompting the need for efficient and sustainable treatment technologies. Conventional physical, chemical, and biological methods remain limited by high cost, low selectivity, or secondary pollution. Biopolymer-based nanofiber adsorbents, particularly those made from chitosan (CS) and polyvinyl alcohol (PVA), have gained increasing attention for their biodegradability and versatility. This review highlights electrospinning as an effective method for producing CS/PVA nanofiber films with nanoscale diameters and ultrathin structures, which are difficult to achieve via conventional casting. The section mainly explores how key fabricating factors – like polymer concentration, voltage, and flow rate – directly impact the structure and quality of electrospun fibers. Moreover, many recent developments have integrated functional materials into CS/PVA nanofiber films through electrospinning, aiming to enhance their effectiveness in treating contaminated water. Electrospun CS/PVA nanofiber films show great promise as an eco-friendly solution for sustainable water purification. In this review, the studies mentioned provide a diverse perspective and highlight key fabricating and modifying factors surrounding this sustainable material, offering meaningful contributions to the advancement of the field.

1. Introduction

Nowadays, humans have focused their efforts on science and technology, applying them to many types of industries, which is a threat to the development and sustainability of the whole ecosystem. The use of dyes in various industries and the release of heavy metals from industrial activities pose serious risks to human health and the environment, requiring their removal from water before discharge or reuse. Therefore, utilizing various methods to treat the wastewater has gained attention from many researchers. Common pollutant removal methods include chemical precipitation (Peng and Guo, 2020), photocatalysis (Sarkar et al., 2020), membrane filtration (Rosman et al., 2018), and adsorption (Georgouvelas et al., 2021). Among emerging approaches, electrospun nanofiber films stand out for their high surface area, interconnected porosity, and tunable functionalities. Not only nano-sized fiber, but electrospinning can also produce polymeric fibers with micro-sizes suitable for a specific application. It is known for being a simple and inexpensive technique that does not require using heat during the process, and this is a benefit for any solution that is sensitive to temperature. Chitosan (CS), derived from chitin – a natural polysaccharide – has gained attention for water purification due to its biodegradability and the presence of active amino and hydroxyl groups that help pollutant binding. However, the electrospinnability of pure CS is limited by its poor solubility and high viscosity in aqueous media (Shiravandi et al., 2023). To address these limitations, CS is commonly blended with PVA – a non-toxic, water-soluble, electrospinnable polymer whose high surface area and -OH groups enhance contaminant adsorption (Wu et al., 2022b). They can be synthesized as pristine CS/PVA blends, crosslinked structures, and functionalized composites with additives such as nanoparticles, MOFs, or conductive polymers. The resulting CS/PVA nanofiber films combine the desirable properties of both components, enabling improved mechanical strength, processability, and multifunctional performance in water treatment, while drawbacks include limited long-term durability and possible dissolution in aqueous media without stabilization.

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The properties of CS/PVA nanofiber films depend on electrospinning parameters (voltage, flow rate, collector distance, and solution properties) and post-treatments (crosslinking, functionalization), which have been optimized in recent years to meet specific application requirements. Each method gives notable advantages for different fields, but mostly for water treatment. This review focuses on two main aspects of electrospun CS/PVA films: (1) the effect of technology parameters on fiber morphology and (2) the incorporation of functional materials to enhance applications in water and wastewater treatment.

2. Effect of technology parameters on CS/PVA nanofiber films by electrospinning

The quality and effectiveness of CS/PVA nanofiber films largely depend on how they are made. Parameters such as polymer concentration, applied voltage, and flow rate all play critical roles in determining the electrospinnability of the solution and the structural properties of the resulting film.

2.1. Polymer concentration

Polymer concentration strongly affects the electrospinnability of CS/PVA solutions. If the concentration is too low, the solution tends to form beads instead of continuous fibers. Koosha and Mirzadeh found that a total polymer concentration of 7 wt.% allows electrospinning, except in pure CS solutions (CS/PVA 100/0), which produce beaded structures due to protonation of -NH_2 groups into -NH_3^+, causing electrostatic repulsion that disrupts fiber development (Koosha and Mirzadeh, 2015). Similar to the study of Koosha and Mirzadeh, Olvera Bernal et al. successfully synthesized electrospun nanofibers using CS concentrations of 2.5, 3, 3.5, and 4 wt.% in combination with 5 wt.% PVA. The resulting fiber clearly indicates that CS concentration plays a crucial role in determining fiber quality. When amino groups are protonated into -NH_3^+, they repel each other, causing the polymer chains to stretch out. In contrast, at lower CS concentrations, reduced chain entanglement and weaker interactions compromise jet stability (Olvera Bernal et al., 2023). Conversely, at lower CS concentrations, the degree of polymer chain entanglement and interaction is reduced. As a result, the fibers can not hold their structure – they start to fall apart into short, broken segments. These segments may further fragment into smaller sections, forming spherical droplets, while the remaining connected parts generate thin filament-like structures (Jia et al., 2007). Czibulya et al. revealed from the preliminary experiments that the closer the viscosity of a CS/PVA mixture is to that of pure PVA, the more favorable the electrospinning process becomes. Excessively high viscosity – often associated with elevated CS content beyond the optimal ratio – can lead to poor spinnability and the formation of inhomogeneous fiber networks (Czibulya et al., 2021). Thus, an optimal balance of concentration and viscosity is essential for stable jet formation and uniform fibers.

2.2. Applied vontage

The applied voltage plays a key role in determining how the polymer jet stretches – when the setting is correct, it helps create smooth, continuous fibers. Yousef et al. electrospun CS/PVA nanofibers (30/70 v/v) at 22 kV, 14 cm tip-to-collector distance, and 0.8 mL/h flow rate, resulting in uniform, defect-free fibers within the nanoscale range. Simultaneously, a synthesis process for fibers electrospun under identical conditions – same polymer ratio, collector distance, and flow rate – but with a higher voltage of 28 kV was also conducted. As the voltage increased, the fibers became noticeably thinner while still maintaining a uniform structure with very few defects. They stayed well within the nanoscale range, and the smaller diameters at higher voltages make sense – stronger electric fields stretch the polymer jet more effectively, resulting in finer fibers (Yousef et al., 2024). Vu et al. also found that solutions with a higher PVA content were easier to electrospin, as they needed lower feed rates and voltages to work well. While lower feed rates and higher voltages help stretch the fibers more effectively, they also speed up solvent evaporation – often causing blockages at the needle tip, especially in solutions with CS concentrations above 4-5 % (w/w) (Vu et al., 2022). Based on a series of trial-and-error experiments by Nokhasteh et al., it was determined that, due to the cationic nature of CS, the most influential electrospinning parameters affecting fiber formation are voltage (V) and tip-to-collector distance (D) – with voltage having the most significant impact. To get the electrospinning process started, the polymer solution needs to carry enough charge – this happens when the voltage is high enough to let electrostatic forces overcome surface tension and trigger jet formation (Nokhasteh et al., 2019). However, if the electric field is too strong, it can cause excessive repulsion between ionic groups in the CS chains, which may break the fiber stream and lead to discontinuous fibers (Wróblewska-Krepsztul et al., 2019). To evaluate the effects of these parameters, the voltage was varied from 15 to 30 kV in 3 kV increments. Throughout these experiments, the flow rate and collector speed were kept constant to isolate the influence of voltage.

2.3. Flow rate of the solution

Similar to the above technology parameters, the solution flow rate must be carefully controlled – higher flow rates may cause fiber agglomeration or incomplete solvent evaporation, while very low rates can interrupt jet stability. Vu et al. prepared a PVA/CS solution using an ethanol-acetic acid solvent mixture by electrospinning under the condition of a fixed voltage of 28 kV and a feed rate that was varied between 0.1 and 0.4 mL/h. The finest fibers (285 ± 65 nm) were achieved at 0.2 mL/h, while a slightly higher rate of 0.3 mL/h produced thicker fibers with fewer defects (Vu et al., 2024). A feed rate that is too low can create a vacuum inside the needle, while an excessively high rate may cause polymer buildup at the tip, disrupting the formation of a stable Taylor cone (Theron et al., 2004). Several studies have highlighted how feed rate plays an important role in shaping fiber morphology (Rezaei et al., 2023). Fiber diameter first decreases with increasing feed rate, then rises beyond the optimal rate, which gives the narrowest diameter distribution. However, Ding et al. found that increasing the feed rate did not have a major effect on the average fiber diameter. This suggests that, at least under certain conditions, the morphology, size, and consistency of electrospun PVA fibers are not heavily influenced by feed rate (Ding et al., 2010).

3. Incorporation of functional materials into CS/PVA films for enhanced water treatment

To further strengthen the performance and widen the application field of CS/PVA nanofiber films, recent research has investigated the incorporation of many functional materials into the polymer matrix during electrospinning. For instance, ZnO beads enhance Cu(II) adsorption and antibacterial activity (Xu et al., 2017), while cerium metal organic framework (Ce-MOF) improves dye adsorption efficiency (Alatawi, 2025). The integration of such functional components allows the resulting nanofibers to be tailored for specific purposes, particularly in water treatment applications where multifunctionality is highly desirable. This section reviews recent functional materials and their effects on CS/PVA nanofiber films via electrospinning.

3.1. Heavy metals removal

Recently, several studies have highlighted the use of ionic liquids to modify adsorbent materials, making them more effective at capturing heavy metal ions from wastewater (Shekhawat et al., 2015). For certain heavy metals such as arsenic, environmentally friendly nanofibers can be developed by combining nano zero-valent iron (nZVI) with CS-based nanofibers. nZVI is a highly effective arsenic adsorbent, while CS provides strong metal-binding ability, and PVA acts as a stabilizing agent with antimicrobial properties (Chauhan et al., 2014). Another trend in incorporating functional materials in CS/PVA films is loading nanoparticles with high adsorption capacity into the solution to strengthen the original film. Among the range of nanomaterials studied, clay-based materials such as montmorillonite, halloysite nanotubes, or bentonite have gained attention, attracting researchers thanks to their favorable physicochemical properties and broad industrial applicability.

Table 1: Summary of functionalized CS/PVA-based electrospun nanofiber films for heavy metal adsorption

Polymers	Enhanced agents	Synthetic parameters	Main characteristics	Ref.
CS/PVA	Ionic liquid	- Voltage: 23 kV - Flow rate: 0.1 mL/h - Distance: 15 cm	- Average diameters before and after adsorption remained nearly identical, at 167.1 nm and 167.6 nm. - Maximum Pb(II) adsorption: 166.34 mg/g with 82.5 % removal efficiency.	(Rosli et al., 2022)
CS/PVA	Zerovalent ion	- Voltage: 15 kV - Distance: 10 cm - Flow rate: 5 μL/min	- Fiber diameter < 100 nm. - High sorption capacity, reaching 200.0 ± 10.0 mg/g for As(V) and 142.9 ± 7.2 mg/g for As(III).	(Chauhan et al., 2014)
CS/PVA	Functionalized halloysite nanotubes	- Voltage: 18.5 kV - Flow rate: 1.1 mL/h - Distance: 9 cm	- Fiber diameter: 256 – 318 nm - Maximum adsorption capacities of 454.5 mg/g for Cd(II) and 476.2 mg/g for Pb(II).	(HMTShirazi et al., 2022)

Electrospinning produces nanofiber membranes that enhance adsorption capacity and treatment speed, allowing integration of multiple functional materials, unlike RO or UF membranes that are typically optimized for removing only one or two types of pollutants. Although functionalized materials can support the CS/PVA film during the adsorption process, several issues need to be considered. The introduction of functional materials can lead to aggregation within the polymer matrix, resulting in fiber defects and inconsistent morphology. Furthermore, in some cases, crosslinkers like glutaraldehyde used to stabilize the film structure may introduce toxicity risks.

3.2. Dyes removal

Recent studies using CS combined with materials such as PVA, polyaniline, β-cyclodextrin, graphene oxide, UiO-66, or nanodiamond have shown great potential in creating advanced adsorbent materials for the treatment of wastewater containing dyes and heavy metals. These composites exhibit large surface areas, porous nanostructures, high mechanical strength, and tunable chemical properties provided by functional components – for example, PANI adds conductivity, β-CD provides storage spaces for pollutant capture, and MOFs like UiO-66 enhance selective adsorption. In addition, techniques such as two-phase electrospinning or surface coating have been employed to further improve treatment efficiency and reusability. Overall, incorporating functional agents into CS/PVA nanofiber films markedly enhances dye adsorption, with performance strongly dependent on the type of additive and the solution pH.

Table 2: Summary of functionalized CS/PVA-based electrospun nanofiber films for dyes adsorption

Polymers	Enhanced agents	Synthetic parameters	Main characteristics	Ref.
CS/PVA	Polyaniline/silica hybrid nanostructures	- Voltage: 20 kV - Flow rate: 0.5 mL/min - Distance: 15 cm	- Specific surface area of 61 m^2/g. - Fiber diameter of 220 to 245 nm. - Increased adsorption to 110 mg/g for Congo red, 90 mg/g for methyl orange, and 45.2 mg/g for methylene blue. - Optimal uptake occurred at pH 5 for anionic dyes (CR, MO) and pH 9 for the cationic dye (MB).	(Bayat et al., 2021)
CS/PVA	UiO-66/nanodiamonds	- Voltage: 22 - 25 kV - Distance: 15 cm	- Average fiber diameter < 100 nm. - Increased methylene blue adsorption from 769 to 1429 mg/g over pristine.	(Ahmadijokani et al., 2023)
PVA	β-cyclodextrin grafted chitosan (β-CD-g-CS)	- Voltage: 20 kV - Flow rate: 0.1 mL/min - Distance: 12 cm - Concentration of β-CD-g-CS 3 % w/w, the mass ratio of β-CD-g-CS/PVA 30:70.	- Fiber diameter of 150 - 200 nm - Adsorption of 296.5 mg/g for Acid Blue 26	(Norouzi and Abdouss, 2024)

However, the common drawback of these studies is the lack of comprehensive evaluation under practical conditions such as multicomponent wastewater, variable pH, or the presence of many competing ions. In addition, some materials, such as PANI or graphene oxide, have high synthesis costs and may affect biodegradability or environmental toxicity if not thoroughly treated after use. In addition, most of the research has only stopped at the laboratory scale, without practical data on industrial-scale, long-term use or economic efficiency when recycling materials. Overall, the works have made important contributions to expanding the research direction on complex bio-nano adsorbent materials but need to be further improved in the direction of long-term stability, environmental friendliness, and practical application.

3.3. Antibacterial ability

Beyond heavy metal and dye removal, developing nanofiber films with antibacterial activity remains challenging. Thus, modifying technologies should focus on improving the bacteria-removing property to ensure the quality of these films. CS itself is also a widely used biopolymer that has attracted growing attention owing to its natural antibacterial properties. Therefore, when a CS/PVA solution is spun into a nanofiber film, which has a high surface area and a porous structure combining the bacteria-resistant property of CS, it provides an ideal platform for sustained antimicrobial activity and contact-based killing. Besides, to enhance its microorganism removal not only do they rely on CS, but researchers also utilize the functionalization of nanomaterials to prepare a highly effective adsorbent for the elimination of all the pollutant agents from the water resources without costing much. The reported studies confirm the strong antibacterial activity (> 90 %) of functionalized CS/PVA-based nanofiber films. HTCC-modified PVA showed high reusability over five cycles, while PAN/CS/Fe_3O_4 extended the antibacterial spectrum to both *E. coli* and *S. aureus*. Future work should focus on improving morphological control, multi-cycle performance, and safety evaluations for practical water treatment use.

Table 3: Summary of functionalized CS/PVA-based electrospun nanofiber films for antibacterial applications

Polymers	Enhanced agents	Synthetic parameters	Main characteristics	Ref.
PVA	N-(2-hydroxy) propyl-3-trimethylammonium chitosan chloride (HTCC)	- Voltage: 10 - 30 kV - Flow rate: 0.6 – 1.2 mL/h - Distance: 15.8 cm	- Mean fiber diameter: 135 - 330 nm. - Antibacterial efficacy: > 90 % against *E. coli*. - Reusability: Stable after 5 cycles.	(Wu et al., 2022a)
PAN/CS	Fe_3O_4	- Voltage: 20 kV - Flow rate: 0.003 mm/min	Antibacterial efficacy: > 90 % (*E. coli* and *S. aureus*).	(Hu et al., 2023)

4. Conclusions

Electrospun CS/PVA nanofiber films represent a versatile and sustainable method for water and wastewater treatment, owing to their high surface area, tunable functionality, and inherent biocompatibility. Their performance is strongly governed by electrospinning parameters – such as polymer concentration, applied voltage, and solution flow rate – that directly influence fiber morphology and stability. Incorporating functional additives, including ionic liquids, metal- and clay-based nanomaterials, polymeric and carbon-based materials, and antibacterial agents, further enhances their contaminant removal efficiency. Despite this progress, critical challenges remain, particularly regarding long-term stability, additive aggregation, cost-effectiveness, and insufficient testing under realistic conditions. Moving forward, research should focus on optimizing fabrication strategies, clarifying the relationship between processing parameters and contaminant removal, improving reusability and environmental safety, and scaling up production. Addressing these aspects will accelerate the transition of CS/PVA nanofiber films from laboratory development to practical deployment in sustainable water and wastewater treatment. Overall, this review underscores both the opportunities and the challenges, providing a roadmap for translating CS/PVA nanofiber films from fabrication to sustainable application in water and wastewater treatment.

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