Electrospinning Techniques for the Development of Heavy Metal Removal Membranes: Principle, Properties

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Abstract:

Water scarcity and pollution represents critical global challenges, with anthropogenic activities releasing increasing amounts of contaminants into water bodies. Traditional wastewater treatment methods often fail to effectively remove emerging contaminants, such as pharmaceuticals, organic dyes, pesticides and heavy metals from industries. Electrospun nanofibrous membranes (ENMs) have emerged as promising alternatives for water filtration, offering distinctive structural features, including high specific surface area, interconnected porous structures, and high porosity. Hence, we aim to provide a brief overview of electrospinning including the principle, methods and applications of heavy metal removal from the wastewater.

Keywords: electrospinning, electrospun, heavy metal removal, absorption, wastewater

1. Introduction:

Water is the most essential element on earth for all living things. Approximately 70% of Earth's surface is covered by water. No one can survive without water. On a daily basis, the activity related to agricultural, industrial and domestic cares, requires large amount of water. While conducting these activities, water discharged as waste water. The wastewater from industrial and domestic uses are dumped into the natural resources as rivers, sea, pond or open. Industrial wastewater contains heavy and toxic metals like Hg, Pb, Cr, Ni, Co, Cu, Cd, Ag, and As (Qasem, et al. 2021, Briffa, et al.2020). Heavy and toxic metals from industrial wastewater entered to the drinking water through the ground water channels. However, the industries dump wastewater into the natural resources without treatment or filtering. Consequently, the industrial wastewater affects the quality of ground water and drinking water and the water gets contaminated. The contaminated water is very harmful for all living things and may causes diseases such as cancer, kidney diseases, alzheimer, high blood pressure, brain damage, hearing disability and lower IQ level in children (Briffa, et al.2020, Aziz et al. 2023). To avoid this problem, the contaminated water should be processed or undergo through efficient treatment before being discharged into the natural water resources. As a result, water less harmful to all living things.

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The water treatment process takes out or reduce the water contaminants, making it suitable for agricultural, industrial and domestic uses. The process of wastewater treatment includes removal of solid elements, harmful microorganisms, and organic /inorganic compounds present in the wastewaters. Hence, wastewater treatment usually performed in three steps. In first step, solid elements removed from wastewater through filtration and coagulation. In the second step, the water goes through biological treatment for removal of microorganisms like bacteria, fungi, and algae. Then in last step, any unwanted bodies or impurities that are left out in the above two steps are removed, producing the water suitable for environment and activity related to agricultural, industrial and domestic cares. As water is very much important for all the living things, it is required to invent novel methodologies for wastewater, as water has limited availability (Ethaib et al. 2022).

Electrospun nanofiber membranes (ENMs) have rapidly emerged as a transformative technology in water treatment, offering high specific surface area, interconnected porosity and tunable surface chemistry that enable efficient removal of a wide range of contaminates including heavy metals, dyes antibiotics, oils and pathogens. The versatility of electrospinning allows fabrication of membranes with tailored properties by adjusting polymer composition, incorporating functional nanomaterials and applying surface modifications, enabling customization for specific filtration applications (Tang et al 2022.).

ENMs are applied across various membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), forward osmosis (FO), pervaporation and membrane distillation. ENMs generally outperform in permeability, selectivity, antifouling performance and mechanical robustness compared to traditional phase inversion membranes. However, challenges remain in scaling up production, optimizing selective layers, enhancing mechanical strength, and addressing fouling and long term stability. For water purification process, MF and UF membranes are used with pore size approximately 0.03 to 10 microns and 0.002 to 0.1 microns respectively. As MF membrane has large pore size, it removes large particles and various microorganism whereas UF can remove bacteria, soluble molecules as well as some virus and humic materials. RO membranes are non porous therefore it effectively removes all inorganic contaminations, salt, pesticides, bacteria, cysts and natural organic contamination. NF membranes are highly pores and the size of pore in the range of 0.001micron consequently they effectively removes alkalinity and hardness of water. Thus, MF membrane commonly used for prefilter treatment to RO and nanofiltration. However, to implement these technologies on large scale, it has some limitation such as thermal stability and high pressure, the formation of toxic intermediates, short lifetime of the membrane, and their self-cleaning process. Also, membrane technology requires large amount of energy as compare to conventional wastewater treatments. ENMs solve critical shortcomings of traditional filtration methods, including low efficiency, high energy consumption, and difficulty in recycling (Subrahmanya, et al. 2021, Qasem, et al. 2021, Liao et al. 2017).

2. Electrospinning technique

2.1 Principle of Electrospinning:

Electrospinning is a technique that produce nanofibers with diameter less the 1µm by applying high voltage power supply to polymer solution. The process involves three fundamental components: a high voltage power supply, a syringe with metallic needle and a collector plate as shown in fig.1. The principle relies on electrostatic forces when a polymer solution is subjected to high voltage, charged droplets from at the nozzle tip. As the voltage increases, electrostatic repulsion overcome surface tension of solution, creating a Taylor cone and jet. A charges jet is ejected towards the grounded collector plate where solvent evaporation occurs, solidified nanofibers collected on collector plate (Seeram, et al. 2005).

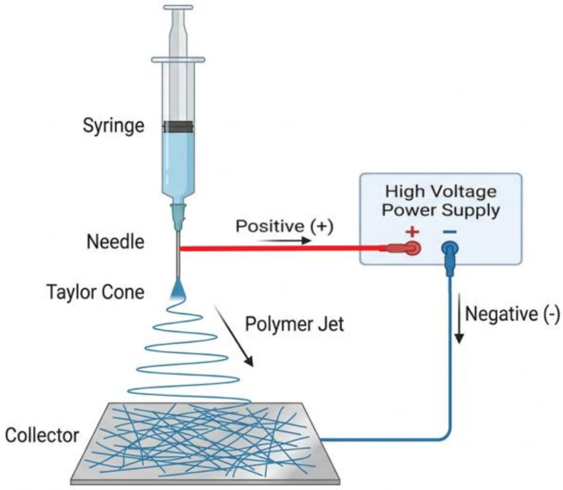

Fig 1: Electrospinning machine working principle

2.2 Electrospinning Process:

The generalize nanofiber synthesis steps using electrospinning method shown in figure. First the desired polymer dissolved in appropriate solvent with controlled concentration and viscosity and loaded into syringe with metallic needle. With the use of a syringe pump, the solution can be fed through the needle at a constant and controllable rate. When a high voltage (usually in the range of 1 to 30 kV) is applied, the pendent drop of polymer solution at the tip of needle will become highly electrified and the induced charges are evenly distributed over the surface. As a result, the drop will experience two major types of electrostatic forces: the electrostatic repulsion between the surface charges and the coulombic forces exerted by the external electric field. Under the action of these electrostatic interactions, the liquid drop will be distorted into a conical object commonly known as Taylor cone. With increasing field, a critical value is attained when the repulsive electrostatic force overcomes the surface tension and a charged jet of fluid is ejected from the tip of the Taylor cone. The discharged polymer solution jet undergoes a whipping process wherein the solvent evaporates, leaving behind a charged polymer fibers, which is highly stretched and reduced in diameter as it travels before laying itself randomly on a grounded collector.

2.3 Process Parameters:

The critical electrospinning parameters that control the fibers morphology and membrane properties were discussed in Table1. The fine-tuning or controlling these parameters enables optimization of membrane porosity, fiber diameter, and filtration performance (Rocha et al. 2024).

Sr. No	Parameter related to	Controlling Parameter	Range	Effect on nanofiber/ membrane
1	Solution	Molecular weight of polymer		High molecular weight leads to uniform fiber. Low molecular weight provides stable and uniform jet
2		Conductivity		Higher conductivity leads to low diameter fiber
3		Concentration	2-20%	Higher concentration increases fiber diameter and affects viscosity
4		Viscosity	7.2-22.5 Pa.s	Higher value leads to uniform and defect free fiber
5	Process	Voltage	10-30kV	Higher voltage decreases fiber diameter and provide stability to jet.
6		Needle diameter	Around 200nm	smaller diameter increases porosity and defect free.
7		Flow rate	0.5-5mL/h	Higher flow rate increases fiber diameter
8		Distance between needle and collector	10-25cm	Longer distance gives more time to solvent evaporation and that affects morphology and pore size of membrane
9	Environment	Temperature	20-40°C	Low temperature increase viscosity promoting large diameter fiber

10		Humidity	35-65%	Low humidity increases evaporation rate and affects morphology

3. Properties of ENMs:

ENMs are built from a web of overlapping nano to submicron fiber created under a high voltage electric field. This fibrous architecture gives very high porosity up to 90% and large surface area allowing many accessible pathways for fluid flow and that provides more interaction with contaminates. The pores are highly interconnected and twisted, leading to high permeability at low pressure, good rejection and often low energy demand as compared with dense membrane (Chong et al. 2025, Agrawal et al. 2021). The mechanical properties can be tuned by polymer choice, electrospinning parameters and post treatments. By optimizing ENMs membrane can achieve high mechanical strength suitable for filtration and other applications (Nauman et al. 2021, Borah et al.2024). Finally, surface hydrophilicity or hydrophobicity and wettability are easily controlled by proper polymer selection and functionalization, effectively minimizes the contact area with water and reduces wetting issues (Al-Husaini et al. 2025).

4. ENMs for Heavy metal removal:

ENMs have been extensively used for treatment of water because of the high performance towards the separation or degradation of pollutant in waste water. The physisorption, chemisorption, electrostatic attraction, or a combination of these mechanisms have been used for it. ENMs prepared for heavy metal removal combine high surface area, high porosity, interconnected pore networks and easy surface functionalization, which together support fast adsorption and high water permeability. Their removal performance depends strongly on the functional groups onto the fiber surface, because functional group such as amino, amidoxime, thiol, phosphate or inorganic active sites governs metal binding through chelation, electrostatic attraction, ion exchange, surface complexation (Huang et al. 2014).

Magaly Granda et. al studied the polymer layer sequence influences the properties and performance of the multilayer membranes. The incorporation of PAN and N6 notably enhanced the structural stability and mechanical performance of the multilayer membranes. CS/N6/PAN exhibited superior adsorption performance, achieving removal efficiencies of up to 77% for Cd^{2+} and 82.8% for Cr^{6+} (Granda et al. 2025). Eucommia ulmoides leaf extract (EUOL stabilized silver nanoparticles (EUOL@AgNPs) incorporated sulfonated polyether sulfone (SPES)/polyethersulfone (PES) electrospun nanofiber membranes (SP ENMs) were prepared by electrospinning. The produced ENMs adsorbent have shown high heavy metal binding capacity even after 10 times recycle and reuse removal of lead and cadmium iron from water (Talukder et al. 2022). Electrospun alginate nanofibre membranes show potential for the bio-sorption of heavy metals from aqueous solutions with maximum monolayer sorption capacity of 15.6 $mg.g^{-1}$ at a pH of 4 (Mokhena et al. 2017).

In cationic nanofiber membranes, XPS shows oxidation of hydroxyl/ether groups to carbonyl/carboxyl as Cr(VI) is reduced to Cr(III), again supporting a mechanism where surface O^- donor groups participate in redox and then coordinate the resulting Cr(III) (Fang,etal. 2021).

Mahapatra, A. et. al. successfully prepared Fe_2O_3–Al_2O_3 mixed oxide nanocomposite fibers by electrospinning of iron acetylacetonate and PVP polymer solution. The diameters of the fibers are found to be in the range of 200–500nm by TEM study. Complete removal of mixed oxide nanocomposite fibers was achieved followed by copper (21%), lead (52%), nickel (67%) and Hg (89%). Finally, the metal affinity to the mixed oxide nanocomposite fibers was found to be in the sequence of Cu < Pb < Ni < Hg and the preference of this sorbent for a metal ion may be explained on the basis of electronegativity of the metal ions and on the basis of their cation/anion state. The loaded adsorbent can be efficiently reinstated by diluted HCl and a regeneration efficiency of 90% was achieved using 0.05 mol/L HCl (Mahapatra et al. 2013).

Electrospun nanofibers combined with functional metal oxides (Fe_2O_3, Al_2O_3, SiO_2, CeO_2) offers remarkable heavy metal adsorption efficiency via sorption and surface complexation (Nalbandian et al. 2022). In addition, stronger electrostatic attraction/ complexation of functional group to metal ions increases at higher pH that reflects surface charge effect (Tahir et al. 2023, Rocha et al. 2024).

5. Conclusion, challenges and future trends:

Electrospun nanofiber membranes represents a transformative technology for water filtration, offering exceptional performance in contaminant removal across diverse applications. Their high porosity, large surface area, and ease of functionalization enable efficient removal of heavy metals. This was occurred because of coordination/ chelation to tailored surface groups, soft- metal interactions, surface complexation and ion exchange and electrostatic attraction modulated by pH and fiber charge. Critical challenges remain in scaling production, reducing costs and establishing regulatory framework. Multi-jet system, continuous production methods, and green solvent systems are essential for industrial adoption. Future research must prioritize long term stability testing, real wastewater applications and comprehensive life cycle assessments to validate electrospun membranes as viable alternatives to conventional filtration technologies.

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