Nonwoven Electrospun Membranes

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A flexible and dependable method that has been extensively employed to construct nanofibrous scaffolds that resemble the extracellular matrix made from polymeric materials is electrospinning (ES). ES is superior to other techniques because of its unique capacity to create nanofibers with a high surface-to-volume ratio, low cost, simplicity of setup, freedom in material choice, and ability to alter the surface attributes and usefulness of the nanofibers.

Keywords: green solvents ; tissue engineering ; essential oils ; volatile organic compounds

1. Biomimetic from Extracellular Matrix and Polymeric Nanofibers

Biomimetics or biomimicry is the practice of imitating models, systems, and elements from nature to solve complex human problems. It involves drawing inspiration from natural selection solutions found in nature and applying those principles to human engineering ^[1]. Living organisms have developed specialized structures and materials through natural selection over millions of years. Biomimetics has facilitated the creation of innovative technologies that draw inspiration from biological solutions found at both macro and nanoscales. Nature has found solutions to engineering challenges such as self-healing, tolerance to environmental exposure, resistance, hydrophobicity, and self-assembly ^{[2][3]}. Designs inspired by biomimicry will ultimately enable human productions to be more efficient, resilient, and sustainable. Biomimicry has applications in various sectors of human activity, including medicine, research, industry, economy, architecture, urban planning, agriculture, and management. It can be directly or indirectly applied to all sectors. Some biomimetic processes have been in use for years, such as the artificial synthesis of certain vitamins and antibiotics. More recently, biomimetics have been proposed for use in electrospun nanofibrous scaffolds that mimic important characteristics of the native extracellular matrix (ECM). This provides a promising strategy for restoring functions and achieving positive outcomes in tissue regeneration ^{[4][5]}.

Nanofibers in cellular scaffolds imitate the structure of native extracellular matrix (ECM) elements found in diverse tissues and organs such as bone, cartilage, tendon, and skin. This biomimetic approach is based on the principle of mimicking the natural fibrous organization of tissues at the nanoscale level ^[6]. The nanofibrous scaffold can provide cues to cells, promoting their growth and facilitating the synthesis of authentic extracellular matrices. The electrospun nanofibrous scaffold plays a pivotal role in determining the mechanical properties of tissue scaffold. The nanoscale structures of the scaffold enable interactions with cells, allowing for them to actively engage with the matrix, leading to functionalization, remodelling, and resembling the natural cellular remodelling process within the ECM ^{[Z][8]}. Continuous efforts are being made to develop biomimetic scaffolds that provide structural support for cell growth, proliferation, and differentiation. These scaffolds are also employed for bringing bioactive molecules, such as growth factors and signalling cues, to support tissue regeneration and enhance cellular responses.

The objective of tissue engineering is to replicate the ECM, which is composed of a variety of proteins like collagen, laminin, and fibronectin that act as cell-binding ligands. In order to encourage cell adhesion between cellular frameworks and the surrounding environment of the ECM, integrin-recognizing peptide sequences are essential ^{[9][10]}. Traditional synthetic biodegradable aliphatic polyesters like PLA, PLGA, and PCL continue to be the ideal materials to produce biomimicking nanofibrous scaffolds owing to their exceptional processability, biocompatibility, and mechanical performance. These synthetic polymeric nanofibers have effectively replicated the physical dimensions and morphology of collagen, which serves as a key constituent of the native extracellular matrix (ECM) and the primary structural protein in the human body. Consequently, significant efforts have been made to create collagen-based scaffolds that can closely mimic the natural environment ^[11].

Various scaffolds have been developed successfully to imitate the three-dimensional (3D) structure of the interstitial ECM. However, limited progress has been made in reproducing the two-dimensional (2D) basement membrane (BM) of the ECM. These membranes play a crucial role in establishing the functional polarization of epithelial and endothelial cell layers throughout the body and are essential for artificial organ technologies ^{[12][13]}. Synthetic polymeric nanofibrous

scaffolds hold the potential to act as an outstanding biomimetic platform for systematically studying cell–matrix interactions. Biomimetic nanofibrous scaffolds provide a platform for studying cell–matrix interactions and contribute to the design and fabrication of future biomimetic scaffolds in a precise and rational manner.

2. Electrospinning Process and Membrane Morphology

Electrospinning has gained recognition for its ability to create scaffolds that mimic the extracellular matrix (ECM), making it a valuable addition to conventional scaffold-production techniques such as gas foaming, solvent-casting, fibre bonding, freeze-drying, particulate leaching, etc., ^{[14][15]}. Electrospinning is a highly versatile and cost-effective process that produces long, continuous fibres with diameters ranging from 10 nanometres to some micrometres, achieved by applying high electrical voltage ^{[16][17][18]}. A typical electrospinning setup as depicted in **Figure 1** comprises four main components: a high voltage source, a spinneret (typically a hollow metal needle), a collector (grounded or negatively biased), and a syringe pump ^{[19][20][21]}. The syringe pump is employed to propel a polymer solution or melt through the spinneret. As the polymer liquid (solution or melt) is subjected to a high electrical potential, electric charges build up on the face of the liquid drop at the tip of the needle ^{[19][22][23]}.



Figure 1. Schematic setup of simple electrospinning machine.

Once the electric field strength surpasses the surface tension of the droplet at a critical voltage, a charged jet is expelled from the tip of the droplet. The jet is continuously elongated and whipped by electrostatic repulsion until it reaches the grounded collector. Throughout this process, the solvent evaporates, and the jet solidifies, resulting in the formation of fibres. Ultimately, the collected fibres come together to form a nonwoven fibrous membrane ^{[24][25]}.

Although the setup for electrospinning may seem simple, the actual production of fibres is a complicated process that demands cautious concern of various parameters for effective optimization. Nanofiber membranes produced through electrospinning can be tailored to achieve the desired morphology, structure, and functionalities by adjusting several operational, material, environmental, and post-processing parameters ^[26]. Operational parameters in electrospinning include the applied voltage, feed rate of the solution or melt, distance between tip and collector, collector, and speed.

Material parameters encompass the type and concentration of the polymer, molecular weight, viscosity, conductivity of the solution, surface tension, and the influence of additives. Environmental parameters refer to the ambient conditions within the chamber, such as humidity and temperature ^{[27][28]}. Post-processing strategies play a major role in determining the features of nanofibers. Factors such as drying conditions, heat treatment, and hot-pressing techniques greatly influence the final characteristics of the nanofiber membrane. It is crucial to consider all these parameters adequately in order to achieve optimized conditions for the formation of nanofiber membranes ^{[29][30]}. By controlling various parameter

| Parameters | Effect on Fiber Morphology |
|-------------------------------------|--|
| Solution (material) parameters | |
| Solvent vapor pressure | Increased porosity is associated with greater volatility ^[31] . |
| Polymeric concentration | Higher concentrations (within the optimal range) lead to an increase in fiber diameter ^[32] . |
| Solvent choice | The choice of solvent is crucial, as it can significantly affect the solubility and rheological properties of the spinning solution. Different solvents can lead to variations in fiber diameter and morphology ^[33] . |
| Solution viscosity | Higher viscosity (within the optimal range) results in an increase in fiber diameter. However, exceeding the critical viscosity value can lead to the formation of beaded or deformed nanofibers, and may even cause clogging of the spinneret ^[34] . |
| Solution surface tension | The surface tension of the spinning solution affects the ability of the solution to form a stable jet. A lower surface tension promotes the formation of thinner fibers, while a higher surface tension results in thicker fibers. Surfactants are sometimes added to adjust the surface tension and improve fiber formation ^[35] . |
| Solution conductivity | Increasing the conductivity leads to a decrease in fiber diameter, and higher conductivity can result in more pronounced bending instabilities, leading to the formation of non-uniform or beaded fibers ^[36] . |
| Processing (Operational) parameters | |
| Voltage | There is no definitive correlation between fiber diameter and voltage; however, it is commonly observed that increases in applied voltage cause a reduction in fiber diameter. Additionally, higher voltages may result in a higher probability of bead formation ^[37] . |
| Flow rate | Enhancement of the fiber diameter and the occurrence of bead formation are commonly observed at higher feed rates (above the minimum rate) ^[38] . |
| Needle-collector distance | Within the optimal range, the fiber diameter tends to decrease as the spinneret to the collector distances increases ^[39] . |
| Ambient (Environmental) parameters | |
| Temperature | Increasing the temperature generally leads to a decrease in fiber diameter $\frac{[40]}{2}$. |
| Humidity | Higher humidity levels tend to induce the formation of circular pores in the fibers [41]. |
| | |

Table 1. Effect of parameters on morphology of nanofibrous membranes.

3. Recent Advancement of Electrospinning

3.1. Advancement in Electrospinning Machine

In addition to the traditional electrospinning technique, various modifications of this method have been recently developed. These include co-electrospinning or co-axial electrospinning, multi-needle, and needleless electrospinning. The multineedle and needleless electrospinning techniques are employed to improve the productivity of the conventional electrospinning process ^[42]. On the other hand, co-axial electrospinning has been developed to produce core–shell and multilayer composite nanofibrous structures, offering improved functionalities and superior quality compared to conventional electrospinning methods. In co-axial electrospinning, two separate nanofiber components are fed through different coaxial capillary channels and combined to form core–shell composite nanofibers ^[43].

The introduction of co-axial electrospinning has played an important role in the comprehensive production of various functional nanomaterials. For instance, co-axial electrospinning has enabled the efficient production of two-layer core-shell polymer nanofibers. Co-electrospinning, on the other hand, is commonly employed to fabricate single-layer and bilayer nanofibers. However, these nanofiber structures have limitations in terms of assembly configurations and functionalities ^{[44][45]}. By increasing the number of nanofiber layers, the connectivity and functionalities of composite materials can be improved. Recent research has demonstrated the fabrication of multifunctional nanofibers with more than two layers using co-electrospinning. Additionally, the needleless electrospinning system has been widely adopted by researchers to increase fibre productivity ^[46]. This system utilizes two high voltage sources, one connected to the rotary drum collector and the other to the conductive wire, as illustrated in **Figure 2**.



Figure 2. Schematic representation of needleless electrospinning setup [47].

3.2. Post-Electrospinning Process for Membrane Modification

Although the electrospinning setup is simple, the production of fibres is complex and requires careful consideration of multiple parameters for optimization. Electrospun nanofiber membranes can be tailored to achieve the desired morphology, structure, and functionalities by controlling various operational, material, environmental, and post-processing parameters, such as drying temperature and humidity ^{[48][49]}. After the formation of nanofibers on the collector, residual solvents may still be present in the mat.

Therefore, additional post-treatment methods are typically employed to ensure complete drying. The drying process is typically carried out in a dry or vacuum oven at a temperature slightly below the boiling point of the solvent employed ^[50]. This controlled temperature allows for the residual solvent to evaporate slowly without forming pores, which could occur if a higher temperature were used for drying. Maintaining low humidity during the drying process is crucial to prevent moisture from permeating the nanofiber membrane. High humidity could potentially cause phase separation or pore formation within the nanofibers, which should be avoided to preserve their integrity and desired properties ^{[51][52]}.

3.3. Replacement of Toxic Organic Solvent by Green Solvent

Electrospinning has traditionally relied on the use of VOCs as solvent to dissolute polymeric materials. The selection of solvents is based on their capacity to dissolve the polymer chains effectively and evaporate rapidly over the short distance between the nozzle and the collector during the electrospinning process. During this process, large amounts of such toxic vapor may degrade the indoor air quality and cause serious health problems for humans. Moreover, in various applications such as tissue engineering, biomedical, and agriculture, the toxicity of these organic solvents is a critical concern ^{[53][54]}. Residual traces of these chemicals can have negative long-term environmental impacts and pose health hazards. For instance, prolonged exposure to toluene is suspected to cause organ damage, while chloroform and DCM are classified as likely carcinogens to humans according to the World Health Organization ^[55].

Similarly, acetonitrile, acids, formaldehyde, tetrahydrofuran, dimethylformamide, tetrafluoroethylene, methylene chloride, dichloroethane, and pyridine have also been connected to bad effects on human health. Additionally, many air fresheners contain five main ingredients: formaldehyde, phthalates, parabens, petroleum distillates, and p-dichlorobenzene, which can pose serious health hazards such as nausea, infertility, neurological dysfunction, leukaemia, and cancer ^[56]. This highlights the necessity for alternative, non-toxic, and environmentally friendly solvents ^[57].

References

- 1. Wang, X.; Ding, B.; Li, B. Biomimetic electrospun nanofibrous structures for tissue engineering. Mater. Today 2013, 16, 229–241.
- Türker, E.; Yildiz, Ü.H.; Yildiz, A.A. Biomimetic hybrid scaffold consisting of co-electrospun collagen and PLLCL for 3D cell culture. Int. J. Biol. Macromol. 2019, 139, 1054–1062.
- 3. Stocco, T.D.; Antonioli, E.; Romagnolli, M.L.; Sousa, G.F.; Ferretti, M.; Lobo, A.O. Aligned biomimetic scaffolds based on carbon nanotubes-reinforced polymeric nanofibers for knee meniscus tissue engineering. Mater. Lett. 2020, 264, 127351.
- Jing, X.; Li, H.; Mi, H.-Y.; Liu, Y.-J.; Tan, Y.-M. Fabrication of fluffy shish-kebab structured nanofibers by electrospinning, CO2 escaping foaming and controlled crystallization for biomimetic tissue engineering scaffolds. Chem. Eng. J. 2019, 372, 785–795.
- 5. Qian, Y.; Chen, H.; Xu, Y.; Yang, J.; Zhou, X.; Zhang, F.; Gu, N. The preosteoblast response of electrospinning PLGA/PCL nanofibers: Effects of biomimetic architecture and collagen I. Int. J. Nanomed. 2016, 11, 4157.
- Jia, W.; Li, M.; Kang, L.; Gu, G.; Guo, Z.; Chen, Z. Fabrication and comprehensive characterization of biomimetic extracellular matrix electrospun scaffold for vascular tissue engineering applications. J. Mater. Sci. 2019, 54, 10871– 10883.
- 7. Chahal, S.; Kumar, A.; Hussian, F.S.J. Development of biomimetic electrospun polymeric biomaterials for bone tissue engineering. A review. J. Biomater. Sci. Polym. Ed. 2019, 30, 1308–1355.
- Chantre, C.O.; Gonzalez, G.M.; Ahn, S.; Cera, L.; Campbell, P.H.; Hoerstrup, S.P.; Parker, K.K. Porous biomimetic hyaluronic acid and extracellular matrix protein Nanofiber scaffolds for accelerated cutaneous tissue repair. ACS Appl. Mater. Interfaces 2019, 11, 45498–45510.
- 9. Vashaghian, M.; Zaat, S.J.; Smit, T.H.; Roovers, J.P. Biomimetic implants for pelvic floor repair. Neurourol. Urodyn. 2018, 37, 566–580.
- 10. Zhao, X.; Zhou, L.; Li, Q.; Zou, Q.; Du, C. Biomimetic mineralization of carboxymethyl chitosan nanofibers with improved osteogenic activity in vitro and in vivo. Carbohydr. Polym. 2018, 195, 225–234.
- Tonda-Turo, C.; Ruini, F.; Ceresa, C.; Gentile, P.; Varela, P.; Ferreira, A.M.; Fracchia, L.; Ciardelli, G. Nanostructured scaffold with biomimetic and antibacterial properties for wound healing produced by 'green electrospinning'. Colloids Surf. B Biointerfaces 2018, 172, 233–243.
- 12. Murugan, R.; Ramakrishna, S. Nano-featured scaffolds for tissue engineering: A review of spinning methodologies. Tissue Eng. 2006, 12, 435–447.
- Serio, F.; da Cruz, A.F.; Chandra, A.; Nobile, C.; Rossi, G.R.; D'Amone, E.; Gigli, G.; Del Mercato, L.L.; de Oliveira, C.C. Electrospun polyvinyl-alcohol/gum arabic nanofibers: Biomimetic platform for in vitro cell growth and cancer nanomedicine delivery. Int. J. Biol. Macromol. 2021, 188, 764–773.
- Ojha, G.P.; Pant, B.; Acharya, J.; Park, M. Prussian Red Anions Immobilized Freestanding Three-Dimensional Porous Carbonaceous Networks: A New Avenue to Attain Capacitor- and Faradic-Type Electrodes in a Single Frame for 2.0 V Hybrid Supercapacitors. ACS Sustain. Chem. Eng. 2022, 10, 2994–3006.
- 15. Ojha, G.P.; Pant, B.; Acharya, J.; Park, M. An electrochemically reduced ultra-high mass loading three-dimensional carbon nanofiber network: A high energy density symmetric supercapacitor with a reproducible and stable cell voltage of 2.0 V. Nanoscale 2021, 13, 19537–19548.
- Tijing, L.D.; Woo, Y.C.; Yao, M.; Ren, J.; Shon, H.K. 1.16 Electrospinning for Membrane Fabrication: Strategies and Applications. In Comprehensive Membrane Science and Engineering, 2nd ed.; Drioli, E., Giorno, L., Fontananova, E., Eds.; Elsevier: Oxford, UK, 2017; pp. 418–444.
- 17. Zheng, Y. 3—Fabrication on bioinspired surfaces. In Bioinspired Design of Materials Surfaces; Zheng, Y., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 99–146.
- 18. Pant, B.; Ojha, G.P.; Kim, H.-Y.; Park, M.; Park, S.-J. Fly-ash-incorporated electrospun zinc oxide nanofibers: Potential material for environmental remediation. Environ. Pollut. 2019, 245, 163–172.
- 19. Pant, B.; Ojha, G.P.; Kuk, Y.-S.; Kwon, O.H.; Park, Y.W.; Park, M. Synthesis and Characterization of ZnO-TiO2/Carbon Fiber Composite with Enhanced Photocatalytic Properties. Nanomaterials 2020, 10, 1960.
- 20. Pandey, P.; Thapa, K.; Ojha, G.P.; Seo, M.-K.; Shin, K.H.; Kim, S.-W.; Sohn, J.I. Metal-organic frameworks-based triboelectric nanogenerator powered visible light communication system for wireless human-machine interactions. Chem. Eng. J. 2023, 452, 139209.

- 21. Pant, B.; Prasad Ojha, G.; Acharya, J.; Park, M. Ag3PO4-TiO2-Carbon nanofiber Composite: An efficient Visible-light photocatalyst obtained from electrospinning and hydrothermal methods. Sep. Purif. Technol. 2021, 276, 119400.
- 22. Su, C.; Li, Y.; Dai, Y.; Gao, F.; Tang, K.; Cao, H. Fabrication of three-dimensional superhydrophobic membranes with high porosity via simultaneous electrospraying and electrospinning. Mater. Lett. 2016, 170, 67–71.
- Lee, M.; Ojha, G.P.; Oh, H.J.; Kim, T.; Kim, H.Y. Copper//terbium dual metal organic frameworks incorporated side-byside electrospun nanofibrous membrane: A novel tactics for an efficient adsorption of particulate matter and luminescence property. J. Colloid Interface Sci. 2020, 578, 155–163.
- 24. Lasprilla-Botero, J.; Álvarez-Láinez, M.; Lagaron, J. The influence of electrospinning parameters and solvent selection on the morphology and diameter of polyimide nanofibers. Mater. Today Commun. 2018, 14, 1–9.
- Sagitha, P.; Reshmi, C.R.; Manaf, O.; Sundaran, S.P.; Juraij, K.; Sujith, A. Chapter 8—Development of nanocomposite membranes by electrospun nanofibrous materials. In Nanocomposite Membranes for Water and Gas Separation; Sadrzadeh, M., Mohammadi, T., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 199–218.
- Jose Varghese, R.; Sakho, E.h.M.; Parani, S.; Thomas, S.; Oluwafemi, O.S.; Wu, J. Chapter 3—Introduction to nanomaterials: Synthesis and applications. In Nanomaterials for Solar Cell Applications; Thomas, S., Sakho, E.H.M., Kalarikkal, N., Oluwafemi, S.O., Wu, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 75–95.
- Akdere, M.; Schneiders, T. 9—Modeling of the electrospinning process. In Advances in Modeling and Simulation in Textile Engineering; Akankwasa, N.T., Veit, D., Eds.; Woodhead Publishing: Sawston, Cambridge, UK, 2021; pp. 237– 253.
- Davoodi, P.; Gill, E.L.; Wang, W.; Shery Huang, Y.Y. Chapter Two—Advances and innovations in electrospinning technology. In Biomedical Applications of Electrospinning and Electrospraying; Kasoju, N., Ye, H., Eds.; Woodhead Publishing: Sawston, Cambridge, UK, 2021; pp. 45–81.
- Bambole, V.; Yakhmi, J.V. Chapter 14—Tissue engineering: Use of electrospinning technique for recreating physiological functions. In Nanobiomaterials in Soft Tissue Engineering; Grumezescu, A.M., Ed.; William Andrew Publishing: Norwich, NY, USA, 2016; pp. 387–455.
- Shin, M.; Awasthi, G.P.; Sharma, K.P.; Pandey, P.; Park, M.; Ojha, G.P.; Yu, C. Nanoarchitectonics of Three-Dimensional Carbon Nanofiber-Supported Hollow Copper Sulfide Spheres for Asymmetric Supercapacitor Applications. Int. J. Mol. Sci. 2023, 24, 9685.
- Bui, H.; Pham, V.H.; Pham, V.D.; Hoang, T.H.C.; Pham, T.B.; Do, T.C.; Ngo, Q.M.; Nguyen, T.V. Determination of low solvent concentration by nano-porous silicon photonic sensors using volatile organic compound method. Environ. Technol. 2019, 40, 3403–3411.
- 32. Cremar, L.; Gutierrez, J.; Martinez, J.; Materon, L.; Gilkerson, R.; Xu, F.; Lozano, K. Development of antimicrobial chitosan based nanofiber dressings for wound healing applications. Nanomed. J. 2018, 5, 6–14.
- 33. Pant, B.; Park, M.; Park, S.-J. Drug Delivery Applications of Core-Sheath Nanofibers Prepared by Coaxial Electrospinning: A Review. Pharmaceutics 2019, 11, 305.
- Wang, C.; Cheng, Y.W.; Hsu, C.H.; Chien, H.S.; Tsou, S.Y. How to manipulate the electrospinning jet with controlled properties to obtain uniform fibers with the smallest diameter?—A brief discussion of solution electrospinning process. J. Polym. Res. 2011, 18, 111–123.
- 35. Deitzel, J.M.; Kleinmeyer, J.; Harris, D.; Beck Tan, N.C. The effect of processing variables on the morphology of electrospun nanofibers and textiles. Polymer 2001, 42, 261–272.
- Angammana, C.J.; Jayaram, S.H. Analysis of the Effects of Solution Conductivity on Electrospinning Process and Fiber Morphology. IEEE Trans. Ind. Appl. 2011, 47, 1109–1117.
- Bosworth, L.A.; Downes, S. Acetone, a Sustainable Solvent for Electrospinning Poly(ε-Caprolactone) Fibres: Effect of Varying Parameters and Solution Concentrations on Fibre Diameter. J. Polym. Environ. 2012, 20, 879–886.
- 38. Chang, S.; Fane, A.G. The effect of fibre diameter on filtration and flux distribution—Relevance to submerged hollow fibre modules. J. Membr. Sci. 2001, 184, 221–231.
- Abdel-Hady, F.; Alzahrany, A.; Hamed, M. Experimental Validation of Upward Electrospinning Process. ISRN Nanotechnol. 2011, 2011, 851317.
- 40. De Vrieze, S.; Van Camp, T.; Nelvig, A.; Hagström, B.; Westbroek, P.; De Clerck, K. The effect of temperature and humidity on electrospinning. J. Mater. Sci. 2009, 44, 1357–1362.
- 41. Cai, Y.; Gevelber, M. The effect of relative humidity and evaporation rate on electrospinning: Fiber diameter and measurement for control implications. J. Mater. Sci. 2013, 48, 7812–7826.

- 42. Amith, V.; Sridhar, R.; Angadi, G.; Murthy, H.N. Recent Advancement in Electrospun nanofibrous mats with emphasis on their applications. IOP Conf. Ser. Mater. Sci. Eng. 2021, 1065, 012008.
- 43. Liu, Y.; Hao, M.; Chen, Z.; Liu, L.; Liu, Y.; Yang, W.; Ramakrishna, S. A review on recent advances in application of electrospun nanofiber materials as biosensors. Curr. Opin. Biomed. Eng. 2020, 13, 174–189.
- 44. Patel, S.; Patel, G. A Review and Analysis on Recent Advancements in Bubble Electrospinning Technology for Nanofiber Production. Recent Pat. Nanotechnol. 2019, 13, 80–91.
- 45. Di Vincenzo, M.; Tiraferri, A.; Musteata, V.E.; Chisca, S.; Sougrat, R.; Huang, L.B.; Nunes, S.P.; Barboiu, M. Biomimetic Artificial Water Channel Membranes for Enhanced Desalination. Nat. Nanotechnol. 2021, 16, 190.
- Rostamabadi, H.; Assadpour, E.; Tabarestani, H.S.; Falsafi, S.R.; Jafari, S.M. Electrospinning approach for nanoencapsulation of bioactive compounds; recent advances and innovations. Trends Food Sci. Technol. 2020, 100, 190–209.
- 47. Prahasti, G.; Zulfi, A.; Munir, M.M. Needleless electrospinning system with wire spinneret: An alternative way to control morphology, size, and productivity of nanofibers. Nano Express 2020, 1, 010046.
- 48. Sagitha, P.; Reshmi, C.; Sundaran, S.P.; Sujith, A. Recent advances in post-modification strategies of polymeric electrospun membranes. Eur. Polym. J. 2018, 105, 227–249.
- 49. Shaulsky, E.; Nejati, S.; Boo, C.; Perreault, F.; Osuji, C.O.; Elimelech, M. Post-fabrication modification of electrospun nanofiber mats with polymer coating for membrane distillation applications. J. Membr. Sci. 2017, 530, 158–165.
- 50. Ray, S.S.; Chen, S.-S.; Li, C.-W.; Nguyen, N.C.; Nguyen, H.T. A comprehensive review: Electrospinning technique for fabrication and surface modification of membranes for water treatment application. RSC Adv. 2016, 6, 85495–85514.
- 51. Chen, H.; Huang, M.; Liu, Y.; Meng, L.; Ma, M. Functionalized electrospun nanofiber membranes for water treatment: A review. Sci. Total Environ. 2020, 739, 139944.
- 52. Khulbe, K.C.; Matsuura, T. Membrane Modification. In Nanotechnology in Membrane Processes; Springer: New York, NY, USA, 2021; pp. 135–170.
- 53. Shen, W.; Ao, F.; Ge, X.; Ning, Y.; Wang, L.; Ren, H.; Fan, G. Effects of solvents on electrospun fibers and the biological application of different hydrophilic electrospun mats. Mater. Today Commun. 2022, 30, 103093.
- 54. Maulvi, F.A.; Soni, T.G.; Shah, D.O. A review on therapeutic contact lenses for ocular drug delivery. Drug Deliv. 2016, 23, 3017–3026.
- Yilmaz, E.; Soylak, M. Chapter 5—Type of green solvents used in separation and preconcentration methods. In New Generation Green Solvents for Separation and Preconcentration of Organic and Inorganic Species; Soylak, M., Yilmaz, E., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 207–266.
- 56. Avossa, J.; Herwig, G.; Toncelli, C.; Itel, F.; Rossi, R.M. Electrospinning based on benign solvents: Current definitions, implications and strategies. Green Chem. 2022, 24, 2347–2375.
- Madikizela, L.M.; Ncube, S.; Chimuka, L. Chapter Twelve—Green chemistry features in molecularly imprinted polymers preparation process. In Comprehensive Analytical Chemistry; Marć, M., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 86, pp. 337–364.

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