Nanomaterials Blended Membranes for the Built Environment

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Abstract. Water and wastewater treatment is one of the key issues in the built environment. Membrane processes are effective methods for water and wastewater treatment. Fouling tendency of polymeric membranes hindered their widespread application in water and wastewater treatment. Recent research in membrane technology has been focused on nanomaterial blended polymeric membranes to reduce fouling. This study investigates nanomaterial blended polymeric membranes for sustainable water and wastewater treatment in the built environment. Polymeric membranes blended with various nanomaterials, such as zinc oxide nanoparticles and carbon nanotubes, were synthesised, characterised and tested. Membrane performance variability was evaluated by using quantitative analysis. According to the findings of this study, carbon nanotube blended membranes have the potential to improve water and wastewater treatment efficiency in built environment. In addition, consumer protection law perspective was also incorporated to address the regulatory requirements for water quality and nanomaterial safety. The interdisciplinary method promotes the responsible use of high performance membrane technologies as well as protecting consumer health and rights.

Keywords: Built Environment · Consumer Protection · Membranes · Nanomaterials · Water and Wastewater Treatment

1 Introduction

Polymeric membranes have poor mechanical, thermal, and chemical resistance while being flexible, durable, affordable, and having high separation qualities [1]. Furthermore, one of the biggest drawbacks of membrane technology is the fouling problem [2]. The amount of permeate obtained decreases as a membrane becomes fouled. In addition, membrane's separation performance decreases [3]. Fouling is caused by the accumulation of colloids, macromolecules, salts, and similar substances on the membrane surface or inside the membrane pores [4].

It was demonstrated that by reducing hydrophobic interactions between foulants and the membrane surface, i.e. increasing membrane hydrophilicity lowers membrane fouling [5–7]. Consequently, the development of inexpensive polymeric membranes with strong fouling resistance has attracted a lot of interest lately [8].

© The Author(s) 2026
L. Bragança et al. (Eds.): ReSBE 2026, LNCE 909, pp. 765–771, 2026.
https://doi.org/10.1007/978-3-032-35104-3_89

Nanoparticles are frequently utilised as additives to enhance membrane properties in the manufacturing of fouling-resistant membranes with high permeate flux. Aluminium oxides, zirconium oxide, titanium oxide, cerium oxide, silicon oxide, and zinc oxide nanoparticles (ZnO) are a few examples [3]. Numerous studies have shown that titanium oxide nanoparticles are beneficial in reducing membrane fouling [9]. For fouling resistance, however, ZnO is a great substitute for titanium oxide nanoparticles due to its low cost and high surface-to-volume ratio. It was demonstrated that adding ZnO improves permeability and hydrophilicity of membranes [10]. Carbon nanotubes (CNT) have exceptionally high aspect ratio, strength, and stiffness [11]. CNT blended membranes have been demonstrated to have a high flux and to be more hydrophilic [12, 13].

The fabrication of membranes using nanoparticles has important implications for both environmental sustainability and consumer protection. The challenges are the stability of nanoparticle blended membranes, and the risk of nanoparticle release into treated water. In circular systems, the treated water is repurposed for both residential and commercial uses. Therefore, achieving excellent technical performance is as important as ensuring consumer protection and regulatory compliance. Thus, the aim of this study is to evaluate the performance, durability, and consumer protection effects of CNT and ZnO blended membranes.

2 Materials and Methods

CNTs were functionalised using an acid mixture prior to use, as described previously [12–14]. The membranes were prepared using the phase inversion method as described elsewhere [15–19]. N-methyl-2-pyrrolidone or N,N-dimethylformamide were used as solvents and ZnO or CNT as additives in membrane synthesis. Nanoparticles were first dispersed in the solvent and ultrasonicated for complete dispersion. The membrane solution was then obtained by adding polyethersulfone. An automatic film applicator was used to cast the resulting membrane solution onto a glass plate. The glass plate was then immersed in a coagulation bath to produce membranes. The prepared membranes thoroughly rinsed and kept in distilled water until use. Note that CNT-0 and CNT-1 denote bare and 1% CNT (with respect to polymer) containing membranes, respectively. Similarly, ZnO-0 and ZnO-2 denotes bare membrane and the membrane containing 2% ZnO (with respect to polymer), respectively.

Equation (1) was used to calculate membrane porosity (ε) by measuring the dry (w_d, g) and wet weights (w_w, g) of the membranes;

$$\varepsilon = (w_w - w_d)/(\rho \times A \times h) \tag{1}$$

where A stands for membrane area (cm^2), h for membrane thickness (cm), and ρ for water density.

A contact angle goniometer was used to measure the contact angle (CA) using the sessile drop technique. Measurement was performed after applying a 1 μL drop of distilled water on the membrane surface.

Membrane filtration tests were carried out using a dead-end membrane filtration unit for CNT blended membranes and a cross-flow membrane filtration unit for ZnO blended

membranes. Permeability and selectivity experiments were carried out at a constant transmembrane pressure of 0.5 bar. Equation (2) was used to calculate the water flux (J_w, L/m^{2}h);

$$J_w = V/(A \times \Delta t) \tag{2}$$

where V stands for the permeate volume (L) and Δt for time (h).

Protein like materials are common contaminants in water treatment, and they seriously impede membrane filtration [20–23]. Bovine serum albumin (BSA) was used as the model protein in this study. Membrane selectivity was evaluated by filtering BSA for an hour. Equation (3) was used to calculate the BSA rejection ratio (R,%);

$$R = \left(C_f - C_p\right)/C_f \tag{3}$$

where C_f stands for the BSA concentration in feed (mg/L) and C_p stands for the BSA in permeate (mg/L).

3 Results and Discussion

Addition of 2% of ZnO with respect to polyethersulfone resulted in 12% porosity increase and 7% water flux increase (Fig. 1). This increase is probably because of the hydrophilic nature of ZnO, which promotes faster solvent and nonsolvent exchange during phase inversion which probably resulted in a more open and interconnected pore structure. On the other hand, membrane porosity increased by 19% and water flux increased fourfold with CNT addition (Fig. 1). By providing low-friction pathways, CNTs enhance pore connectivity. The role of CNTs as nanoscale water transport facilitators is consistent with this increase in porosity and flux [14].

In circular water systems, adequate solute rejection is essential for consumer protection, even when permeability improvements are intended to lower energy usage. When 2% ZnO was incorporated into the membranes, both rejection and permeability increased 7% (Fig. 1). This simultaneous enhancement suggests that ZnO improves the homogeneity of pore size distribution and surface interactions with the rejected solute. The CNT blended membranes showed a significant increase in permeability, as well as BSA rejection (Fig. 1). The observed improvement in rejection rate and higher permeability demonstrates the ability of CNTs to favorably overcome the permeability-selectivity imbalance commonly encountered in polymeric membranes

Addition of nanomaterials results in substantial differences in the structure and properties of the membranes, as indicated by differences in porosity, flux, and BSA rejection, as depicted in Fig. 1. The choice of additive is of great importance in the design of membranes for circular water systems in built environment, as the properties of the membranes are largely dependent on the type of nanomaterials added.

Membranes used in circular water systems in built environment must maintain their performance and water quality over a long period. The results of this study show that the addition of ZnO and CNTs improves membrane performance compared to the bare membrane. The addition of CNTs increases selectivity and permeability drastically. On the other hand, the addition of ZnO creates a balance between rejection and permeability.

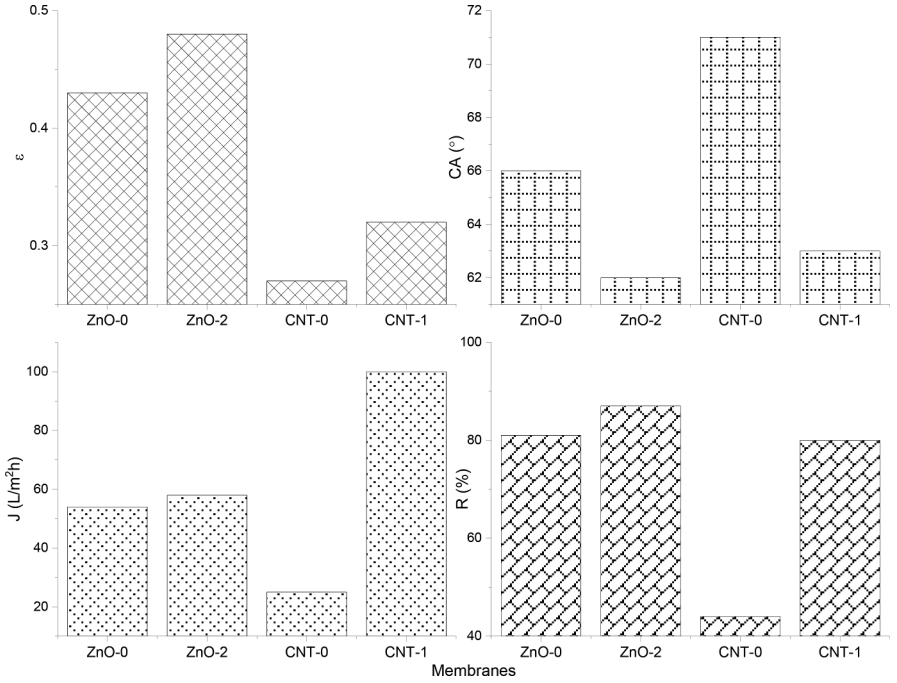


Fig. 1. Changes in porosity, contact angle, flux, and BSA rejection

Therefore, the role of nanomaterials in membrane performance should be evaluated with a holistic approach, considering long-term performance, safety, and efficiency.

The use of nanomaterials in ultrafiltration membranes for water treatment involves a clear set of rights and obligations applicable to all parties involved in the water supply chain from a consumer protection and regulatory law standpoint. According to the EU 2020/2184 directive, consumers have a fundamental right to access clean, safe, and lawful water. In return, filtration membrane manufacturers, water utilities, and system operators are obligated to ensure that new materials, including nanomaterials, do not degrade water quality throughout their service life. This includes tasks such as conducting appropriate risk assessments, preventing unwanted nanoparticle release, and guaranteeing long-term material performance in compliance with public health protection regulations.

One of the advantages of ZnO or CNT in water recycling is the higher rejection rate. However, there are some concerns about the leaching of ZnO or CNT over time, especially when water treatment systems are chemically cleaned. CNTs are tightly embedded in the polymer matrix, which severely restricts their mobility and potential for release into the treated water. CNTs have the potential to perform well even with low additive content, as demonstrated by the significant increase in permeability and high rejection rate achieved with a small amount of additive loading. For ZnO blended membranes probably material remains largely immobile in the initial stages. However, further research is needed on the long-term leaching of ZnO or CNT in water treatment systems.

4 Conclusion

The findings of the study reveal that, in comparison to bare membranes, blending ZnO or CNTs improves the efficiency of the membranes. Blending CNTs increases the selectivity and permeability, and blending ZnO balances the rejection and permeability. The CNT blended membranes are applicable in energy-efficient environments without compromising the long-term efficiency of water quality. Moreover, the strong interlocking of CNTs in the polymer matrix prevents the leakage of CNTs during the long-term usage and harsh chemical cleaning processes. Nevertheless, to ensure the safety of consumers, the long-term stability of ZnO or CNT blended membranes should be evaluated. In conclusion, the findings reveal that the nanoparticle blended ultrafiltration membranes, help to overcome the disadvantages of the conventional polymeric membranes. In this study, the significance of the selection of nanomaterials is emphasized to find a compromise between the separation efficiency and the protection of consumers. All these aspects are interconnected and play an important role in the correct application of state-of-the-art membrane technology. According to the findings of this study, CNT blended membranes have the potential to improve water and wastewater treatment efficiency in built environment.

Acknowledgement. This paper is based upon work from "COST Action CA21103 - Implementation of Circular Economy in the Built Environment", supported by COST (European Cooperation in Science and Technology - www.cost.eu). This research was partially supported by a grant (111R012) from Scientific and Technological Research Council of Turkey and Suleyman Demirel University (FBY-2018-5377/SDU3785).

References

1. Peng, F.B., Hu, C.L., Jiang, Z.Y.: Novel ploy(vinyl alcohol)/carbon nanotube hybrid membranes for pervaporation separation of benzene/cyclohexane mixtures. J. Membr. Sci. **297**, 236–242 (2007)
2. Balta, S., Sotto, A., Luis, P., Benea, L., Van der Bruggen, B., Kim, J.: A new outlook on membrane enhancement with nanoparticles: the alternative of ZnO. J. Membr. Sci. **389**, 155–161 (2012)
3. Koyuncu, I.: Su/Atık su Arıtılması ve Geri Kazanılmasında Membran Teknolojileri ve Uygulamaları. Yıldızlar Ofset, Ankara (2018)
4. Geise, G.M., Lee, H.S., Miller, D.J., Freeman, B.D., Mcgrath, J.E., Paul, D.R.: Water purification by membranes: the role of polymer science. J. Polym. Sci. B Polym. Phys. **48**(15), 1685–1718 (2010)
5. Gohari, R.J., Halakoo, E., Nazri, N.A.M., Lau, W.J., Matsuura, T., Ismail, A.F.: Improving performance and antifouling capability of PES UF membranes via blending with highly hydrophilic hydrous manganese dioxide nanoparticles. Desalination. **335**(1), 87–95 (2014)
6. Leo, C.P., Lee, W.P.C., Ahmad, A.L., Mohammad, A.W.: Polysulfone membranes blended with ZnO nanoparticles for reducing fouling by oleic acid. Sep. Purif. Technol. **89**, 51–56 (2012)
7. Damodar, R.A., You, S.J., Chou, H.H.: Study the self cleaning, antibacterial and photocatalytic properties of TiO2 entrapped PVDF membranes. J. Hazard. Mater. **172**(2–3), 1321–1328 (2009)

8. Celik Madenli, E., Cakmakci, O.: Preparation and characterization of PAN/CNT nanocomposite fiber supports for membrane filtration. Desalin. Water Treat. **60**, 137–143 (2017)
9. Rahimpour, A., Jahanshahi, M., Rajaeian, B., Rahimnejad, M.: TiO2 entrapped nanocomposite PVDF/SPES membranes: preparation, characterization, antifouling and antibacterial properties. Desalination. **278**(1–3), 343–353 (2011)
10. Celik, M.E., Sen, F., Ercin, A.: Zinc oxide nanoparticle blended Polyethersulfone ultrafiltration membranes. Fırat Univ. J. Eng. Sci. **35**(2), 637–645 (2023)
11. Gojny, F.H., Wichmann, M.H.G., Kopke, U., Fiedler, B., Schulte, K.: Carbon nanotube-reinforced epoxy-composites: enhanced stiffness and fracture toughness at low nanotube content. Compos. Sci. Technol. **64**, 2363–2371 (2004)
12. Celik, E., Liu, L., Choi, H.: Protein fouling behavior of carbon nanotube/polyethersulfone composite membranes during water filtration. Water Res. **45**(16), 5287–5294 (2011)
13. Celik, E., Park, H., Choi, H., Choi, H.: Carbon nanotube blended polyethersulfone membranes for fouling control in water treatment. Water Res. **45**(1), 274–282 (2011)
14. Celik, E., Choi, H.: Carbon nanotube/Polyethersulfone composite membranes for water filtration. In: Escobar, I., Bruggeb, B. (eds.) Modern Applications in Membrane Science and Technology. ACS Symposium Series, American Chemical Society, Washington DC (2011)
15. Celik, M.E., Cakmakcı, O., Isguder, I., Yigit, N.O., Kitis, M., Koyuncu, I.: Effects of the solvent ratio on carbon nanotube blended polymeric membranes. In: Figoli, A., Hoinkis, J., Altinkaya, S.A., Bundschuh, J. (eds.) Application of Nanotechnology in Membranes for Water Treatment. CRC Press, London (2017)
16. Celik, M.E., Kesiktas, D.: Mixed matrix membranes for dye removal. Membr. Water Treat. **14**(4), 175–180 (2023)
17. Celik Madenli, E., Ciftci, Z.I.: Effects of the carbon nanotube and polymer amounts on ultrafiltration membranes. Environ. Eng. Res. **27**(4), 210626 (2022)
18. Celik Madenli, E., Yanar, N., Choi, H.: Enhanced antibacterial properties and suppressed biofilm growth on multi-walled carbon nanotube (MWCNT) blended polyether- sulfone (PES) membranes. J. Environ. Chem. Eng. **9**(2), 104755 (2021)
19. Celik-Madenli, E. et al.: Effects of the solvent ratio on carbon nanotube blended polymeric membranes. In: Application of Nanotechnology in Membranes for Water Treatment. CRC Press, London (2017)
20. Vanangarnudi, A., Dumee, L.F., Duke, M.C., Yang, X.: Nanofiber composite membrane with intrinsic Janus surface for reversed-protein-fouling ultrafiltration. ACS Appl. Mater. Interfaces. **9**(21), 18328–18337 (2017)
21. Liu, X.T., Wang, M.S., Zhang, S.J., Pan, B.C.: Application potential of carbon nanotubes in water treatment: a review. J. Environ. Sci. **25**(7), 1263–1280 (2013)
22. Ding, Y.Y., Ma, B.W., Liu, H.J., Qu, J.H.: Effects of protein properties on ultrafiltration membrane fouling performance in water treatment. J. Environ. Sci. **77**, 273–281 (2019)
23. Huner, I.D., Gulec, H.A.: Fouling behavior of poly(ether) sulfone ultrafiltration membrane during concentration of whey proteins: effect of hydrophilic modification using atmospheric pressure argon jet plasma. Colloids Surf. **160**, 510–519 (2017)

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