Polysulfone/TiO₂ Thin Film Nanocomposite for Commercial Ultrafiltration Membranes

Saja H. Salim, Riyad H. Al-Anbari*, Adawiya J. Haider

1Ministry of Municipalities and Public Works, General Works and Maintenance Department – Iraq
2Department of Civil Engineering, University of Technology – Iraq
3Department of Applied Sciences, University of Technology – Iraq

Article information

Received: December, 13, 2021
Accepted: January, 09, 2022
Available online: March, 05, 2022

Keywords:
Spray pyrolysis,
Polysulfone (PSF),
Titanium dioxide (TiO₂)

*Corresponding Author:
Saja H. Salim
riyadhassan2003@yahoo.com

Abstract
Due to low water fluxes, commercial ultrafiltration (UF) membranes used in water treatment need to be improved. High-quality UF membranes were fabricated from polysulfone (PSF)/titanium dioxide (TiO₂) nanocomposite fibers as substrates using the spray pyrolysis method. The influence of nano-TiO₂ on the UF nanocomposite membrane was studied. Scanning electron microscopy (SEM), contact angle, and porosity were evaluated to characterize the mechanical characteristics of the membranes. The results show that adding TiO₂ to the substrates increased the hydrophilicity and porosity of the substrates. The pure water flux of the Thin Film Nanocomposite (TFN) membrane manufactured utilizing a PSF substrate coated with 0.1 wt% TiO₂ nanoparticles (denoted as Pc 0.1) improved at a rate of 35.28 l/m².h, and for a PSF substrate coated with 0.2 wt% TiO₂ nanoparticles (denoted as Pc 0.2) improved at a rate of 44 l/m².h. Additionally, increasing TiO₂ nanoparticle loading to 0.1 and 0.2 wt. percent resulted in higher water flow over 20 l/m².h PSF commercial membrane. The results of the UF performance show that Pc 0.2 membrane offered the most promising results, with a high-water flux than commercial membranes without nano-TiO₂ (Pc).

Introduction
The Use of Nanoparticles (NPs) in polymeric membranes made them increase rapidly due to their unique properties such as nanoscale size, wide surface area, high reactivity, and degree of functionalization for water and wastewater treatment[1]. Domestic and industrial effluents are responsible for a large part of pollution on the planet [2]. The implementation of clean technologies on water treatment minimizes the negative impacts on the environment and improves water resources[3]. However, the inappropriate disposal of these effluents has caused concern for the scientific community, which challenges applying repairing processes for these environmental damages [4]. Conventional wastewater treatment processes include biochemical methods, centrifugation, ultracentrifugation, thermal treatments, and each of these processes has severe limitations, whether energetic, treatments (thermal and mechanical), or chemical [5]. Techniques that have been receiving more attention due to
their energy efficiency use membranes as an active principle for their operation, because it presents a clean technology, simplicity of operation, and has broad applicability, in addition to being possible to combine with other processes [6].

Membranes are semi-permeable separation barriers that act as a kind of filter, which can restrict, totally or partially, the transport of one or more chemical species present in the phases [7]. Furthermore, the pores of the membranes are responsible for the properties and the countless applications of the membranes, promoting separations between the particles and fractioning molecules of different molar masses [8]. They are prepared by using various techniques such as phase inversion, evaporation, or extrusion. For example, depending mainly on the materials that make up the membrane as well as various types of application, ranging from classical pressure processes, such as Microfiltration – MF, Nanofiltration – NF, Ultrafiltration – UF, and Reverse Osmosis RO to more recent emerging processes such as membrane contractors [9].

Among polymeric membranes, those produced with polysulfone (PSF) as the main component have been widely used to treat industrial effluents due to their desired properties such as stability, high mechanical strength, and ease of modification [10]. The modification of PSF membranes presents an excellent opportunity to improve their performance in wastewater treatment [11].

Until now, studies on nanomaterials and hydrophilic macromolecules used in the modifications of PSF ultrafiltration/microfiltration membranes for application in water treatment were extensively analyzed [12]. These modified membranes exhibited a remarkable improvement in water permeability, salt rejection, and anti-fouling characteristics of PSF modified membranes compared to pure PSF membranes [13]. However, because PSF, in its pure form, presents a very hydrophobic characteristic as the main limitation, modifications are necessary to improve its properties [14]. Therefore, the addition of inorganic components to the polymeric solution in the preparation of membranes are widely used to obtain nanocomposite membranes through the addition of inorganic nanoparticles such as clay [15], oxide of zinc (ZnO) [16], titanium dioxide (TiO₂) [17], graphene oxide (OG) [18], and inorganic salts, with the aim of improvement of the morphological, mechanical, and flow properties of polymeric membranes [19]. The addition of titanium dioxide nanoparticles to polysulfone membranes will make changes significant in the morphological structure, increasing the amount and size of pores present in the top surface and cross-section of such nanocomposite membranes [20]. In addition, it will promote resistance to scale formation and improvements in permeability [21]. Selectivity, mechanical and chemical resistance give the membranes the desired properties, thus favoring their application for the treatment of liquid effluents such as the greywater treatment. Thus, studies of insertion of nanoparticles in obtaining hybrid membranes applied in the treatment of greywater effluents represent an important contribution to academia and society, in addition to serving as support for future work.

A search of the literature revealed that few studies deal with TiO₂/PSF in the UF process. The current work addresses this research gap by producing TiO₂ NPs loaded PSF for Greywater (GW) treatment using the UF procedure. In this study, TiO₂ NPs are produced using a spray pyrolysis technique, then incorporated into a PSF commercial membrane (Pc) with polymer solution at various concentrations of TiO₂ with weight 0.1% (Pc0.1) and 0.2% (Pc0.2). SEM, XRD, contact angle, and Pure Water Flux, were used to characterize the commercial membranes.

### 2. Experimental Procedure

#### 2.1. Materials

The chemicals used in this study and suppliers are represented in Table 1.
Table 1: The chemicals materials, specifications and suppliers.

| No. | Chemicals                     | Specifications                        | Supplier                       |
|-----|-------------------------------|---------------------------------------|--------------------------------|
| 1   | Polysulfone polymer pellets   | Specific Gravity (g/cm³) 1.23          | Huaian Ruanka, China           |
|     | (PSF)                         | Water Absorption (%) 0.2               |                                |
|     |                               | Modeling Shrinkage Rate (%) 0.7       |                                |
| 2   | Titanium Dioxide Nanoparticles | Empirical formula TiO₂                | Skyspring Nanomaterials        |
|     | (TiO₂)                        | Crystal structure Anatase             |                                |
|     |                               | Purity (%) > 99.5                     |                                |
|     |                               | APS (nm) 10-30                        |                                |
|     |                               | SSA (m²/g) > 50                       |                                |
| 3   | Dimethylformamide solvent     | Chemical formula C₃H₇NO                 | Sigma Aldrich                  |
|     | (DMF)                         | Molar mass (g·mol⁻¹) 73.095           |                                |
|     |                               | Appearance Colorless liquid           |                                |
|     |                               | Density (g/ml) 0.95                   |                                |
| 4   | Tetrahydrofuran solvent       | Chemical formula C₄H₈O                 | Sigma Aldrich                  |
|     | (THF)                         | Molar mass (g·mol⁻¹) 72.107           |                                |
|     |                               | Appearance Colorless liquid           |                                |
|     |                               | Density (g/ml) 0.89                   |                                |
|     |                               | Molar mass (g·mol⁻¹) 78.13            |                                |
|     |                               | Appearance Colorless liquid           |                                |
|     |                               | Density (g/ml) 1.1004                 |                                |
| 5   | Polyvinylpyrrolidone solvent  | Chemical formula (C₆H₉NO)n             | Sigma Aldrich                  |
|     | (PVP)                         | Molar mass (g·mol⁻¹) 2,500             |                                |
|     |                               | Appearance white to light yellow      |                                |
|     |                               | Density (g/ml) 1.2                    |                                |

2.2. Membrane Type Selection
The membranes used are polysulfone polymer types. In the current study, two types of membranes were used (i.e., commercial) purchased from Zhangjiagang Chuntai Environmental Protection Mechanical Engineering, China, and self-prepared characteristics features of commercial polysulfone membrane as shown in Table 2.

Table 2: Specifications of PSF commercial membrane.

| Parameter                | Unit          | Value                      |
|--------------------------|---------------|----------------------------|
| Material                 | --------------| Polysulfone (PSF)          |
| Origin                   | --------------| China                      |
| Area                     | cm²           | 15 x 12                    |
| Porosity                 | %             | 48.3 ± 2.6                 |
| Mean pore radius         | Nm            | 6.9 ± 0.56                 |
| Pure water flux          | l/m²h         | 19.7 ± 3.2                 |
| Mean surface roughness   | Ra-nm         | 2.9 ± 0.23                 |
| Layer thickness          | Mm            | 200                        |
| Fabrication method       | --------------| NIPS                       |
| Price                    | $             | 65 for 1 Piece             |
2.3. Instrumentations
Spray pyrolysis (SP) (Invents, Turkey) is the process in which a thin film is deposited by spraying a solution on a heated surface. The device consists of many specifications, as shown in Figure 1.

Figure 1: (A) Spray Pyrolysis device, (B) Device Diagram.

2.4. Preparation of Polysulfone Polymer Solution
Table 3 summarizes the specifications of the dope solution used in fabricating the spray pyrolysis process. This membrane was prepared before the dope solution preparation, and a vacuum oven was used to dry up the PSF pellets for a minimum of 3 h at about 90 °C to remove the moisture [22]. PSF particles were added to (25 g) and 0.025 g of PVP in (100 ml) of the mixture of DMF: THF as 70%:30% to enhance membrane mechanical properties due to improved solvent-induced fusion of interfering junction points. Solvents were converted from concentration in milliliters to grams using the following equation [23]:

\[
\rho = \frac{m}{V}
\]

Where; \( \rho \) = Density in g/ml for each solvent, \( m \) = Mass of solvent in gram unit/g, and \( V \) = Volume of solvent in milliliter unit /ml. The resulted mixture was stirred for 2 hours at 700 rpm and 70 °C. After that, a pale-yellow solution was obtained and then sonicated using ultrasonic (40 kHz) for 1 h at room temperature before the spray pyrolysis process started. This technique cleared any trapped air bubbles and got a clear homogeneous solution.

| Spray Pyrolysis | PES (g) | PVP (g) | DMF (g) | *THF (g) |
|-----------------|---------|---------|---------|----------|
| PSF             | 25      | -       | 66.5    | 26.7     |
| PSF/PVP         | 25      | 0.025   | 66.5    | 26.7     |

2.5. Preparation of PSF-TiO₂ (0.1 and 0.2 g) Solution
Initially, (0.1 or 0.2 g) of TiO₂ nanoparticles were dispersed in (25 ml) of DMF: THF as 70%: 30% using the ultrasonic device for 2 h at 50 °C. Then, the resulted dispersed solution of TiO₂NPs was added carefully to 100 ml of the solution under vigorous stirring at room temperature. After that, the mixture was sonicated for 10 h at 50 °C to produce a white clear homogeneous solution of PSF-TiO₂.

2.6. Membrane Fabrication
The spraying procedure worked by loading 10 ml from the prepared stock solution of PSF, PSF-TiO₂ 0.1 g, or PSF-TiO₂ 0.2 g were packed separately in the device nebulizer content. Compressed air was allowed to flow into the nebulizer sector from a height of 30 cm on a carrier material to nebulize the polymer solution. The nebulized polymer drops were collected on the aluminium substrate on the hot stage at 70 °C with an open: close pulse to 2:10 seconds. Table 4 summarizes the optimized Spray Pyrolysis Nanomaterials (SPNMs) parameters. The generated random nanofibers were collected on a plate collector covered by aluminum foil upon completing the SP procedure. Subsequently, the resultant SPNMs were dipped in a deionized water bath for three days to eliminate any left-over solvents or Polyvinylpyrrolidone solvent (PVP). Finally, the nanofibrous mats were dried
in the air at room temperature for one day before storing them in a desiccator cabinet (Secador) for further treatment and instrumental characterization. This is the same mechanism used to make commercial membrane coatings by adding the same concentrations of nano-titanium oxide, as shown in Figure 2.

### Table 4: Spray Pyrolysis conditions of SPNMs.

| Spray Pyrolysis Parameters | SPNMs |
|----------------------------|-------|
| Volume of solution         | 10 ml |
| Open: Close Pulse          | 2:10  |
| The temperature of the collecting stage | 70°C  |
| Membrane fabrication time  | 18 h  |

**Figure 2:** diagram of Polysulfone membrane fabrication.

#### 2.7. Characterization of Nanofiber Substrates and TFMs Membranes

The morphological studies of the PSF/TiO$_2$ substrate and the membranes were conducted by a scanning electron microscope (EO Elektronen-Optik-Service GmbH, Germany). The energy dispersion of X-ray (XRD-6000, Shimadzu Japan) was used to determine the TiO$_2$ nanoparticle distribution in the Thin Film Nanocomposites (TFNs) membranes. Water contact angles of the nanofiber substrates were investigated based on the sessile drop method and determined using a contact angle instrument (FI-02130 Espoo, Finland). All tests were carried in (Physics and Chemistry Department/Nano-science and Technology /Al Zahra University /Iran).

Porosity was determined using the following Equation (2) [24]:

$$\text{Porosity (\%)} = \frac{\text{wt}_{w} - \text{wt}_{d}}{\text{pk} \times \frac{\text{wt}_{w} - \text{wt}_{d}}{\text{pk} + \rho_{p}}} \times 100$$

Where; $\text{wt}_{w}$: is the weight of the membrane in the wet state, $\text{wt}_{d}$: is the weight of the membrane in the dry state, $\rho_{k}$: is the isopropanol density, and $\rho_{p}$: is the polymer density. Each value of porosity is the average of three different measurements.

#### 2.8. Performance of The Membranes

##### 2.8.1. Pure Water Flux and Rejection

Flux and rejection measurements were performed in cross-flow ultrafiltration mode. Three ultrafiltration membranes were used in separate processes. The flat sheet membrane was initially washed with deionized water before the experiment. Then, a Polysulfone flat sheet membrane cut into a square sheet with a surface area of 18 cm$^2$, was placed inside the membrane module, as shown in Figure 3. The membrane module consists of four vents, input and output for both feed and permeate. The membrane module was connected to a vessel, which contained feed solution, and a pressure gauge was placed at the membrane module inlet. Pure water flux was determined using deionized water as feed solution at pressure 2 bar followed by measurement of peat water flux,
where the membrane was operated for two hours. Permeate was collected periodically (15, 30, 45, 60, 75, 90, 105, and 120 minutes) for 22 days. Pure water flux (PWF) is calculated by the following equation (3) [24]:

\[ J_{w1} = \frac{V}{A \cdot T} \]  

(3)

Where: \( J_{w1} \) = PWF (m\(^3\)/m\(^2\)·s), \( V \) = volume of permeate (m\(^3\)), \( T \) = permeation time (s), and \( A \) = membrane surface area (m\(^2\)).

Figure 3: Schematic diagram of ultrafiltration experimental system.

3. Result and Discussion

3.1. Scanning Electron Microscopy (SEM)

The SEM measurement of the membrane reveals that Pc 0.1 and Pc 0.2 are composed of irregularly shaped pores within a size range of 0.7-7 micrometer, which is larger than that found in the Pc membrane. This indicates that the substrate Pc0.1 and Pc0.2 membranes are structurally better than Pc, which has smaller pore sizes, resulting in high pollutant hindrance. Furthermore, after adding titanium dioxide nanoparticles, it was observed that the number of pores was reduced by increasing the proportion of nano titanium dioxide because the oxide nanoparticles block the pores, as shown in Figure (4 a-c).

S. H. Maruf et al. showed that a membrane with a lower roughness has a stronger antifouling ability [25]. Pc 0.2 membrane coating with nano-TiO\(_2\) would therefore be expected to improve antifouling performance. The SEM results were in agreement with the results of previous research [26].

Figure 4: SEM images of a. Pc, b. Pc0.1, and c. Pc0.2.

3.2. X-Ray Diffraction (XRD) Analysis

The X-ray measurement of commercial polysulfone membranes showed the presence of several peaks, which it could not be determined for any of the commercial ingredients. Other peaks were due to other components that increase the membrane's strength. However, X-ray measurement showed the presence of the main peak of the carbon-polymeric structure at 16.68 degrees, which proves the presence of polysulfone within the composition, as shown in Figure 5a. The X-ray measurement of commercial membranes containing titanium oxide, in Figure 5 b-c, showed the presence of the polymer crest, but it was weaker than that of polymers containing titanium dioxide. In addition, X-ray measurement showed the characteristic peak of the titanium oxide, which appeared at approximately 25 degrees in both membranes. These results were in agreement with the results of previous research [27].
3.3. Contact Angle Wettability Analysis

The addition of TiO$_2$ nanoparticles to spinning fluid increased the hydrophilicity of TFN substrate. The contact angle of support layer dropped from 65.4° for Pc to 33.7° for Pc 0.1 and 28.6 for Pc 0.2, indicating an increase in hydrophilicity. The surface wettability was shown to be impacted by surface energy and shape. The contact angle has been averaged five times to limit the influence of morphology. Table 4 shows that the total porosity of the substrate for all membranes. Low porosity resulted from uniform dispersion at low TiO$_2$ concentrations, and large porosity resulted from aggregation at high TiO$_2$ concentrations. The substrate thickness increased with the amount of TiO$_2$ nanoparticles.

In line with previous research [26], the average fiber diameter increased with the loading of TiO$_2$ nanoparticles. Thickness and porosity were closely connected to membrane performance. The best substrates for Pco.2 membranes are thin and porous, as shown in Figure 6.

Table 4: Effect of TiO$_2$ concentration on the properties of PSF substrates.

|         | Contact Angle | Porosity % |
|---------|---------------|------------|
| Pc      | 65.4          | 51         |
| Pc0.1   | 33.7          | 69         |
| Pc0.2   | 28.6          | 55         |

Figure 6: Contact angle measurements commercial membranes (a) Pc (b) Pc0.1, and (c) Pco.2.
3.4. Performance of the Membranes
3.4.1. Pure Water Flux (PWF)

Figure 7 presents the water flux of different commercial membranes evaluated by the cross-flow UF process. The experiments were conducted using distilled water at a flow rate of (1.32 l/min) and pressure of (2 bar and 2 h) for the total operation. The results showed that the Pc0.1 and Pc0.2 membranes substrates from TiO₂/PSF nanocomposite substrates had much higher water flux than the Pc membrane without TiO₂. When adding 0.1% TiO₂, the water fluxes of the membrane improved 19% , but adding too much TiO₂ water flux was only slightly higher. The last results show that the structural improvements properties of TiO₂/PSF substrates could minimize the transport resistance against water permeation. This expectation stems from the hydrophilic nature of TiO₂NPs, which will cause an increase in the hydrophilicity of membranes surface [28] and change the membrane surface morphology and internal structure. Average pure water fluxes (PWF) for Pc, Pc0.1, and Pc0.2 are 20, 35.28, and 44 l/m²·h, respectively.

![Figure 7: Pure Water Flux of PSF membranes without and with different TiO₂ concentrations.](image)

4. Conclusion

This study concluded that incorporating TiO₂/PSF homogeneous spinning dope could be spray paralysis successfully. The substrates of UF membranes were fabricated with different average fiber diameters. It was found that TiO₂ nanoparticles impacted the morphology and structure of the substrates. Furthermore, the mechanical strength of TiO₂/PSF substrate decreased as the TiO₂ loading increased. Yet, incorporating TiO₂ in fibers could enhance the wettability of the TFN membranes. Also, results showed that the water fluxes of the TFN membrane prepared from the nanocomposite substrate increased with increasing TiO₂ concentrations. Thus, there is a high potential of the present PSF/TiO₂ mixed-matrix fiber mats as a substrate material to improve the water flux of the UF membrane.

References
[1] A. J. Haider, R. A. Rsool, M. J. Haider, R. A. Rsool, and A. B. Dheyab, “Properties of LiCo0. 5Ni0. 45Ag0. 05O2 thin films for high storage energy capacity by Pulsed Laser Deposition,” *Energy Reports*, vol. 6, pp. 85–94, 2020.
[2] S. I. AL-Saedi, A. J. Haider, A. N. Naje, and N. Bassil, “Improvement of Li-ion batteries energy storage by graphene additive,,” *Energy Reports*, vol. 6, pp. 64–71, 2020.
[3] Z. Pan et al., “Membrane technology coupled with electrochemical advanced oxidation processes for organic wastewater treatment: Recent advances and future prospects,” *Chem. Eng. J.*, vol. 376, p. 120909, 2019.
[4] M. B. R. Silva, P. V. de Azevedo, and T. L. B. Alves, “Analysis of environmental degradation in the upper reaches of the watershed of the Paraiba River,” *Bol. Goiano Geogr.*, vol. 34, no. 1, pp. 35–53, 2014.
[5] B. L. Abbood, K. A. Sukkar, and J. A. Al-najar, “Characterization and Aerodynamics of Synthesized Polymeric Nanofibers via Electrospinning Process to Capture PM 10 and PM 2 . 5 from Air,” vol. 1, no. 4, pp. 91–104, 2021, doi: 10.53293/jasn.2021.4101.1070.
[6] S. H. Salim, “ENVIRONMENTAL IMPACT OF RUSAFA WATER PROJECT IN BAGHDAD, IRAQ,” *J. Eng. Sustain. Dev.*, vol. 22, no. 2 (Part-4), 2018.
[7] X. Du, Y. Shi, V. Jegatheesan, and I. Ul Haq, *A review on the mechanism, impacts and control methods of*
membrane fouling in MBR system, vol. 10, no. 2, 2020.

[8] E. Dadvar, R. R. Kalantary, H. Ahmad Panahi, and M. Peyravi, “Efficiency of Polymeric Membrane Graphene Oxide-TiO2 for Removal of Azo Dye,” J. Chem., vol. 2017, 2017, doi: 10.1155/2017/6217987.

[9] S. S. Al-ratrou, “Synthesis of fouling-resistant ultrafiltration membranes from nanostructured composites for water treatment applications SYNTHESIS OF FOULING-RESISTANT ULTRAFILTRATION MEMBRANES FROM NANOSTRUCTURED COMPOSITES FOR WATER,” no. August, 2015.

[10] S. H. Salim, R. H. Al-Anbari, and A. J. Haider, “Polymeric Membrane with Nanomaterial’s for Water Purification: A Review,” in IOP Conference Series: Earth and Environmental Science, 2021, vol. 779, no. 1, p. 12103.

[11] A. J. Haider, R. Al-Anbari, H. M. Sami, and M. J. Haider, “Photocatalytic Activity of Nickel Oxide,” J. Mater. Res. Technol., vol. 8, no. 3, pp. 2802–2808, 2019, doi: 10.1016/j.jmrt.2019.02.018.

[12] A. Haider, R. Al-Anbari, G. Kadhim, and Z. Jameel, “Synthesis and photocatalytic activity for TiO2 nanoparticles as air purification,” in MATEC Web of Conferences, 2018, vol. 162, p. 5006.

[13] C. Techniques and A. Pradesh, “Structural, Raman and Infrared properties of V 2 O 5 and,” vol. 6, no. 3, pp. 1746–1748, 2021, doi: 10.53293/jasn.2021.3869.1049.

[14] H. M. Mousa, H. Alfadhel, M. Ateia, and G. T. Abdel-Jaber, “Polysulfone-iron acetate/polyamide nanocomposite membrane for oil-water separation,” Environ. Nanotechnology, Monit. Manag., vol. 14, p. 100314, 2020.

[15] M. A. Al-Kinani, A. J. Haider, and S. Al-Musawi, “Design and Synthesis of Nanoencapsulation with a New Formulation of Fe@ Au-CS-CU-FA NPs by Pulsed Laser Ablation in Liquid (PLAL) Method in Breast Cancer Therapy: In Vitro and In Vivo,” Plasmonics, pp. 1–11, 2021.

[16] A. A. Atiyyah, A. J. Haider, and R. M. Dhahi, “Cytotoxicity properties of functionalised carbon nanotubes on pathogenic bacteria,” IET nanobiotechnology, vol. 13, no. 6, pp. 597–601, 2019.

[17] K. Zarshenas, G. Jiang, J. Zhang, M. A. Jauhar, and Z. Chen, “Atomic scale manipulation of sublayer with functional TiO2 nanofilm toward high-performance reverse osmosis membrane,” Desalination, vol. 480, p. 114342, 2020.

[18] K. H. Jawad and B. A. Hasson, “Developing Strategy for a Successful Antioxidant , Anticancer Activity via an Improved Method Prepared to Porous Silicon Nanoparticles,” vol. 1, no. 4, pp. 1–11, 2021, doi: 10.53293/jasn.2021.3890.1054.

[19] V. H. T. Nguyen, M. N. Nguyen, T. T. Truong, T. T. Nguyen, H. V Doan, and X. N. Pham, “One-pot preparation of alumina-modified polysulfone-graphene oxide nanocomposite membrane for separation of emulsion-oil from wastewater,” J. Nanomater., vol. 2020, 2020.

[20] U. S. E. P. Agency, J. Davis, A. Wang, and J. Shtakin, “Nanomaterial Case Studies: Nanoscale Titanium Dioxide in Water Treatment and in Topical Sunscreen,” US EPA Res. Triangle Park, no. November, pp. 13–14, 2010, doi: EPA/600/R-09/057F.

[21] J. M. Gohil and R. R. Choudhury, Introduction to Nanostructured and Nano-enhanced Polymeric Membranes: Preparation, Function, and Application for Water Purification, no. January 2019, 2018.

[22] I. S. Al-Husaini, W. J. Lau, A. R. M. Yusoff, M. Z. Al-Abri, and B. A. Al Farsi, “Synthesis of functional hydrophilic polyethersulfone-based electrosyn nanofibrous membranes for water treatment,” Journal of Environmental Chemical Engineering, vol. 9, no. 1. 2021, doi: 10.1016/j.jece.2020.104728.

[23] Z. Shen et al., “Fabrication of a novel antifouling polysulfone membrane with in situ embedment of mxene nanosheets,” Int. J. Environ. Res. Public Health, vol. 16, no. 23, 2019, doi: 10.3390/ijerph16234659.

[24] L. G. Tiron, C. Pintilie, M. Vlad, I. G. Birsan, and Baltă, “Characterization of Polysulfone Membranes Prepared with Thermally Induced Phase Separation Technique,” IOP Conf. Ser. Mater. Sci. Eng., vol. 209, no. 1, 2017, doi: 10.1088/1757-899X/209/1/012013.

[25] S. H. Maruf, A. R. Greenberg, and Y. Ding, “Influence of substrate processing and interfacial polymerization conditions on the surface topography and permeative properties of surface-patterned thin-film composite membranes,” J. Memb. Sci., vol. 512, pp. 50–60, 2016.

[26] S. S. Al-ratrou, “Synthesis of fouling-resistant ultrafiltration membranes from nanostructured composites for water treatment applications,” 2015.

[27] C. Zhang, M. Huang, L. Meng, B. Li, and T. Cai, “Electrosyn polysulfone (PSf)/titanium dioxide (TiO2) nanocomposite fibers as substrates to prepare thin film forward osmosis membranes,” Journal of Chemical Technology and Biotechnology, vol. 92, no. 8, pp. 2090–2097, 2017, doi: 10.1002/jctb.5204.

[28] A. M. Vijesh, P. C. Shyma, V. Prakash, and B. Garudachari, “Preparation and Characterization of
Polysulfone Based Hollow Fibre Composite Membranes for Water Purification,” *J. Appl. Membr. Sci. Technol.*, vol. 22, no. 2, 2018, doi: 10.11113/amst.v22n2.130.