Superhydrophobic and Breathable Polyacrylonitrile/Silica/Perfluoroalkyl Ethyl Methacrylate Nanofiber Membranes Prepared by Solution Blow Spinning

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ABSTRACT: Hydrophobic and breathable nanofiber membranes have attracted considerable attention owing to their applications in various fields. In this study, we fabricated superhydrophobic and breathable nanofiber membranes using solution blow spinning. We optimized the spinning process parameters by analyzing their effects on the structure and properties of the nanofiber membranes. And the nanofiber membranes achieved superhydrophobicity through hydrophobic modification treatment. The average fiber diameter and pore size of the obtained membrane were 0.51 and 13.65 μm, respectively. The membranes exhibited superhydrophobicity, breathability, and mechanical properties: water vapor transmission of 12.88 kg/m²/day, air permeability of 10.97 mm/s, water contact angle of 150.92°, maximum tensile stress of 5.36 MPa, and maximum elongation at break of 12.27%. Additionally, we studied the impact of heat treatment on the nanofiber membranes. The membranes prepared in this study can be applied to protective garments, outdoor clothing, antifouling materials, etc. Because of its relatively higher production efficiency, solution blow spinning is a prospective method for producing functional nanofibers.

1. INTRODUCTION
Electrospun functional membranes have attracted tremendous attention owing to their capabilities for filtration, adsorption, separation, and so on. During electrospinning, a polymer solution is ejected from a capillary under a strong electrostatic force; subsequently, the solvent evaporates and forms ultrafine fibers on the collector below the capillary.¹² However, the requirement of a high voltage gradient and low productivity limit the applications of electrospinning. These challenges can be overcome by solution blow spinning (SBS), which is a relatively novel method used to prepare functional membranes. In this method, a high-velocity gas flow provides the driving force for the fabrication of nanofibers. The pressurized high-velocity gas causes pressure drop and shearing at the gas/solution interface, resulting in the stretching of the polymer solution toward a fixed collector. As the solvent evaporates, the streams of stretched polymers rapidly form fibers.²,³

Several studies on functional membranes prepared by SBS have been reported in recent years.¹⁴⁻⁸ Song et al. reported a phenolphthalein polyethersulfone/silica (SiO₂) composite nanofibrous membrane and a composite membrane modified with cross-linked PVP possessing an excellent and stable antifouling performance.⁵,⁶ Polyacrylonitrile (PAN)-based composite nanofiber membranes have considerable potential for air and water filtration as well as biorefinery applications. In addition, poly(vinylidene fluoride) (PVDF) nanofiber membranes possess high filtration efficiency for applications in microenergy harvesting equipment and wearable electronic textiles.⁷ Zhao et al. fabricated porous silicon carbide nanofiber membranes that exhibit good electrochemical performance for use as electrode materials in supercapacitors.⁸ Nanofibrous membranes prepared from polylactic acid can be used for various applications, such as high-efficiency oil/water separation,⁹ oil absorption,¹⁰ controlled release of linalool,¹¹ absorbable sutures and medical implants,¹² antimicrobial filtration, and membrane separation.²

Waterproof and breathable nanofiber membranes (WBNMs) are of great interest because of their high hydrophobicity, good breathability, and excellent mechanical properties. They also exhibit a stable antifouling performance, which is important for
Currently, WBNMs are mainly fabricated by electrospinning. Yu et al. fabricated a type of WBNM consisting of F-SiO$_2$ and polyurethane (PU), which exhibited an excellent hydrostatic pressure of 50 kPa and moisture permeability of 10.4 kg/m²/h. Maksoud et al. reported a PU-based nanofibrous membrane exhibiting excellent hydrophobicity, air permeability, and water vapor transmission rate (WVTR). A novel fluoride-free functional membrane prepared by modifying PAN nanofibers with poly(dimethylsiloxane) (PDMS) was found to exhibit enhanced water resistance (80.9 kPa), air permeability (9.9 mm/s), and tensile stress (12.5 MPa). Some studies have also revealed that PVDF, poly(tetrafluoroethylene), and PDMS/polystyrene can be used to prepare WBNMs.

To the best of our knowledge, SBS has not been used widely to prepare WBNM. In the only study reported by Li et al., the authors fabricated a waterproof PAN nanofiber by solution blow spinning of fluorine-containing polyacrylate and PAN. The membrane exhibited excellent hydrophobicity [water contact angle (WCA) of 137.11°] but lacked moisture permeability. In this study, we fabricated PAN-based nanofiber membranes with superhydrophobicity and breathability using the SBS method. The prepared nanofiber membranes displayed better superhydrophobicity, breathability, and mechanical properties than conventional WBNMs. This type of membrane will be widely applied in producing self-cleaning, antifouling, and medical materials.

Moreover, the SBS method has high production efficiency and significant potential for industrialization. Thus, we choose the SBS method to fabricate superhydrophobic and breathable membranes and we expect to explore the potential production processes for such membranes.

### 2. MATERIALS AND METHODS

To fabricate pristine PAN nanofiber membranes with a desirable performance, the spinning process parameters were first optimized. Then, hydrophobic SiO$_2$ nanoparticles and perfluoroalkyl ethyl methacrylate (PFM) were added to the precursor solution to improve the hydrophobicity. Finally, a thermal treatment was carried out to enhance the mechanical

**Table 1. Different Spinning Process Parameters Used for Preparing Pristine PAN Membranes by SBS**

| sample | polymer solution concentration (wt %) | gas pressure (MPa) | NCD (cm) | injection rate (mL/min) | nozzle diameter (mm) |
|--------|--------------------------------------|-------------------|---------|-------------------------|---------------------|
| 1      | 8                                    | 0.15              | 70      | 0.3                     | 0.34                |
| 2      | 10                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 3      | 12                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 4      | 14                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 5      | 12                                   | 0.05              | 70      | 0.3                     | 0.34                |
| 6      | 12                                   | 0.1               | 70      | 0.3                     | 0.34                |
| 7      | 12                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 8      | 12                                   | 0.2               | 70      | 0.3                     | 0.34                |
| 9      | 12                                   | 0.15              | 40      | 0.3                     | 0.34                |
| 10     | 12                                   | 0.15              | 50      | 0.3                     | 0.34                |
| 11     | 12                                   | 0.15              | 60      | 0.3                     | 0.34                |
| 12     | 12                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 13     | 12                                   | 0.15              | 70      | 0.2                     | 0.34                |
| 14     | 12                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 15     | 12                                   | 0.15              | 70      | 0.4                     | 0.34                |
| 16     | 12                                   | 0.15              | 70      | 0.5                     | 0.34                |
| 17     | 12                                   | 0.15              | 70      | 0.3                     | 0.5                 |
| 18     | 12                                   | 0.15              | 70      | 0.3                     | 0.4                 |
| 19     | 12                                   | 0.15              | 70      | 0.3                     | 0.34                |
| 20     | 12                                   | 0.15              | 70      | 0.3                     | 0.26                |
properties of the membranes. The schematic of the entire process is shown in Figure 1.

2.1. Fabrication of Pristine PAN Membranes. The precursor solution was prepared by dissolving PAN powder \( (M_n = 150,000; \text{CAS number: 25014-41-9; Kxinda Polymer Materials Co., China}) \) in \( N, N\)-dimethylacetamide (99.0%, CAS number: 127-19-5, Shanghai Sinopharm Chemical Reagent Co., China). The solution was thoroughly stirred on a thermostatic heating agitator (DF-101S, Henan Aibote Technology Co., China) until the mixture turned transparent yellow. The prepared precursor solution was then loaded into a syringe placed on an injection pump to fabricate pristine PAN nanofiber membranes via SBS. The SBS apparatus was manufactured by Qingdao PSTECH Co., China. The spinning process parameters, including the injection rate, concentration of the polymer solution, nozzle-to-collector distance (NCD), nozzle diameter, and gas pressure affect the structure of the final pristine PAN membrane. Therefore, we investigated the effects of these spinning process parameters on the structure of the pristine PAN membrane and optimized the fabrication conditions. The details of different experiments are presented in Table 1, and the image of the prepared pristine PAN nanofiber membrane is shown in Figure 2.

2.2. PAN/SiO\(_2\)/PFM Nanofiber Membranes. Hydrophobic SiO\(_2\) nanoparticles and fluoride have been widely used to enhance the hydrophobicity of membrane network systems. This is because the inorganic nanoparticles enhance the surface roughness of the membranes, and fluoride helps reduce the surface energy of the membranes. Therefore, to improve the hydrophobic performance of the precursor solution, we prepared a superhydrophobic precursor solution by mixing PAN with hydrophobic SiO\(_2\) nanoparticles and fluoride. SiO\(_2\) was first modified to make it hydrophobic. Five hundred milligrams of SiO\(_2\) (15 nm; CAS number: 14808-60-7, MACKLIN Biochemical Reagent Co., China) was mixed with 50 mL of absolute ethanol (99.7%, CAS number: 64-17-5, Enox Chemicals Company, China) in a beaker. After ultrasonic treatment for 3 h, the mixture was stirred at 600 rpm and ambient temperature for 30 min to achieve a uniform dispersion. Subsequently, hexadecyltrimethoxysilane (1 mL) and absolute ethanol (5 mL) were added successively into the SiO\(_2\) solution, and the mixed solution was poured into a graduated cylinder. Then, 1.5 mL of the mixed solution was centrifuged in a centrifuge tube at 6000 rpm for 8 min. Finally, the supernatant liquid was poured out, and the remaining solution with white SiO\(_2\) nanoparticles was dried in an oven (DS-B, Shanghai Ruyi Constant Temperature Equipment Center, China) at 90 °C for 4 h to obtain hydrophobic SiO\(_2\) nanoparticles.

The hydrophobic SiO\(_2\) nanoparticles and PFM (99%, CAS number: 65530-66-7, MACKLIN Biochemical Reagent Co., China) were mixed in different mass ratios (SiO\(_2\)/PFM = 4:1, 2:1, 4:3, and 1:1) to prepare the hydrophobic agent. The mixture was then added to the optimum PAN solution (Section 2.1) and stirred for 1 h to obtain the superhydrophobic precursor solution. The precursor solution was transferred to the injection pump, and the superhydrophobic PAN/SiO\(_2\)/PFM membranes were finally fabricated in accordance with the optimal spinning process parameters (as discussed in Section 3.1).

2.3. Thermal Treatment. The fabricated nanofiber membranes were heated in an oven for 2 h to enhance their mechanical properties. Considering the melting point of PAN
(138−141 °C), the temperatures used for thermal treatment were 100, 120, 140, and 160 °C.

2.4. Characterization. The microstructures of the prepared composite membranes were characterized using scanning electron microscopy (SEM; SU9000, Shanghai VIHENT Optoelectronic Technology Co., China) at a magnification of 3000×. Based on the SEM images, nanofiber diameter distribution was acquired using the SEM software Image-Pro Plus 6.0. The chemical structures of the membranes were determined using a Fourier transform infrared (FTIR) spectrometer (Thermo Scientific, Guangdong Shengze Technology Co., China). The pore size was measured using an aperture analyzer (SPDA-20, Beijing JINYANG Wanda Technology Co., China), and the porosity of the membrane was calculated using the formula

\[
P = \left(1 - \frac{m}{t \times s \times \rho}\right) \times 100\%
\]

where \(P\) is the porosity (%), \(m\) is the mass of the membrane (g), \(t\) is the thickness of the membrane (cm), \(s\) is the area of the

Figure 4. (a) Diameter and (b) pore size of pristine PAN nanofiber membranes prepared at different PAN concentrations.

Figure 5. SEM images of pristine PAN nanofiber membranes prepared at different gas pressures: (a) sample 5 (0.05 MPa), (b) sample 6 (0.1 MPa), (c) sample 7 (0.15 MPa), and (d) sample 8 (0.2 MPa).
membrane (cm$^2$), and $\rho$ is the membrane density (g/cm$^3$). The membrane was weighed using an electronic balance (LE104E/02, METTLER TOLEDO Co., Switzerland), and the membrane thickness was measured using a digital fabric thickness gauge (YG-141N, Hangzhou Noted Scientific Equipment Co., China).

The hydrophobicity of the membrane was determined based on the WCA and hydrostatic pressure. The WCA of the nanofiber membrane was measured using an optical contact-angle measuring instrument (BDL-SDJY, Dongguan Bo Laide Equipment Co., China), and the hydrostatic pressure of the membrane was measured using a fabric moisture permeability tester (YG(B)-812Q, Wenzhou Darong Textile Instrument, China).

The breathability of the membrane was characterized by determining the moisture and air permeability rates. A computer-type moisture permeability tester (YG601, Ningbo Textile Instrument, China) was used to determine the moisture permeability rate of the membrane. The air permeability rate was measured using an automatic air permeability instrument (YG461E-III, Wenzhou Jigao Instrument Co., China).

**Figure 6.** (a) Diameter and (b) pore size of pristine PAN nanofiber membranes prepared at different gas pressures.

**Figure 7.** SEM images of pristine PAN nanofiber membranes prepared at different NCD values: (a) sample 9 (40 cm), (b) sample 10 (50 cm), (c) sample 11 (60 cm), and (d) sample 12 (70 cm).
mechanical properties of the nanofiber membranes were evaluated using an electronic strength instrument (YG004, Chang Yi Textile Instrument Co., China).

3. RESULTS AND DISCUSSION

3.1. Effects of Different Parameters on the Fiber Diameter and Pore Size of Pristine PAN Nanofiber Membranes. 3.1.1. PAN Concentration. Figure 3 shows the morphologies of the nanofiber membranes prepared at different PAN concentrations. Bead-like structures are observed in samples 1 and 2, as indicated by the red circles in Figure 3a,b. Some researchers attribute this structure to an insufficiently volatilized precursor solution and unstable jet. Sample 3 exhibits uniform fibers and a relatively bead-free structure, whereas some fibers are entangled in sample 4.

With increase in the PAN concentration, the average fiber diameter increases from 0.26 to 0.67 μm, while the average pore size decreases to 18.43 μm and then increases. The beads in samples 1 and 2 generate larger pores. The stack of thick fibers in sample 4 is also believed to result in a larger pore. Thus, a PAN
concentration of 12 wt % is considered optimal owing to the bead-free structure and relatively small pore size of the obtained membrane. Small pores can effectively prevent penetration of water droplets while allowing water vapor to pass through the membrane (Figure 4).9,24

3.1.2. Gas Pressure. Figure 5 shows the morphological transformation of the nanofibrous membranes with increase in the gas pressure. Samples 5 and 6 display bead-like structures and bundles of fibers, as indicated by the red circles in Figure 5a,b. This is attributed to insufficient stretching, resulting from the low gas pressure. Sample 7 exhibits a uniform morphology, whereas numerous fibrous bundles are observed in sample 8. This is because a large gas pressure prevents the secondary cleavage of the solution jet.25

With increase in the gas pressure, the average fiber diameter first decreases and then increases slightly, as shown in Figure 6a. This may be because a high gas pressure lowers the viscosity of the polymer and causes the fibers to bundle. The average pore size of the prepared membranes decreases with increase in the gas pressure except for sample 6, as shown in Figure 5b. Sample 6
presents a larger pore size, which is attributed to its nonuniform fibers. Thus, a gas pressure of 0.15 MPa is considered optimal because of the formation of thinner fibers and smaller pores (sample 7).

3.1.3. NCD. The morphologies of the fibers obtained at different NCDs are shown in Figure 7. Samples 9–11 exhibit bead-like structures (indicated by red circles in Figure 6a) and numerous bundles of fibers. At NCD = 70 cm, the fibers are uniform and smooth without bundle formation. This may be because an appropriate NCD ensures effective cleavage of the precursor solution jet. With increase in the NCD from 40 to 70 cm, the average fiber diameter decreases continuously, as shown in Figure 8. As pointed out by Dadol, a longer distance between the nozzle and the collector enables greater stretching of the fibers and better dissipation of the solvent, resulting in thinner fibers. Accordingly, the average pore size of the nanofiber membranes becomes smaller. Sample 12 possesses thinner fibers and a smaller pore size than those of samples 9–11. Therefore, 70 cm was selected as the optimized NCD for further experiments.

3.1.4. Injection Rate. Figure 9 shows the morphologies of the nanofibers prepared at different injection rates. Sample 13 exhibits uniform fibers, and sample 14 exhibits uniform and...
continuous fibers without bead-like structures. However, bundles of fibers are observed in samples 15 and 16. The amount of precursor solution per unit volume in the nozzle increases with increase in the injection rate. Thus, the shear force

Figure 14: (a) FTIR spectrum, (b) pore size, (c) porosity, (d) WCA, (e) hydrostatic pressure, (f) WVTR, (g) air permeability, and (h) tensile stress–strain curves of PAN/SiO$_2$/PFM nanofiber membranes prepared at different SiO$_2$/PFM mass ratios.
on the surface per unit volume of solution decreases, which prevents thinning of the solution stream and fibers.\textsuperscript{24}

The diameter of the nanofiber membranes is proportional to the injection rate, as shown in Figure 10a. At an appropriate range of gas pressure, the injection rate has a positive effect on the fiber diameter. A higher injection rate counteracts the shear force of the gas, which reduces the stretching effect and results in a larger fiber diameter.\textsuperscript{25–27} The average pore size increases with increase in the fiber diameter, as shown in Figure 10b. This is because an increase in the fiber diameter leads to a larger pore size of the nanofiber membranes. Considering the productivity, an injection rate of 0.3 mL/min is optimum for subsequent experiments.

3.1.5. Nozzle Diameter. Figure 11 shows the morphologies of the fibers prepared at different nozzle diameters. Bundles of fibers are observed in sample 17,\textsuperscript{26} as indicated by red circles in Figure 11a. This is because the relative speed between the air flow and the extruded solution is not sufficiently high to stretch the fibers efficiently. However, bundles of fibers are also observed in samples 19 and 20; this may be because the extruded solution jet is too thick for efficient dispersion. Sample 18 exhibits a desirable morphology because the precursor solution jet is sufficiently stretched.\textsuperscript{28,29}

With increase in the nozzle diameter, the fibers first become thinner and then thicker (Figure 12a). The fiber diameter decreases when the nozzle diameter is increased from 0.26 to 0.34 mm. Atif reported that an appropriate nozzle diameter enables the precursor solution jet to be sufficiently stretched. The fiber diameter increases with further increase in the nozzle diameter.\textsuperscript{25} Moreover, the pore sizes of the prepared membranes vary with the fiber diameter. Sample 18 exhibits high porosity and excellent water vapor permeability owing to its thin fibers and small pore size. Consequently, a nozzle diameter of 0.34 mm was used for the preparation of WBNMs with a relatively compact and porous structure.

In summary, the optimal spinning process parameters are PAN concentration of 12 wt %, gas pressure of 0.15 MPa, NCD of 70 cm, injection rate of 0.3 mL/min, and nozzle diameter of 0.34 mm. The pristine PAN nanofiber membrane prepared using these spinning process parameters exhibits an average fiber diameter of 0.44 μm, average pore size of 18 μm, and average porosity of 90%.

3.2. PAN/SiO\textsubscript{2}/PFM Nanofiber Membranes. As shown in Figures 13 and 14, the hydrophobic modification treatment significantly affects the structure and performance of the nanofibrous membranes. Figure 13 shows the morphologies of the PAN/SiO\textsubscript{2}/PFM nanofiber membranes prepared at differ-

![Figure 15. SEM images of the nanofibrous membranes subjected to heat treatment at different temperatures: (a) 100 °C, (b) 120 °C, (c) 140 °C, and (d) 160 °C.](image-url)
Figure 16. (a) Tensile stress—strain curves, (b) pore size, (c) porosity, (d) WCA, (e) hydrostatic pressure, (f) air permeability, and (g) WVTR of the nanofiber membranes subjected to heat treatment at different temperatures.
ent SiO$_2$/PFM mass ratios. The hydrophobic SiO$_2$ nanoparticles attach to the fibers extensively, which enhances the roughness of the surface of the fibers. The FTIR spectra in Figure 14a show the appearance of characteristic absorption peaks at 1072 and 779 cm$^{-1}$ after the hydrophobic modification treatment; these peaks are attributed to the stretching vibrations of $-\text{CF}_3$ and $-\text{CF}_2$ in PFM. Meanwhile, the absorption peaks at 1106, 804, and 469 cm$^{-1}$ in the FTIR spectra are attributed to the Si–O–Si asymmetric stretching, Si–O symmetrical stretching, and Si–O–Si bending vibration, respectively. The characteristic absorption peaks mentioned above verify the presence of PFM and hydrophobic SiO$_2$ nanoparticles in the nanofiber membrane. As evident from Figure 14b,c, the average pore size and average porosity of the nanofiber membranes decrease after the hydrophobic modification treatment. It is speculated that the hydrophobic SiO$_2$ nanoparticles attached to the fibers narrow the pores between the fibers.

Although hydrophobic SiO$_2$ nanoparticles are beneficial for improving the hydrophobicity, PFM has a primary influence on the hydrophobicity of the nanofiber membranes. As shown in Figure 14d,e, the WCA and hydrostatic pressure increase with decrease in the SiO$_2$/PFM mass ratio. In particular, the membranes exhibit desirable WCA values of 146.96, 148, 150.92, and 151.78$^\circ$. The WVTR and air permeability were measured to evaluate the breathability of the nanofibrous membranes, and the results are shown in Figure 14f,g, respectively. With decrease in the SiO$_2$/PFM mass ratio, the WVTR and air permeability of the nanofiber membranes decrease owing to the gradual decrease in the porosity.$^{30}$ In addition, the SiO$_2$/PFM mass ratio affects the mechanical properties of the nanofiber membranes (Figure 14h). The tensile mechanical properties of the PAN/SiO$_2$/PFM nanofiber membrane are optimum at a mass ratio of 4:3. The values of maximum tensile stress and elongation at break are 5.36 MPa and 12.27%, respectively.

### 3.3. Impact of Thermal Treatment on PAN/SiO$_2$/PFM Nanofiber Membranes

To improve the mechanical properties of PAN/SiO$_2$/PFM nanofiber membranes, we heat-treated the PAN/SiO$_2$/PFM nanofiber membranes at different temperatures. The nanofiber membrane prepared with SiO$_2$/PFM mass ratio of 4:3 was selected for the thermal treatment owing to its higher tensile strength than that of others.

Compared with Figure 13, several bonded structures exist in the membrane after heat treatment, as indicated by red circles in Figure 15. The appearance of these bonded structures is concurrent with increase in the tensile stress. Bonded structures can prevent the slippage between fibers, thus reinforcing the tensile stress of the membrane. As illustrated in Figure 16a, when the temperature is increased to 140 $^\circ$C, the maximum tensile stress and elongation at break are 7.44 MPa and 20.15%, respectively. However, at 160 $^\circ$C, the values of maximum tensile stress and elongation at break decrease to 6.43 MPa and 16.8%, respectively. This may be attributed to the destruction of the internal molecular chain of the fibers at a very high temperature.$^{31}$

The pore size and porosity of the nanofiber membranes decrease with increase in the heat-treatment temperature. This can be attributed to the formation of bonding structures in the membranes. Moreover, the hydrophobic performance of the nanofiber membrane improves significantly after thermal treatment. The WCA value and hydrostatic pressure increase with increase in the heat-treatment temperature, as shown in Figure 16d,e. On the other hand, air permeability and WVTR decrease owing to the decrease in pore size and porosity, as shown in Figure 16f,g. In summary, the tensile stress, WCA, and hydrostatic pressure of the membrane increased with increase in the heat-treated temperature; however, pore size, porosity, air permeability, and WVTR decreased. Therefore, we need an overall consideration and select an appropriate heat-treated temperature.

### 4. CONCLUSIONS

In conclusion, superhydrophobic and breathable PAN/SiO$_2$/PFM nanofiber membranes were prepared using the SBS method. We investigated the effects of different process parameters on the morphology and structure of nanofiber membranes. The optimum process parameters are: PAN concentration of 12 wt %, gas pressure of 0.15 MPa, injection rate of 0.3 mL/min, NCD of 70 cm, and nozzle diameter of 0.34 mm. We improved the hydrophobicity of the membranes by blending the hydrophobic agent with the PAN solution. The nanofiber membranes exhibit excellent performances: WCA of 150.92$^\circ$, WVTR of 12.88 kg/m$^2$/day, air permeability of 10.97 mm/s, maximum tensile stress of 5.36 MPa, and maximum elongation at break of 12.27%. We also explored the impact of the heat-treated temperature on the properties and structure of the fabricated membrane. WCA and hydrostatic pressure of the membrane increased with increase in the heat-treated temperature; however, pore size, porosity, air permeability, and WVTR decreased.

The SBS method has high production efficiency and significant potential for industrialization. This article explores the potential production processes for the superhydrophobic and breathable PAN/SiO$_2$/PFM nanofiber membranes.

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Notes
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