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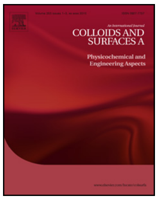

Electrospinning ultrathin continuous cellulose acetate fibers for high-flux water filtration

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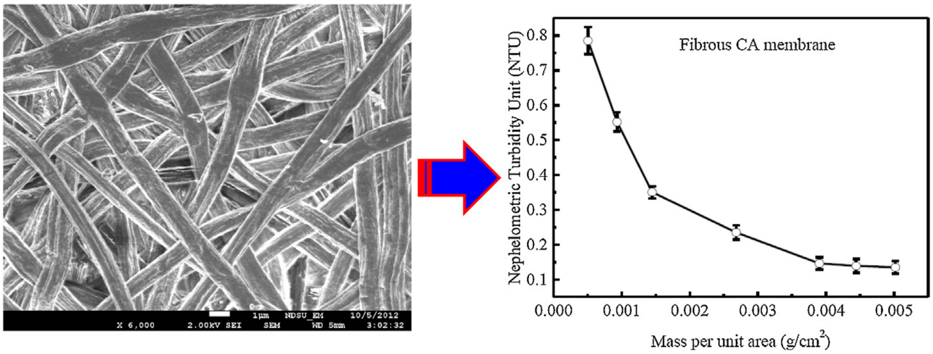
HIGHLIGHTS

- Ultrathin fibrous cellulose acetate (CA) membranes were electrospun.
- Water-filtration efficiency of the fibrous CA membranes was tested.
- Filtration efficiency were correlated to the membrane areal-weight.
- Morphology and filtration mechanisms were characterized by SEM.

GRAPHICAL ABSTRACT

Hot-pressed electrospun fibrous cellulose acetate membranes for water filtratio.



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ABSTRACT

This paper reports the fabrication and filtration characterization of advanced fibrous cellulose acetate (CA) membranes for high-flux water filtration. The ultrathin nonwoven fibrous CA membranes with varying fiber diameter and areal weight were produced by electrospinning and post-processed by hot-press. The filtration efficiency of the ultrathin fibrous CA membranes was characterized by controlled water-filtration tests based on artificial colloids prepared via dispersing polystyrene (PS) particles of the diameters of 5 μm, 2 μm, 500 nm, and 100 nm in water, respectively. Natural river water was further used for evaluating the filtration capability of the electrospun fibrous CA membranes. Experimental results show that the rejection rate of the present fibrous CA membranes to PS particles with the diameter of 2 μm was up to 99.8%. In addition, the filtration efficiency of the electrospun fibrous CA membranes increased with increasing areal weight of the membranes. In the case of the filtering electrospun fibrous CA membranes with the fiber diameter of ~800 nm and membrane areal weight ~0.005 g/cm^2, the measured turbidity of natural river water after filtration can reach as low as 0.135 nephelometric turbidity unit (NTU) while the initial flow flux can reach up to 20,455 L/m^2 h at the feed pressure 14 psi. The study suggests that low-cost electrospun fibrous membranes can be used for stable, high-flux water microfiltration with the filtration efficiency.

1. Introduction

Clean and sustainable water is essential to human life and modern society, which even played a crucial role in the evolution and

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fate of ancient civilizations in the world. Water filtration is one of the fundamental solutions to secure clean water from natural water sources and to recycle life and industrial waste water for reuse. Growing demands of high-quality filtration also drive the development of membrane technology for today's micro and nanofiltration, reverse osmosis, gas separation, diffusion dialysis, etc. [1]. In addition, recent electrospinning technology makes it possible to produce low-cost ultrathin nonwoven fibers with the diameter in the range of a few nanometers up to micrometers [2–14]. Ultrathin electrospun fibers also provide innovative fibrous filtering media for the purpose of low-cost, high-efficiency liquid and gas filtration [4,15–19]. Compared to many commercially available filtering membranes that are produced by conventional fabrication techniques such as phase inversion technique, the pore size distribution of electrospun fibrous membranes can be conveniently tailored in the range of sub-microns up to a few micrometers via simply adjusting the material and process parameters of electrospinning and related post-processes. In addition, electrospun filtering media are also capable of maintaining a high porosity, which guarantees the high-flux liquid filtration.

In the past decade, intensive investigations have been conducted on understanding the microfiltration performance of electrospun fibrous filtering media. Wang et al. [20]. fabricated a ternary high-flux filtering medium consisting of a top-layer of nonporous hydrophilic [polyether-b-polyamide copolymer surface-coated with surface-oxidized multi-walled carbon nanotubes (MWCNTs)], a mid-layer of electrospun fibrous [poly(vinyl) alcohol (PVA)], and a conventional nonwoven microfibrous supporting layer for the purpose of oil-water emulsion separation. The oil-water emulsion filtration test showed that the fibrous medium exhibited a high flux rate up to 330 L/m^2 h at the feed pressure of 100 psi and the total rejection rate to organic solute was up to 99.8% without noticeable fouling. Gopal et al. [21,22]. demonstrated the water filtration of electrospun nonwoven polyvinylidene fluoride (PVDF) and polysulfone (PSU) mats via filtering polystyrene (PS) particles dispersed into water. The study showed that for large flow pore sizes (4.0–10.6 μm for PVDF and 1.2–4.6 μm for PSU), the rejection rate to PS particles with the diameter greater than 3 μm was higher than 92%. The experimental observation also indicated that it was difficult to remove the PS particles with the diameters around 1.0–2.0 μm due to the formation of cake-shaped layer; however, PS particles with the diameter lower than 1.0 μm were absorbed and trapped into the fibrous membranes, i.e., the depth filtration. Aussawasathien et al. [23]. electrospun nonwoven nylon-6 fibrous mats with the thickness ~0.60 mm and fiber diameter ranging from 30 to 110 nm for water filtration. Water filtration test based on PS particles of the diameters of 0.5, 1.0, 6.0, and 10 μm showed that the fibrous filtering media can capture all particles with the size from 10 μm down to 1.0 μm whereas approximately 90% for the particles with the diameter of 0.5 μm. Ma et al. [24] produced regenerated nonwoven fibrous cellulose acetate (CA) mats by electrospinning CA solution (0.16 g/ml) of a mixture solvent of acetone/*N*,*N*-dimethylformamide (DMF)/trifluoroethylene (3:1:1), followed by surface functionalization via thermal and alkali solution treatment, for use as affinity membranes for successful separation of biomolecules in water solution. Shin and Chase [25] fabricated nonwoven coalescence filtering medium for separating secondary dispersions such as droplets in oil by electrospinning nylon-6, polyamide (PA), polyacrylonitrile (PAN) and PS onto nonwoven fiberglass mats. Filtration tests showed that no noticeable difference in filtration efficiency (~71–77%) among the four polymeric fibrous media. In addition, Sundarrajan et al. [26] proposed to engineer electrospun fibrous membranes for nanofiltration by replacing the ultrafiltration mid-layer into conventional thin-film composite membranes (in three-tier arrangement) by nonwoven electrospun fibrous mats, which provided the flexibility to manipulate both the pore size (by reducing fiber diameter) and cross-sectional thickness (by adjusting the electrospinning duration) of the electrospun fibrous membranes. As demonstrated in their experiments, the rejection ratio and flux of salt solution could be adjusted for nanofiltration. Detailed discussions on progress in fabrication and characterization of electrospun fibrous filtering media for water microfiltration can be found in two recent review articles [16,17].

In the present work, we proposed to investigate the dependency of filtration efficiency of novel electrospun fibrous CA membranes upon the fiber diameter and areal weight. Natural river water and controlled artificial colloids consisting of PS particles of varying diameters (5 μm, 2 μm, 500 nm and 100 nm) dispersed in water were utilized for filtration characterization of the present fibrous CA membranes. The rest of the paper was organized as follows. The paper first describes the fabrication of fibrous CA membranes with controlled fiber diameter and areal weight by electrospinning, followed by hot-press, and related structural and filtration characterization. The paper then shows the results of the structural morphology of the ultrathin fibrous CA membranes produced in this study and related water filtration efficiency. The filtration efficiency and water flux of the present electrospun fibrous CA membranes are compared with those of one commercially available filtering membrane. Relevant filtration mechanisms were explored and discussed. Conclusion on the present experimental study is drawn consequently.

2. Experimental

2.1. Materials

Cellulose acetate (CA, Mn = 50,000) powder, organic solvents *N*,*N*-dimethylformamide (DMF, 99%) and acetone (99%), and polystyrene (PS) particles of the diameters of 0.1, 0.5, 2.0 and 5.0 μm were purchased from Sigma-Aldrich Chemical Co. (St. Louis, MO, USA) for use in this study without further purification and treatment. Distilled water used as aqueous solute was obtained from a local chemical shop in campus. Natural river water used for evaluating the filtration efficiency of the electrospun fibrous CA membranes was obtained from the local Red River in city Fargo, North Dakota (USA). For the purpose of filtration comparison, one type of commercially available aqueous filtering membranes was also adopted as the control sample, i.e., Supor® membranes (Catalog number: 28147–640 with the diameter of 47 mm, thickness of 145 μm and pore size of 0.45 μm). High-performance Supor® filtering membranes made of hydrophilic polyethersulfone are fabricated by means of phase inversion and have been extensively used for filtering aqueous solutions to remove fine particles, bacteria, viruses and fungi, which makes them for broad applications in sample preparation, sterile filtration, and infusion therapy, among others. The selection of Supor® membranes is based on the fact that the filtration performance of the electrospun fibrous CA membranes in this study is comparable to that of Supor® membranes at the same areal weight of the membranes.

2.2. Preparation of ultrathin fibrous CA membranes

The nonwoven ultrathin fibrous CA membranes were fabricated by means of the low-cost needle-based electrospinning technique. During this process, CA powder was first dissolved in DMF solvent for 5 h with steady magnetic stirring. Subsequently, 1.0 wt.% acetone was added to the CA solution to yield a well electrospinnable CA/DMF/acetone solution. The solution was then loaded into a 10-ml plastic syringe installed with a stainless steel spinneret (DB Company, Singapore), which had an inner diameter of 0.48 mm.

A rotary disc-like aluminum plate with a diameter of 30 cm was utilized as the fiber collector. The spinneret and aluminum plate were placed with a 25 cm gap and connected respectively to the positive (18 kV) and negative (−5 kV) high-voltage DC power supplies (Gamma High Voltage Research, Inc., Ormond Beach, FL). The resulting electrostatic field of 92 kV/m was applied for stable electrospinning of the ultrathin CA fibers. The flow rate was maintained at 1.8 ml/h by a digitally controlled syringe pump (model number: KDS 200) purchased from KD Scientific, Inc. (Holliston, MA). After each electrospinning test, the nonwoven fibrous CA membrane was peeled off from the rotary aluminum plate and further hot-pressed at a processing temperature of 100 °C. The areal weight of the CA membranes was controlled from 0.0005 to 0.005 g/cm^2 by adjusting the collection duration of the CA fibers in a specific electrospinning process.

2.3. Characterization

Surface morphology of the electrospun nonwoven fibrous CA membranes was analyzed by using a field-emission scanning electron microscope (SEM, JEOL JSM-7600F). Water filtration test was carried out using a vacuum filtration setup consisting of a Buchner funnel, a suction flask, and a vacuum water pump. During a filtration test, an electrospun fibrous CA membrane was tailored into a circular shape with an effective permeation area of 8.04 cm^2 for use as the filtering membrane. PS particles of the diameters of 0.1, 0.5, 2.0 and 5.0 μm were dispersed respectively into distilled water to form 0.05 wt.% aqueous solutions (colloids) as follows. In each case of the PS/water solution of specified PS particle diameter, distilled water of 120 ml was first measured and placed in a beak, and then proper PS particles weighed according to the 0.05 wt.% solution were dispersed into the distilled water and sonicated for 30 min to ensure the formation of a uniform solution (colloid). In each case, a PS/water solution (colloid) of 100 ml was used for water filtration test. To evaluate the filtration performance of the electrospun fibrous CA membranes against nano/micro-particles, the ultraviolet absorbances of the feed solution, filtered solution, and pure distilled water were sampled respectively in the case of each particle diameter by using an Ultraviolet–Visible Near Infrared Spectrophotometer (UV–vis-NIR) (Varian Cary 5000, Agilent Technologies, USA). Presence of the PS particles of a specified size in the collected solution was detected by using a UV spectrophotometer and the PS particle concentration was calculated using the measured absorbance data. The rejection ratio (RR) was determined according to the formula

$$\mathrm{RR} = \left(1 - \frac{C_{\mathrm{filtrate}}}{C_{\mathrm{feed}}}\right) \times 100\% \qquad (1)$$

where C_{feed} and C_{filtrate} are the PS concentrations of before and after the filtration test, respectively. In this study, C_{feed} is the PS mass concentration of the formed PS/water solution, i.e., 0.05 wt.% as specified in this study; C_{filtrate} was estimated according to the net mass decrease of the PS particles in the solution, which was determined by the mass difference of the dried filtering membranes before and after filtration test.

In the case of filtration test of the local river water, a HACH 2100N Turbidimeter (Hach Co., Colorado, USA) was adopted to determine the turbidity of the filtering liquids before and after filtration test. Without pre-treatment and purification, the initial local river water had the average value of turbidity in term of the Nephelometric Turbidity Unit (NTU) as 25.27, which was much higher than that of the tap water of 0.288 NTU. The river water was then used for the filtration test to determine the filtration performance of the electrospun fibrous CA membranes. During the filtration test, the river water (1 l) was injected into the Buchner funnel under a constant water pump pressure of 14 psi. Given a nonwoven fibrous CA membrane of specified areal weight, the filtration test had been repeated for three times to obtain an averaged value of turbidity. In addition, the permeability of both the electrospun fibrous CA and Supor® membranes was studied by measuring the water flux at the constant feed pressure of 14 psi. The water flux was calculated using the relation [27]:

$$F = \frac{V}{A \Delta t} \qquad (2)$$

where F is the water flux (l/m^2 h), V is the permeated water volume (l), A is the effective filtering area of the membranes (m^2), and Δt is the time (min).

3. Results and discussion

3.1. Morphology of fibrous filtering membranes

In this study, nonwoven fibrous CA membranes with three different fiber diameters were fabricated in laboratory by electrospinning the 12 wt.%, 14 wt.% and 16 wt.% CA/DMF/acetone solutions, respectively. The morphology of the electrospun nonwoven fibrous CA membranes were studied by means of both SEM and optical microscopy. Fig. 1 shows the SEM micrographs of the ultrathin nonwoven CA fibers that were produced by electrospinning the CA/DMF/acetone solutions with the CA concentrations of 12 wt.% [Fig. 1(A–D)], 14 wt.% [Fig. 1(E)] and 16 wt.% [Fig. 1(F)], respectively. The average fiber diameters and their standard deviations of the three types of electrospun CA fibers were measured via analyzing 10 SEM micrographs in each case of the CA mass concentration of the CA/DMF/acetone solution based on a graphic analysis software package installed in the SEM system. The results of the CA fiber diameters are tabulated in Table 1, which are 0.96 μm, 1.30 μm and 1.57 μm corresponding to the CA mass concentrations of 12 wt.%, 14 wt.% and 16 wt.%, respectively. It can be observed that at the same process and control parameters adopted in the electrospinning process, the diameter of the CA fibers decreases with decreasing CA mass concentration. Such observation was due to the fact that the viscosity of the CA/DMF/acetone solution decreases with decreasing CA mass concentration.

Furthermore, Fig. 1 (panels A and B) also indicates that before hot-press, the as-electrospun CA fibers are homogeneous, continuous, and highly porous. The surface of the electrospun CA fibers is relatively rough and the average diameter of the CA fibers is approximately 1.0 μm (0.96 μm). In contrast, after hot-press at 100 °C, as shown in Fig. 1 (panels C and D), the CA fibers exhibited in a compact configuration with obvious plastic deformation such that their cross-section lost the circular morphology with the longer axis (~1.0 μm in this case) larger than that of the virgin electrospun CA fibers. The hot-pressing treatment played an important role to generate mechanically more durable fibrous CA membranes with the lower pore size since the hot-press process increased the adhesion between CA fibers. It needs to be mentioned that the glass transition temperature (T_g) and melting temperature (T_m) of CA are 198–205 °C and 224–230 °C, respectively [28,29]. Thus, the substantial morphology change of the overlapping connection between the electrospun CA fibers was induced by the mechanical plastic deformation during the process of hot-pressing treatment at 100 °C but not by melting.

To compare the morphology of the electrospun nonwoven fibrous CA membranes with those of commercially available membranes used for liquid filtration, high-performance Supor® filtering membranes were used for SEM and optical microscopic studies. Fig. 2(A & B) shows the typical surface morphologies of a Supor® membrane at the low and high magnifications, respectively. It can be observed that the Supor® membrane was made of a random

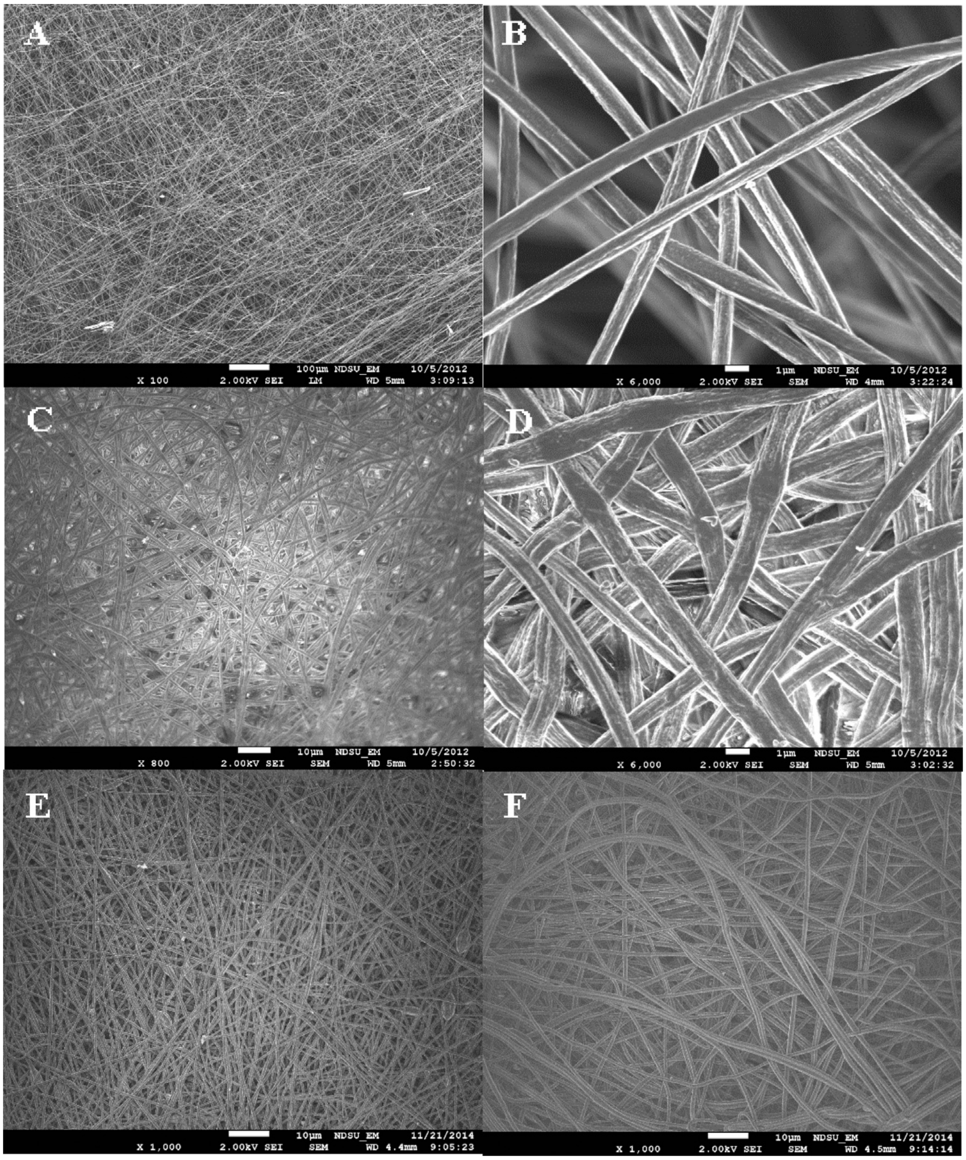

Fig. 1. Panels (A) and (B) are the SEM micrographs of the 12 wt.% CA fibers before hot-pressing treatment at the low and high magnifications, respectively; Panels (C) and (D) are the SEM micrographs of the electrospun CA fibers after hot-pressing treatment at the low and high magnifications, respectively; Panels (E) and (F) are the SEM micrographs of the 14 wt.% and 16 wt.% CA fibers after hot-pressing treatment, respectively (Mass per unit area: ~0.005 g/cm^2).

amorphous porous microstructure, consisting of rod-like particles with the average diameter ranging from 200 nm to 400 nm.

3.2. Polystyrene (PS) nano/micro-particle filtration test

The filtration performance of the present electrospun fibrous CA membranes against PS particles was investigated by filtering 100 ml 0.05 wt.% aqueous PS suspensions (colloids) through the membranes. SEM observations showed that the top surface of the filtering fibrous CA membranes carried varying numbers of PS particles after the filtration test as shown in Fig. 3. It can be observed that there were basically no PS particles with the diameter of 100 nm on the membrane surface [Fig. 3(A)], i.e., the rejection ratio of the electrospun fibrous CA membrane to such type of PS particles is very low. In contrast, a significant number of PS particles with the diameters of 2.0 μm and 5.0 μm were aggregated on the surface of the electrospun fibrous CA membranes [Fig. 3(C & D)], which indicates the large rejection ratios of the present electrospun fibrous CA membranes to these two types of PS particles. The rejection ratio of the present electrospun fibrous CA membrane to the PS particles with the diameter of 500 nm is between the two cases above [Fig. 3(B)]. The filtration results are tabulated in Table 1. It

Table 1
Rejection ratio of the electrospun fibrous CA membranes to the PS particles of diameters of 0.1 μm, 0.5 μm, 2.0 μm, and 5.0 μm, respectivley.

Samples	Fiber diameter (μm)	Membrane thickness (μm)	Particle size (μm)			
			5.0	2.0	0.5	0.1
12 wt.% fibrous CA membrane (M1)	0.96 ± 0.11	80	99.94%	99.91%	76.86%	11.81%
14 wt.% fibrous CA membrane (M2)	1.30 ± 0.15	80	99.90%	99.86%	27.59%	11.45%
16 wt.% fibrous CA membrane (M3)	1.57 ± 0.18	80	99.75%	99.80%	32.00%	8.30%

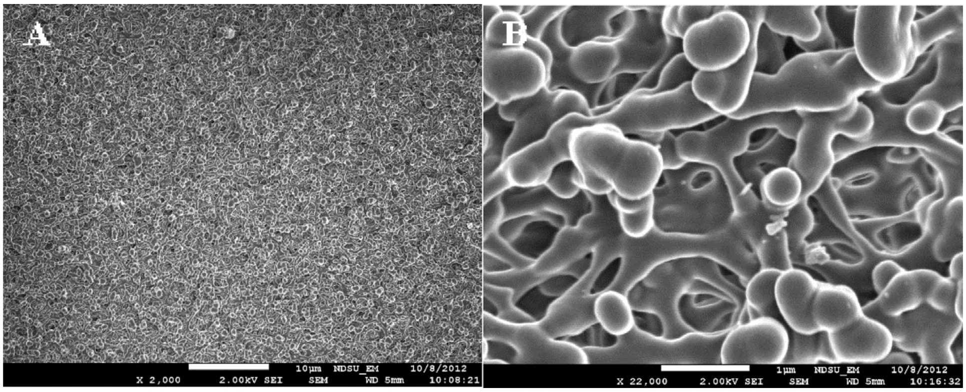

Fig. 2. Panels (A) and (B) are the SEM micrographs of the Supor® membranes at the low and high magnifications, respectively.

can be observed from Table 1 that the rejection ratio of the electrospun fibrous CA membranes to the PS particles of a particular size decreases with increasing fiber diameter, in which the rejection ratios are very close to 100% in the cases of the PS particles with the diameters of 2.0 μm and 5.0 μm. However, the rejection ratio of the present electrospun fibrous CA membranes to the PS particles with the diameter of 0.5 μm has a noticeable variation with the change of the CA fiber diameter, i.e., the rejection ratio of 76.86% for the fibrous CA membranes with the average fiber diameter of 0.96 μm decreases to 27.59% and 32.00% for the fibrous CA membranes with the average fiber diameters of 1.30 μm and 1.57 μm, respectively. This experimental evidence implies that the rejection ratio of the present electrospun fibrous CA membranes to PS particles with the diameter of 0.5 μm is highly sensitive to the fiber diameter, i.e., the pore size of the fibrous CA membranes is close to 0.5 μm. In this case, the fiber diameter directly contributed to the threshold pore size such that the pore size slightly decreased with decreasing fiber diameter. Table 1 also shows that the three types of electrospun fibrous CA membranes did not demonstrate obvious filtration efficiency to PS particles with the diameter of 0.1 μm. In addition, based on the approximate membrane thickness 80 μm, areal weight 0.005 g/cm^2, and CA mass density 1.28 g/cm^3, the porosity of the present electrospun fibrous CA membranes is around 65%, which is around 30% lower than that of similar electrospun fibrous CA membranes reported in the literature (82–85%) [24], i.e., application of post-pressing treatment made more compact fibrous CA membranes.

By comparison with the literature results [21,22], it is found that the present post hot-press process can noticeably increase the rejection ratio of the fibrous CA membranes to the PS particles with small diameters (2.0 μm and 500 nm in the present case). Correspondingly, the UV–vis spectra of the pure distilled water, feed solution and three post-filtered solutions in each case of the PS particle diameter are shown in Fig. 4, which can be closely correlated

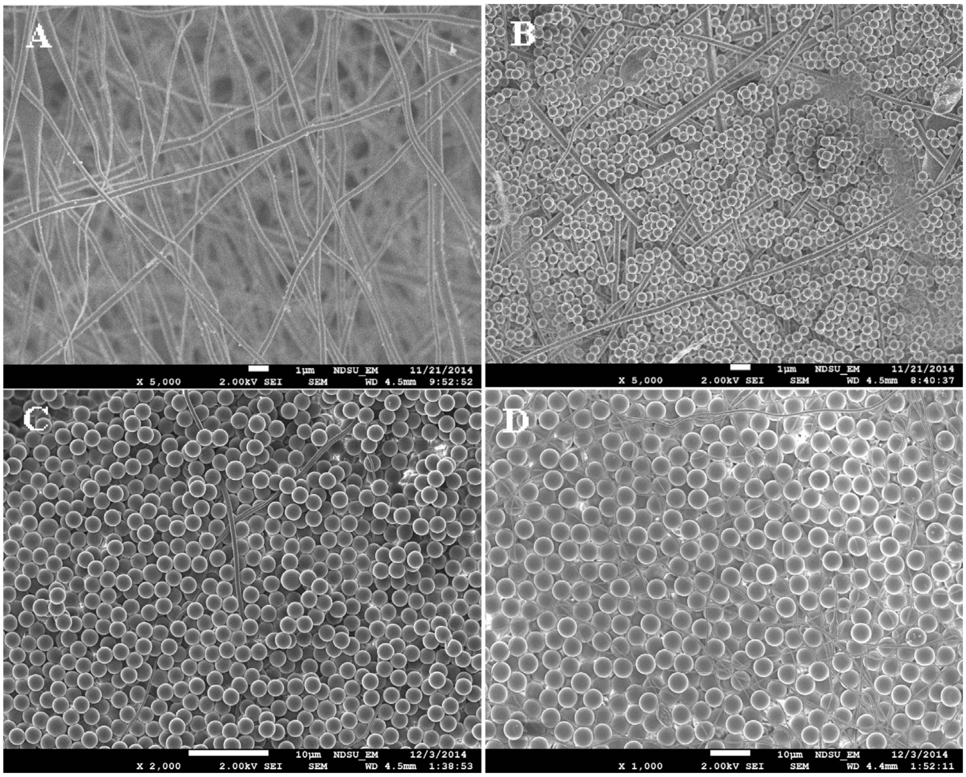

Fig. 3. SEM micrographs of the electrospun fibrous CA membranes (fiber diameter: 0.96 ± 0.11 μm) after filtering aqueous PS colloids with the PS diameter of 0.1 μm (A), 0.5 μm (B), 2 μm (C) and 5 μm (D), respectively.

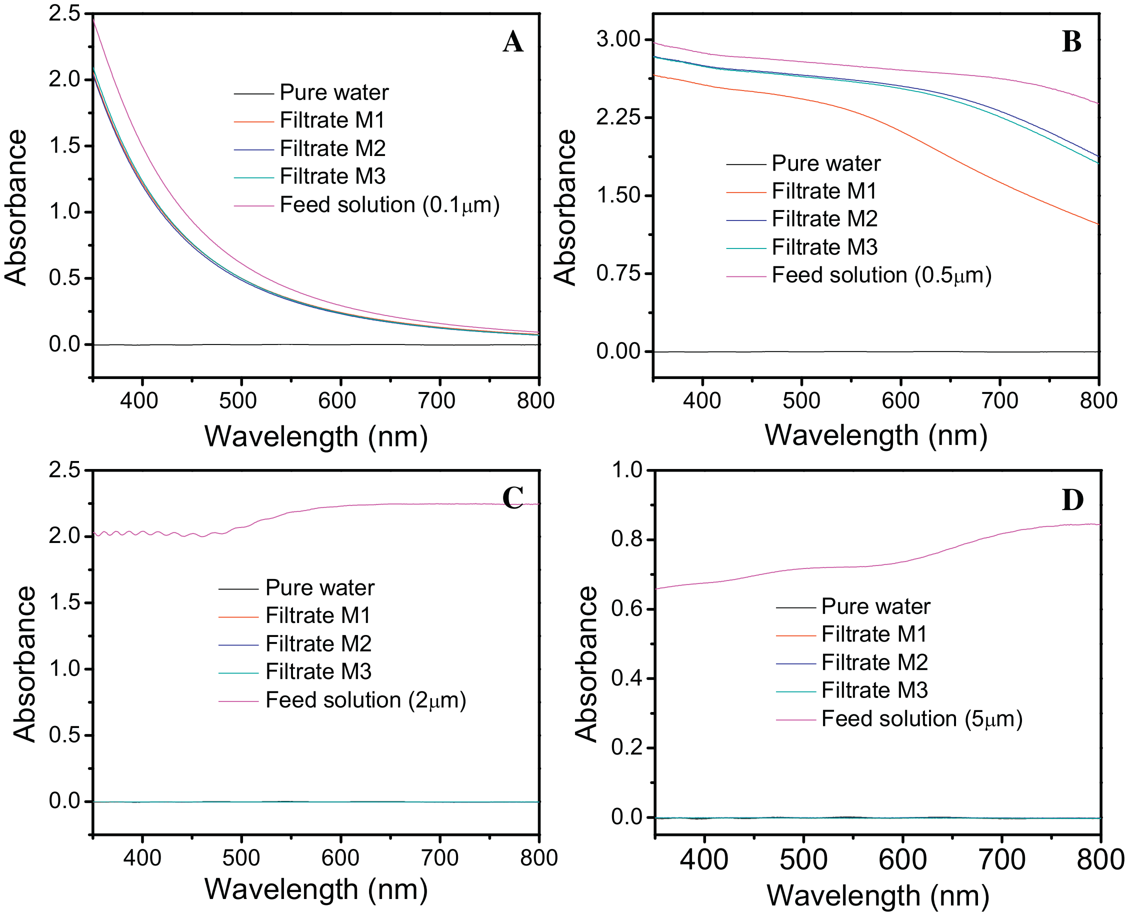

Fig. 4. UV–vis spectra of the pure distilled water, filtrate, and feed solution after filtering PS particles (in water) with the diameters of 0.1 μm (A), 0.5 μm (B), 2 μm (C), and 5 μm (D), respectively.

to the filtration results in Table 1, i.e., the present fibrous CA membranes have nearly 100% rejection ratio to the PS particles with the diameter higher than 2.0 μm.

3.3. *Morphology of membranes after river water filtration*

Table 1 indicates that the electrospun fibrous CA membranes with the average fiber diameter of 0.96 μm (based on 12 wt.% CA/DMF solution) exhibited the best filtration performance to filter PS particles. Therefore, this type of CA membranes was further used for the river water filtration to test the filtration performance of the electrospun fibrous CA membranes. The river water was obtained from the local Red River in Fargo, North Dakota (USA). All of the tests were carried out at room temperature under a constant water pump pressure of 14 psi. As evidenced, Fig. 5 shows the optical images of the Supor® and electrospun fibrous CA membranes before and after the water filtration tests, respectively. The filtration zone of the electrospun fibrous CA membrane shows its filtration efficiency comparable with the Supor® membrane.

Fig. 6 shows the SEM micrographs of the top surface [Fig. 6(A)], cross-section [Fig. 6(B)], and bottom surface [Fig. 6(C & D)] after water filtration test. No obvious change was observed in the morphology and microstructures of the electrospun fibrous CA membrane after the water filtration test, which indicates the excellent mechanical durability and hydraulic stability of the present electrospun fibrous CA membranes. The membrane surface was covered by a densely packed particle layer, consisting of suspended and colloidal matter as shown in Fig. 6(A). The filtered matter was probably made up with clays, silts, inorganic/organic particles, planktons, as well as other microscopic organisms from natural reviver water [30]. From Fig. 6(B), it can be clearly detected that the precipitates were retained mainly on the top surface and also clogged inside the layer of membranes, while almost no precipitates were found to retain on the lower surface of the present electrospun fibrous CA membranes. In this study, the thickness of the electrospun fibrous CA membrane is around 80 μm, much lower than that the Supor® membranes at 145 μm. In addition, the bottom surface of the electrospun fibrous CA membrane was completely free of any particles as shown in Fig. 6(C & D), demonstrating the high-performance filtration of the electrospun nonwoven fibrous CA membranes.

3.4. *Filtration performance for river water*

Fig. 7 presents the variation of the turbidity value of the river water with respect to the areal weight (i.e., mass per unit area, g/cm^2, a measure of the thickness of fibrous membranes) of the present nonwoven electrospun fibrous CA membranes. The diagram shows that the value of turbidity decreased rapidly with increasing areal weight of the present electrospun fibrous CA membranes. As aforementioned, the initial turbidity values of the natural river water and tap water were 25.27 and 0.288 NTU, respectively. After filtration test based on the present fibrous CA membranes, the turbidity values of the natural river water were reduced to 0.785, 0.552, 0.3505, 0.235, 0.146, 0.139, and 0.135 NTU at the areal weight of 0.0005, 0.0009, 0.0015, 0.0027, 0.0039, 0.0044, and 0.005 g/cm^2, respectively. The lowest turbidity value of 0.135 NTU was achieved at the areal weight of 0.005 g/cm^2, which is much lower than the

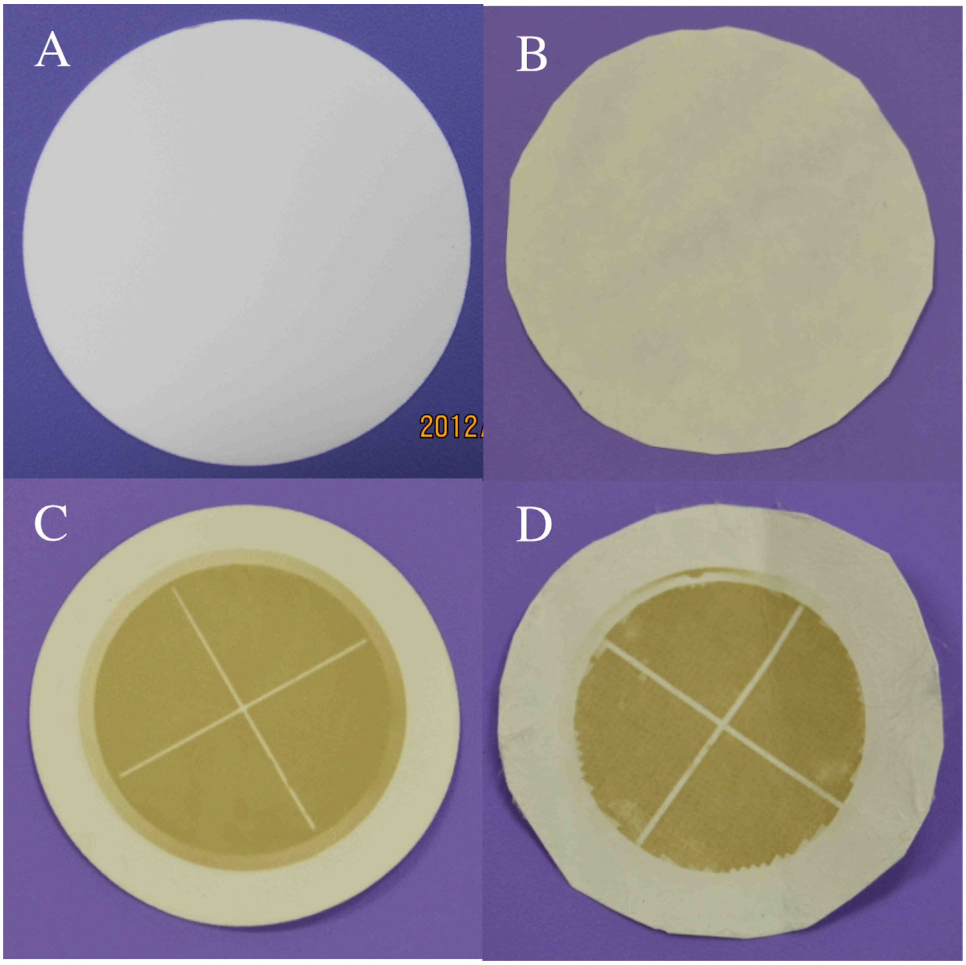

Fig. 5. Panels (A) and (B) are the optical images of the Supor® and electrospun fibrous CA membranes before water filtration test, respectively; Panels (C) and (D) are the Supor® and electrospun fibrous CA membranes after water filtration test, respectively.

turbidity value of 0.288 NTU of the tap water and is only one-sixth the turbidity value of 0.785 NTU based on the electrospun fibrous CA membranes with the areal weight of 0.0005 g/cm^2. In addition, it can also be observed from Fig. 7 that the value of turbidity of the natural reviver water after filtration test decreases rapidly with respect to increasing areal weight of the electrospun fibrous CA membranes (i.e., the membrane depth) till the areal weight of around 0.004 g/cm^2, after which the value of turbidity tends to be constant. It can be understood that with increasing membrane areal weight, overlapping of the multiple ultrathin CA fiber networks can generate the fine sized pores, beneficial to enhance the interception effect of the resulting fibrous CA membranes against particles larger than a certain size. Such effect can also be validated by Fig. 6, in which Fig. 6(B) clearly shows the aggregation of small particles into the cross-sectional CA fibers. However, on the bottom surface of the membrane, no particles can be clearly noticed since the majority of the particles with the size larger than certain value had been intercepted by the top CA fiber layers.

To better compare the filtration performance of the electrospun fibrous CA membranes with that of commercially available ones, control filtration test based on Supor® membranes was also conducted at the same areal weight of ~0.005 g/cm^2, tabulated in Table 2, and the same testing conditions. It can be observed from Table 2 that the turbidity value of the electrospun fibrous CA membranes is about 0.135 NTU, which is lower than that of the Supor® filtering membranes with 0.147 NTU.

To study the effective permeability of the natural river water (~25.27 NTU), the values of water fluxe of the present nonwoven electrospun fibrous CA membranes and commercially available Supor® membranes were measured respectively at the constant feed pressure of 14 psi. According to Formula (2), the flux values of the natural river water are shown in Fig. 8. It is noted that the flux

Table 2
Water-filtration comparison of the electrospun fibrous CA and Supor® membranes (Areal weight: ~0.005 g/cm^2).

Properties	Supor® membrane(Catalog #: 28147–640)	Fibrous CA membrane
Filter media	Hydrophilic polysulfone	Cellulose acetate
Pore size (μm)	0.45	~0.8 (fiber diameter)
Filter diameter (mm)	47	~47
Thickness (μm)	145	~80
NTU	0.147	0.135
Initial water flux (L/m^2 h)	17,308	20,455
Estimated cost ($) (Pack of 100)	~154	<10 (Estimate)

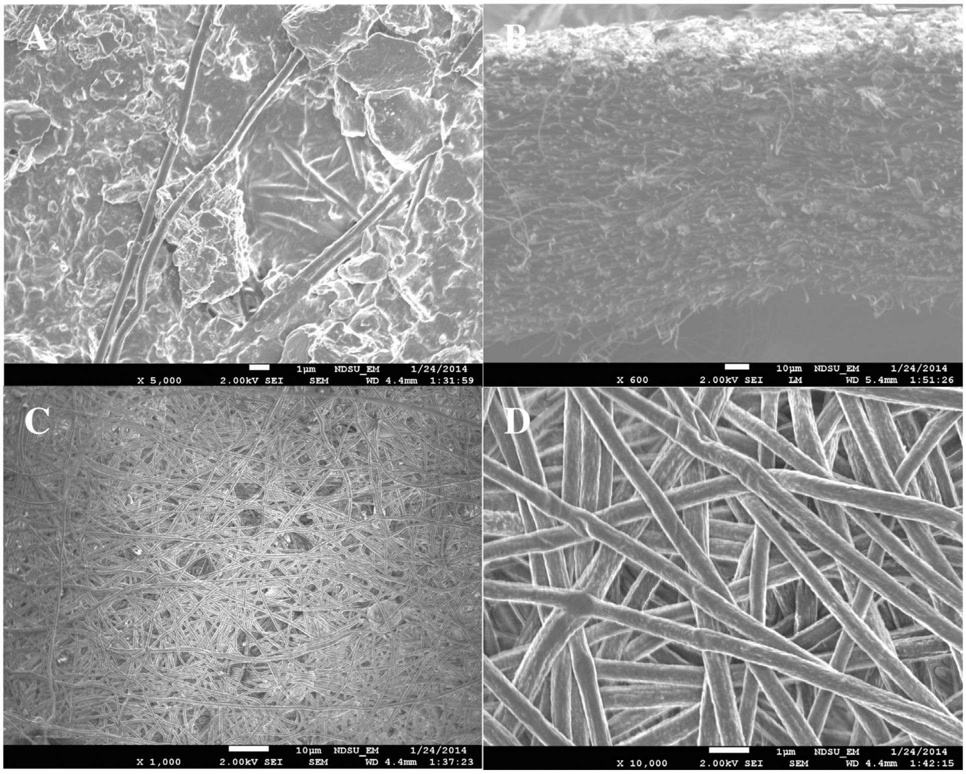

Fig. 6. SEM micrographs of the electrospun fibrous CA membranes after water filtration in different views: (A) top surface; (B) cross-section; (C) and (D) bottom surface at the low and high magnification, respectively (the mass per unit area: ~0.005 g/cm^2).

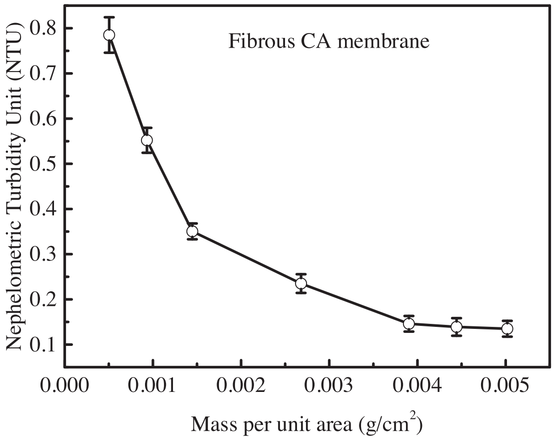

Fig. 7. Variation of the turbidity value of the natural river water with respect to the varying areal weight after filtration test using the present electrospun fibrous CA membranes.

values of both the membranes decreased with increasing filtration time due to fouling of suspended and colloidal matter on the membrane surfaces [22], which corresponds to the SEM micrographs as shown in Fig. 6(A & B). The electrospun fibrous CA membranes demonstrated enhanced river water permeability compared to that of the commercially available Supor® membranes at the first 3 min. The initial flux value (at the beginning of the water filtration test) of the electrospun fibrous CA membranes is as high as 20,455 L/m^2 h, which is higher than that of the Supor® membranes 17,308 L/m^2 h. After 6-min filtration, the steady water flux of both the membranes can still be maintained at a high level of ~2,935 L/m^2 h, which is comparable to those of previously reported electrospun fibrous membranes [31–34].

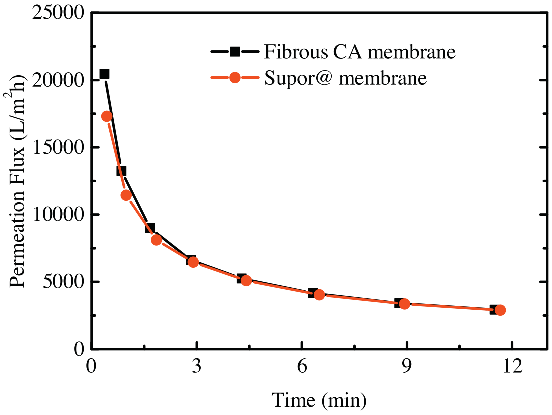

Fig. 8. Variation of the measured permeation flux of the nature river water with respect to the time for both the electrospun fibrous CA and commercially available Supor® membranes (0.005 g/cm^2).

The above experimental observation shows that the filtration performance of the electrospun fibrous CA membranes is better or at least similar to the commercially available Supor® CA membranes on the basis of the same areal weight of the filtering membranes. To achieve the similar filtration performance, electrospun fibrous CA membranes can be produced in low-cost, scalable manner (e.g., needleless electrospinning) and in much lower thickness at a specified areal weight. Multiple material and process parameters (e.g., CA concentration in solution, electrospinning process parameters, etc.) can be also used to tailor the material and geometrical properties of the electrospun fibrous membranes (e.g., the porosity, pore size, membrane thickness, etc.). Therefore, the present study has provided a feasible option of utilizing low-cost electrospun fibrous membranes to potentially substitute some commercially available water-filtering membranes with no reduced water filtration performance on the basis of the same areal weight of the membranes.

4. Conclusion

In this study, nonwoven fibrous CA membranes with varying fiber diameter and areal weight have been successfully fabricated by means of the low-cost electrospinning technique for use in water filtration. Filtration performance of such novel nonwoven fibrous membranes has been successfully characterized by turbidimeter and compared with that of commercially available water-filtering membranes. The present experimental study has showed that electrospun fibrous CA membranes can be used as practicable filtering membranes for high-flux water filtration, comparable to commercially available high-quality microfiltering membranes. In addition, electrospun fibrous membranes have a low cost in fabrication and can also be easily produced in large scale via utilizing low-cost, scalable needleless electrospinning, solution blowing, etc. Moreover, the porosity, pore size and thickness of the electrospun fibrous CA membranes can be conveniently designed and tailored by adjusting the material and process parameters utilized in electrospinning process, which offers an excellent opportunity for microstructural and performance optimization of the filtering membranes. As a result, electrospinning technique can be exploited for producing innovative, commercially viable nonwoven fibrous membranes for liquid filtration.

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