Research Papers

Greensusmater
Vol. 1, No. 1, March 2024
https://doi.org/10.62755/greensusmater.2024.1.1.32-38
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Investigating the influence of polyacrylonitrile nanofiber thickness on particulate matter filtration performance from cigarette smoke

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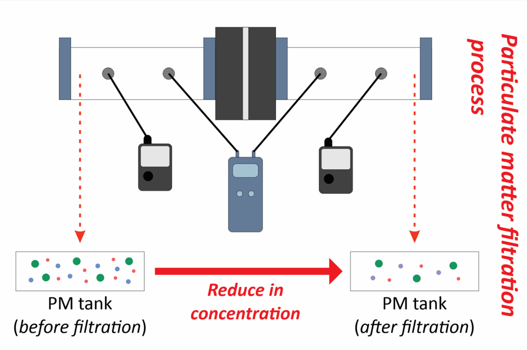
ARTICLE HISTORY: Received: March 9, 2024 | Revised: March 11, 2024 | Accepted: March 13, 2024

ABSTRACT

This study successfully fabricated polyacrylonitrile (PAN) nanofiber in various thicknesses as particulate matter (PM) filtration membranes using the electrospinning method. The PM source used was derived from cigarette smoke. Scanning electron microscopy (SEM) images and Fourier-transform infrared (FTIR) spectra are provided in the manuscript to observe the morphology and chemical composition of the fabricated nanofiber membrane. The thickness of the nanofiber was controlled based on the volume of the polymer solution, which was 4 mL, 6 mL, and 8 mL, and had a thickness of (52 ± 2) μm, (176 ± 27) μm, and (479 ± 38) μm, respectively (denoted as NF-4, NF-6, and NF-8 membranes). The results showed that the nanofiber membrane performed well against PM0.3, PM1, and PM2.5, with efficiency above 95.7%. Furthermore, it was observed that increasing the thickness of the nanofiber resulted in higher filtration efficiency. This trend is evident in the NF-8 membrane, which exhibited an efficiency of (97.9 ± 0.3)%, compared to only (95.7 ± 0.2)% for the NF-4 membrane against PM0.3. However, the pressure drop is also higher ((0.03 ± 0.005) kPa), which causes a trade-off in the quality factor (QF) of fabricated nanofiber performance as a PM filtration membrane.



Keywords: *Nanofiber, Polyacrylonitrile, Particulate Matter Filtration, Efficiency, Pressure Drop, Quality Factor*

1. INTRODUCTION

Air pollution is an environmental problem that poses a significant threat to human health worldwide, ranging from minor upper irritation to chronic respiratory and heart disease, premature mortality, and lung cancer [1, 2]. The World Health Organization (WHO) data reveals that 99% of the world's population is exposed to air containing elevated levels of pollutants [3]. One of the primary components of the most harmful air pollution, impacting air quality, human health, and ecosystems, is particulate matter (PM) [4, 5]. PM is a general term for solid and liquid particles of small size suspended in air [6, 7]. Most of the PM comes from motor vehicle emissions [8], coal combustion [9], industrial emissions [10], and the burning process [11].

Many epidemiological data and clinical studies prove that PM exposure harms human health. Among the various impacts, one of the notable consequences is the onset of cardiovascular dysfunction [12]. The long-term inhalation of PM, especially PM2.5 (diameter size < 2.5 μm), has been identified as a significant risk factor, contributing to an increased likelihood of death and heightened cardiovascular morbidity [13]. This phenomenon happens as fine particles possess a large surface area, enabling them to transport various pollutants [14]. In addition, fine particles also have a longer residence time in the air, so they can quickly and easily enter the respiratory system and cause cardiovascular and respiratory diseases by dissolving in the blood [15]. Moreover, PM can also carry microorganisms, such as bacteria and viruses, that can harm human health [16].

Nanofiber-based filtration membranes, known for their high PM removal efficiency, offer a promising solution for some applications, such as enhancing face masks and respirators for effective virus protection and reducing air pollution from PM [17]. Nanofiber, with an average diameter below 1 μm, exhibits superior removal efficiency against ultrafine PM compared to microfiber with an average diameter of up to 10 μm, especially for particles below 1.0 μm in diameter [18]. In addition, nanofiber filters have higher porosity [19], lower pressure drop [20], and a large surface area, making them suitable for filtration membrane applications [21, 22].

Nanofiber membranes can be fabricated through several methods, including electrospinning. Electrospinning is a method capable of producing selective, cost-effective, and flexible membranes for various polymers [23, 24, 25, 26, 27]. Electrospinning can fabricate fibers continuously with diameters ranging from micro to nanometers [20, 28, 29, 30, 31, 32, 33, 34, 35]. Many polymers can be used for nanofiber membrane fabrication, including polyacrylonitrile (PAN) [36, 37], polyvinyl pyrrolidone (PVP) [38, 39], polyvinyl acetate (PVAc)

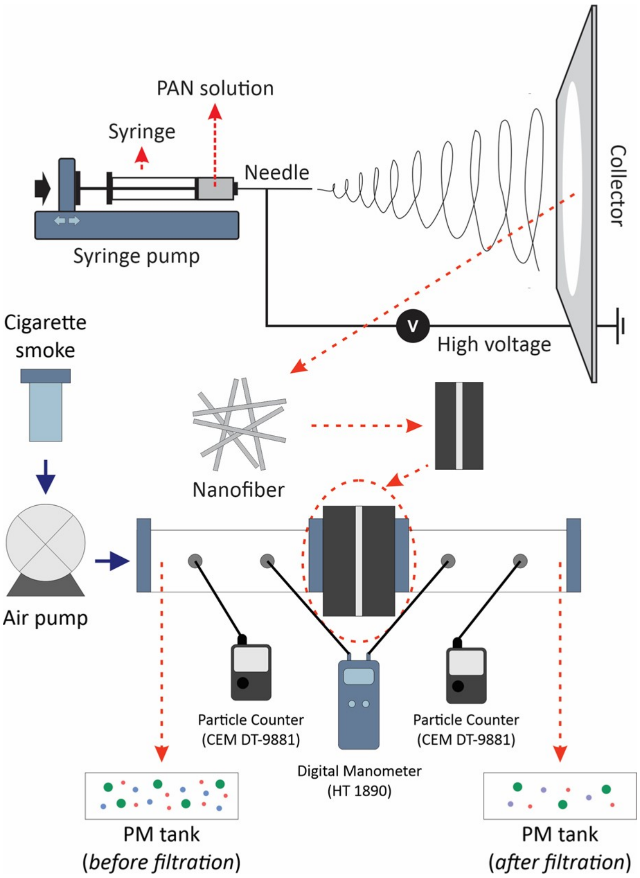


Figure 1. Nanofiber fabrication process using electrospinning method and PM filtration testing setup

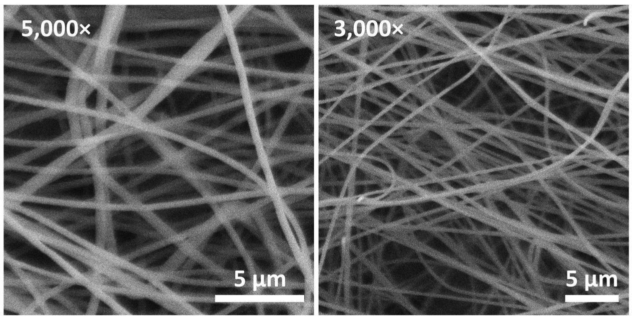


Figure 2. Scanning electron microscopy (SEM) images of fabricated PAN nanofiber with different magnification of 5,000× and 3,000×

[40, 41, 42], polyvinyl alcohol (PVA) [43], polystyrene (PS) [44, 45], polypropylene (PP) [46, 47], and others. Among these polymers, nanofiber membranes made from PAN polymers are often applied as filtration media because they have good chemical, mechanical strength, and thermal stability [48]. In addition, it also has an average diameter of about 141 nm[49]. Considering the average fiber diameter achieved by previous researchers, the PAN membrane is predicted to filter PM that might pass through the membrane. However, research has been widely reported on fabricating nanofiber membranes using PAN polymer material by electrospinning as an air filtration membrane [50, 51]. In this study, we focus on the effect of PAN nanofiber thickness on its performance as a PM filtration membrane. Cigarette smoke, which is widely dispersed in the air, was used as a PM source to mimic the ability of the fabricated membrane to the real sample. The morphology and functional groups of the PAN nanofiber membrane were observed by scanning electron microscope (SEM) and Fourier-transform infrared (FTIR). The fabricated PAN nanofiber-based PM filtration membrane from this research is expected to be utilized as an air filter in indoor devices and respiratory protective equipment, such as masks and respirators.

2. MATERIAL AND METHODS

2.1 Reagents And Instruments

Polyacrylonitrile (PAN) powder (Mw 150,000 g.mol^{-1}) dan N, N-dimethyl formamide (DMF) (Mw 73.09 g.mol^{-1}) were all produced by Sigma Aldrich, Singapore. A commercial cigarette was used as a PM source (PT. Gudang Garam Tbk.). Scanning electron microscopy (SEM, JEOL JSM-6510) and Fourier-transform infrared spectroscopy (FTIR, Thermo Nicolet iS10) were employed to investigate the morphologies and chemical compositions of the fabricated PAN nanofiber-based PM filtration membrane. The particle counter (CEM DT-9881) and digital manometer (HT 1890) were utilized to measure the PM concentrations and pressure drop of the membrane before and after passing the membrane. ImageJ and OriginLab software were used to measure the diameter of the nanofiber and visualize the data in the graph, respectively.

2.2 Nanofiber Fabrication Process

PAN solution, with a concentration of 6 wt%, was achieved by dissolving the PAN polymer in DMF. The solution was stirred for 2 hours at 40 °C with a rotating speed of 600 rpm until a homogeneous solution was obtained. The solution was put into a 10 cc syringe with a 0.50 × 25 mm needle. The syringe was put into the electrospinning machine during the nanofiber fabrication process. The needle was the positive pole, while the ground was connected to the plate collector. The electrospinning process was conducted with a voltage of 7 kV and a tip-to-collector distance of 14 cm. PAN nanofiber-based membranes were made in several thicknesses controlled by the total volume of solution used during the electrospinning process of 4 mL, 6 mL, and 8 mL, denoted as NF-4, NF-6, and NF-8 membranes, respectively. The illustration of the nanofiber fabrication process can be seen in figure 1

2.3 Filtrations Test Process

In this research, cigarette smoke was used as the PM source, and the PM filtration setup is shown in figure 1. The test was carried out by placing the PAN nanofiber-based membrane in the membrane holder. PM concentration was measured using a particle counter in each tank (before and after passing the membrane, recorded as C_0 and C_1, respectively). Data collection was collected five times for each membrane. Then, a digital manometer was installed in each tank to read the pressure difference (a.k.a. pressure drop). The data on particle concentration and pressure drop obtained from the test was subsequently analyzed using the following equation to determine the filtration efficiency (Equation 1) and quality factor (QF) (Equation 2) of the PAN nanofiber-based membrane.

$$\eta = \left(1 - \frac{C_1}{C_0}\right) \times 100\% \tag{1}$$

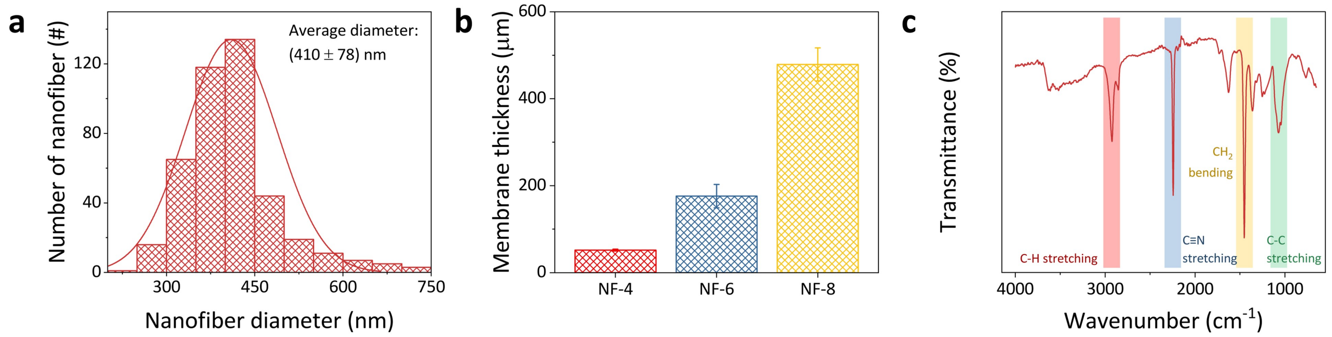


Figure 3. (a) Diameter distribution of fabricated PAN nanofiber. (b) The thickness of nanofiber-based PM filtration membrane with various solution volumes of 4 mL, 6 mL, and 8 mL (denoted as NF-4, NF-6, and NF-8, respectively). (c) Fourier-transform infrared spectroscopy of fabricated PAN nanofiber.

where η is PM filtration efficiency (%), and C_0 and $C-1$ were PM concentrations before and after filtration, respectively [50, 52, 53].

$$QF = -\frac{\ln(1-\eta)}{\Delta P} \tag{2}$$

where Δ P is the pressure drop (Pa) of the air filtration membrane [54, 55, 56, 57, 58].

3. RESULTS AND DISCUSSION

3.1 Morphology, Size Analysis, And Chemical Composition of PAN Nanofiber-Based Membranes

Figure 2 shows the SEM images of PAN nanofiber with two different magnifications of 5,000× and 3,000×. PAN nanofiber is seen to have a smooth and continuous morphology; these results are in accordance with previous studies [59, 60]. Based on the SEM image, nanofiber diameters were measured using ImageJ software (see figure 3a). The measurement results show that the nanofibers have a diameter of 224 nm to 738 nm, with an average diameter of (410 ± 78) nm, tending to have a small diameter. The small diameter is very beneficial in increasing the efficiency of the nanofiber-based PM membrane on the Kuwabara model, which shows that the filtration efficiency is inversely proportional to the diameter of the nanofiber [48, 61, 62, 63, 64]. In this study, the thickness of the nanofiber membrane was varied using the volume of solution, namely 4 mL, 6 mL, and 8 mL (denoted as NF-4, NF-6, and NF-8 membranes, respectively). Figure 3b shows the measurement of nanofiber membrane thickness. The thickness of the membrane is measured by measuring the results of the SEM cross-sectional image of the membrane using ImageJ software. Measurements were made three times (n = 3) at different locations. The result shows that nanofiber membranes have a thickness of (52 ± 2) μm, (176 ± 27) μm, and (479 ± 38) μm for NF-4, NF-6, and NF-8. The result indicates that a more polymer solution volume is used in electrospinning, making the resulting membrane thicker.

In addition to confirming the morphology and thickness of the PAN nanofibers by SEM images, we also provided FTIR spectra of fabricated nanofibers (see figure 3c). An FTIR spectra was conducted to identify functional groups and chemical composition of the fabricated nanofiber. The PAN nanofiber has a peak at a wavenumber of 2923.84 cm^{-1} and 2243.07 cm^{-1}, indicating the presence of C-H and C≡N stretching. There is also a peak at 1452.78 cm^{-1} and 1070.06 cm^{-1}, indicating the CH_2 bending and C-C stretching. The peaks of the PAN nanofiber obtained show the same results as the previous study [64]; this shows that the electrospun PAN nanofiber was successfully made.

3.2 PM Filtration Performance

PM filtration performance tests were carried out to determine the ability of fabricated PAN nanofiber to filter the PM with a size below 2.5 μm (i.e., PM0.3, PM1, and PM2.5). Hence, cigarette smoke was chosen as the PM source due to its presence as a common pollutant in the air. Moreover, its accessibility and ease of application make it suitable for testing in PM filtration equipment. Figure 4a shows the efficiency measurement results of the NF-4 membrane against PM0.3, PM1.0, and PM2.5. Efficiency measurements were made three times (n = 3), where the standard deviation of the repeated measurements was used as the error bar on the graph. The efficiencies obtained are (95.7 ± 0.2)%, (97.5 ± 0.3), and (98.1 ± 0.2)%, respectively. It can be observed that the higher the particle size, the higher the efficiency. This phenomenon is because particles with larger sizes tend to stick more easily and get trapped in the nanofiber membrane, causing greater efficiency. In addition to NF-4, the efficiency of NF-6 and NF-8 membranes were also measured and found to be (97.6 ± 0.1)%, (99.3 ± 0.1)%, and (99.6 ± 0.1)% for NF-6 and (97.9 ± 0.3)%, (99.4 ± 0.1)%, and (99.8 ± 0.1)% for NF-8 against PM0.3, PM1.0, and PM2.5, respectively (see Figure 4b and 4c). Furthermore, the recapitulation efficiency of fabricated membranes shows that thicker membranes give higher efficiency towards all the PM sizes (i.e., PM0.3, PM1.0, and PM2.5) (see Figure 6). This result indicates that the thickness of the PM filtration membrane can influence its efficiency. However, the performance of the PM filtration membrane is not only about efficiency. The pressure drop is also an important aspect. A good PM membrane usually has a low-pressure drop, indicating high breathability, allowing air to pass easily. According to this issue, the digital manometer recorded a pressure drop of (0.01 ± 0.005) kPa, (0.02 ± 0.005) kPa, and (0.03 ± 0.005) kPa for NF-4, NF-6, and NF-8 membranes, respectively. To assess the nanofiber performance as a PM filtration membrane, considering both efficiency and pressure drop, the quality factor (QF) of the PM filtration membrane is calculated using the equation provided in Equation 2. The calculation results show that the QF amounted to 0.31 Pa $^{-1}$ Pa^{-1}, 0.19 Pa^{-1}, and 0.12 Pa^{-1}, for PM0.3, amounted to 0.37 Pa^{-1}, 0.25 Pa^{-1}, and 0.17 $^{-1}$ for PM1.0, and amounted to 0.40 $^{-1}$, 0.28 Pa^{-1}, and 0.20 Pa^{-1} for PM 2.5, respectively (see figure 5). Based

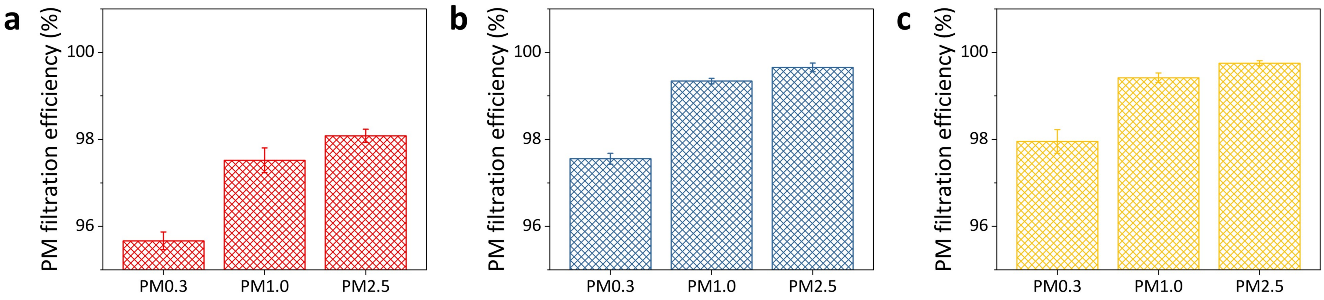


Figure 4. The filtration efficiency of PM0.3, PM1.0, and PM2.5 of (a) NF-4, (b) NF-6, and (c) NF-8 membranes

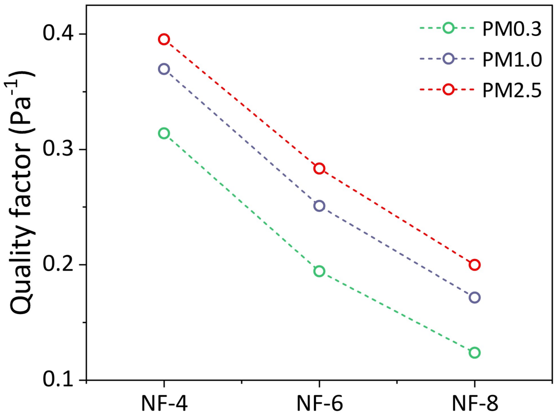


Figure 5. The quality factor of fabricated nanofiber as PM filtration membrane

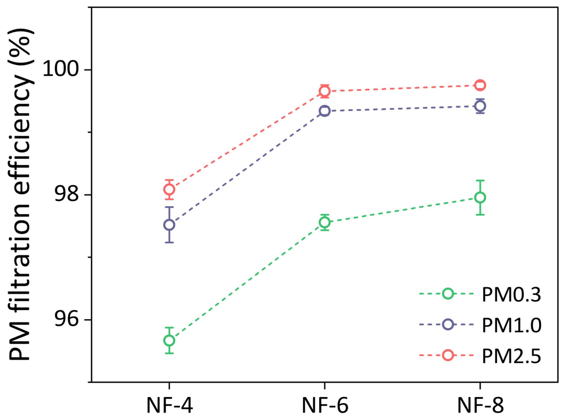


Figure 6. The recap of fabricated PM filtration membrane efficiency towards PM0.3, PM1.0, and PM2.5.

on these values, it can be seen that for each PM, the QF value of the membrane is getting. Although NF-8 has the highest efficiency value, it tends to have a high-pressure drop, causing a low-quality factor. Evaluation of the quality factor of the membrane is very important in getting a membrane that has good efficiency and low-pressure drop.

4. CONCLUSION

This study successfully produced polyacrylonitrile (PAN) nanofiber membranes of various thicknesses for particulate matter (PM) filtration from cigarette smoke, employing the electrospinning technique. Scanning electron microscopy (SEM) images and Fourier-transform infrared (FTIR) spectra were provided to examine the nanofiber membrane's morphology and chemical composition. Nanofiber thickness was achieved of (52 ± 2) μm, (176 ± 27) μm, and (479 ± 38) μm for NF-4, NF-6, and NF-8, respectively. The result revealed excellent PM0.3, PM1, and PM2.5 filtration efficiencies, exceeding 95.7%. Moreover, a clear trend showed that increased nanofiber thickness correlated with higher filtration efficiency. However, this also led to a higher pressure drop ((0.03 ± 0.005) kPa) and a decrease in quality factor (QF).

ACKNOWLEDGMENTS

The authors thank all PT Nanosense Instrument Indonesia and PT Fumalife Sinergi Inovasi employees who have provided technical support in this presented research work.

AUTHOR CONTRIBUTIONS

DW: conceptualization; investigation; formal analysis; writing-original draft.**RA:** visualization; formal analysis; writing-original draft; writing-review and editing **CNM:** visualization; formal analysis; writing-original draft. **KT:** formal analysis; writing-review and editing.**AK:** conceptualization; resources; funding acquisition; supervision; formal analysis; writing-review and editing. All authors approved the final manuscript.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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