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Biocompatible nanofiber based membranes for high-efficiency filtration of nano-aerosols with low air resistance

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\begin{abstract}
Particulate matter (PMs) from combustion emissions (traffic, power plant, and industries) and the novel coronavirus (COVID-19) pandemic have recently enhanced the development of personal protective equipment against airborne pathogens to protect humans’ respiratory system. However, most commercial face masks still cannot simultaneously achieve breathability and high filtration of PMs, bacteria, and viruses. This study used the electrospinning method with polyimide (PI) and polyethersulfone (PES) solutions to form a nanofiber membrane with low-pressure loss and high biocompatibility for high-efficiency bacteria, viruses, and nano-aerosol removal. Conclusively, the optimized nano-sized PI/PES membrane (0.1625 m\textsuperscript{2}/g basis weight) exhibited conspicuous performance for the highest filtration efficiency towards PM from 50 to 500 nm (99.74 \%), good filter quality of nano-aerosol (3.27 Pa\textsuperscript{\textasciitilde}), exceptional interception ratio against 100-nm airborne COVID-19 (over 99 \%), and non-toxic effect on the human body (107 \% cell viability). The PI/PES nanofiber membrane required potential advantage to form a medical face mask because of its averaged 97 \% BEF on Staphylococcus aureus filation and ultra-low pressure loss of 0.98 Pa by referring ASTM F2101–01. The non-toxic PI/PES filters provide a new perspective on designing excellent performance for nano-aerosols from air pollution and airborne COVID-19 with easy and comfortable breathing under ultra-low air flow resistance.
\end{abstract}

1. Introduction

Particulate matters (PMs), viruses, and bacteria are the three most common air pollutants highly caused by human activities (Burke, 2018; Clarke et al., 2014). PMs are primarily divided into three classifications by the aerodynamic diameters of the particle: within 2.5–10 μm (PM\textsubscript{10}), < 2.5 μm (PM\textsubscript{2.5}), and < 0.1 μm (PM\textsubscript{0.1}), respectively called coarse, fine, and ultrafine particles (UFPs) (Zaheer et al., 2018). The number fraction and weight fraction of particles with sizes ranging from 0.1 to 0.5 μm are 73 \% and 82 \%, respectively (Peters et al., 1997). Numerous epidemiology research has indicated that PM\textsubscript{2.5} is connected with breathing disturbance and cardiovascular diseases (Nunen et al., 2021; Kampa and Castanas, 2008). The daily air pollution level is reflected by the Air Quality Index, which is related to PM\textsubscript{2.5} and PM\textsubscript{10} concentrations. Compared to PM\textsubscript{2.5} with larger particles, ultrafine particles (PM\textsubscript{0.1}) could more easily enter pulmonary alveoli and go through pulmonary alveoli epithelium, causing lung inflammation (Oberdörster et al., 1995) and pulmonary deposition (Chalupa et al., 2004; Daigle et al., 2003) due to a larger number concentration (200 million/m\textsuperscript{3}) and higher surface area (Oberdörster et al., 1995; Leung and Chau, 2019).
Moreover, UFPs also load a large number of incinerators, heavy metals, dioxins, hydrocarbons, and other organic chemicals on their surfaces (Anandjiwala and Boguslavsky, 2008). Hence, much research has recently focused on the filter of UFPs owing to their harm to public health (Balazy et al., 2004).

As of June 17, 2022, the World Health Organization (WHO) announced that the coronavirus disease (COVID-19) had spread to 230 countries, with over 54,300,000 infections and 6,300,000 deaths. The size of the coronavirus ranges from 60 to 140 nm as detected using a Transmission Electron Microscope (TEM) (Zhu et al., 2020). Since the virus can be attached to particles smaller than 100 nm, the minimum size of COVID-19 and its aerosols can still be around 100 nm. Furthermore, the human saliva per milliliter contains more than 100,000,000 bacterial cells and harbors a series of pathobionts, such as Pseudomonas aeruginosa, Staphylococcus aureus, Veillonella spp, Klebsiella pneumoniae, Neisseria, Candida albicans, and Prevotella. (Rocas and Siqueira, 2006; Curtis et al., 2011; Ogawa et al., 2012; Hasan et al., 2014). Thus, long-time wear, improper storage, re-use, and poor filtration of masks may result in increased risks of respiratory virus transmission (MacIntyre et al., 2015).

Compared to fibrous-web filters by melt-blown (MB), needle-punched, and wet-laid processes (Lee and Wadsworth, 1990; Anandjiwala and Boguslavsky, 2008; Xia et al., 2019), an electrospun nanofiber can overcome the restrictions of a large-diameter electret filter to develop a highly efficient air filtration membrane (Li et al., 2015). The electrospinning method is simple and can produce micro-meter and nanometer-sized fibers. Nanofiber is suitable for filtering nanoparticles because it acquires traits of large surface area, small pore size, and high porosity (Park and Park, 2005; Reneker and Yarin, 2008). Further, fiber membranes in the electrospinning method can fit any shaped reactor and acquire high porosity and surface adhesion. Hence, they are broadly applied to filter micro-sized and nano-sized particles (Yang et al., 2020; Zhang et al., 2016; Hu et al., 2022). However, the high-pressure loss of nanofiber membranes in the electrospinning method remains a key challenge for marketization. Therefore, this study aims to develop an effective filter with low-pressure loss to remove microorganisms, UFPs from combustion emissions (traffic, power plant, industries), and nano-aerosols of the same size (i.e., 100 nm) as the average size of COVID-19.

2. Experimental methods

2.1. Samples

The sample of this study included polyimide (PI) (see Fig. 1A), polyether sulfone (PES) (see Fig. 1B), dimethylacetamide (DMAc), and sodium chloride (NaCl). These samples are reagent-grade chemicals purchased from Alfa Chemistry, BASF Taiwan Ltd., and Acros Organics, respectively. PI has comprehensive advantages, including anti-corrosion, anti-fatigue high-thermal resistance, high-fraying resistance, impact resistance, low density, and long service life. On the other hand, PES has a high-thermal resistance resin, acquiring high-mechanical resistance, high-electrical isolation, chemical stability, deformation, and plasticity (Zhang et al., 2016).

2.2. Electrospinning process

PI and PES were dissolved in dimethylacetamide to obtain 20 wt % concentrations. Different ratios of PI and PES (25:75, 50:50, 75:25) were dissolved in dimethylacetamide and stirred at room temperature for eight hours. The PI/PES composite nanofibers were obtained from electrospinning the prepared PI/PES polymer solutions through an FES-COS electrospinning apparatus (Falco Co, Taiwan). High DC voltage was applied to generate an electrically charged jet of PI/PES polymer solution, and the sprayed PI/PES polymer solution was dried to shape a nanometer-sized material. A typical installation involves an electrode connected to a 21-gauge needle of a 10 mL syringe that contains polymer solution, while a collector plate connects to another electrode, as shown in Fig. 1C. A pump forces the solution through the spinneret while the sprayed droplets acquire charges on its surface due to the effect of the electric field, causing mutual charge repulsion. The sprayed droplets elongate into a conoid formation with the increase in the electric field intensity under ambient conditions (a temperature of 24.5–27.5 °C and relative humidity of 45–50 %), and the created material is named Taylor cone. Following the electrospinning process, the spinneret sprays polymer fluid to form a fibrous membrane on a collector plate at a distance of 15 cm between the collector plate and the spray nozzle.

As the operating process of electrospinning is simple and flexible, this technique is commonly used in forming different polymers including poly(lactic acid) (You et al., 2005; Huan et al., 2018), poly(glycolic acid) (You et al., 2005; Cruz et al., 2016), poly(lactic-co-glycolic acid) (You et al., 2005; Liu et al., 2017), polyurethane (Dai et al., 2016), and polycaprolactone (Giguera-Lopez et al., 2018) into nanometer-sized materials. Noteworthily, the electrospinning process has independent variables, such as flow rate, applied voltage, collection time, and distance between collector plate and spray nozzle. Adjusting these variables can prove the thickness, porosity, mechanical strength, and morphology of the electrospun materials.

In this study, the optimal electrospinning parameters were kept constant throughout the experiments: 17–22.5 kV applied voltage, 0.1–0.2 mL/h flow rate, and 20–60 min collection time (0.0275–0.1625 g/m² basis weight). For the preparation of fibrous membranes, the thickness is defined by the basis weight (weight per area), and the basis weight depends not only on the collection time but also on the distance between the collector plate and the spray nozzle. PI/PES nanofibers elongate and deposit on a plate collector covered with a PET layer during the electrospinning process.
2.3. Optimal parameters analysis by Taguchi method

Developed by Dr. Taguchi, the Taguchi method (Taguchi, 1990) is suitable for separating the influencing parameters to follow the optimal parameters of a process (Lin et al., 2012). It is properly employed to analyze the significance of factors. Full factorial experimentation depicted 3\(^4\) experiments to carry out the influencing parameters by analyzing the significance of four factors (ratio of PI and PES, flow rate, voltage, and basis weight) at three different levels. The Taguchi design included nine experiments using an orthogonal array L\(_9\) (3\(^4\)). The orthogonal array shows the definite sequence of each test, and the factor design defines a combination set of optimal parameters.

Two quality characteristics (smaller-the-better and larger-the-better) are frequently used to find a combination set of optimal parameters. The S/N ratio equations (Eq. 1 and Eq. 2) are listed below, where the number of test runs is depicted as \(n\), and the value of one test is shown as \(y_i\):

\[
\text{Smaller – the – better : } \frac{S}{N} = -10 \times \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i \right) \tag{1}
\]

\[
\text{Larger – the – better : } \frac{S}{N} = -10 \times \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i} \right) \tag{2}
\]

This study used smaller-the-better to analyze the diameter of a fibrous membrane, considering its filter efficiency is great if the membrane’s diameter is small.

2.4. Characterizations

The Fourier-transform infrared spectrometer (FTIR; Spectrum 100, Perkin Elmer, USA) can be applied to identify the functional group of a fibrous membrane in the scanning range of 450–4000 cm\(^{-1}\). This study employed the TESCAN 5136MM instrument (TESCAN, Czech Republic) to analyze the surface and structure of a fibrous membrane. The diameter of fiber nanofiber was evaluated using SigmaPlot 10.0. The factors of viscosity and conductivity influenced the quality of the electrospinning solution because the latter’s low viscosity caused lesser molecular linking, decreasing the amount of stable fibrous formation. Furthermore, the lesser conductivity of the electrospinning solution caused the low emitting flow rate during the electrospinning process, resulting in lesser fibrous formation. The electrospinning solution tends to have an unstable status if solution conductivity is high, resulting in a wide range of diameter distribution on fibrous formation. A viscometer (Brookfield, LVDV-II-Pro) and a conductivity meter (JENCO, 3010 M) were employed to measure the viscosity and conductivity of the electrospinning solution.

2.5. Experimental devices for filter efficiency test

This study aimed to produce a fibrous membrane with high filter efficiency. Thus, a filter efficiency test was conducted after generating a fibrous membrane. The experimental devices for the test included the particle generation and filter testing systems, as depicted in Fig. 2 A. The particle generation system utilized an exported quantitative atomizer to produce chloride sodium of 50–500 nm for testing particles (Fig. 2 B). The chloride sodium solution (concentration of 1 M) flowed through the atomizer to carry out sub-micro and nanoparticles to simulate the aerosol size of coronavirus and the carrier. The higher concentration of aerosols in the feed has a size of 100 nm, akin to the reported average of COVID-19. Then, the newly generated aerosol particle was moved to a dryer to remove excess moisture as it carried a high ratio of moisture. Subsequently, the aerosol particle was injected into the Kr-85 neutralizer for dissociation. Then, it was dissociated to positive and negative ions due to the \(\beta\) particle and \(\gamma\) rays during the Kr-85 decay process. Noteworthily, positive and negative ions reacted with the \(\beta\) particle and \(\gamma\) rays, achieving Boltzmann charge equilibrium.

The scanning mobility particle sizer (SMPS, Model 3934) was employed to test filter efficiency. The filter testing system device is shown in Fig. 3. The aerosol particle flowed to the particle generation system and through the fibrous membrane with an area of 16 cm\(^2\) before the SMPS filter test. Triple tests were conducted to calculate filter efficiency. The penetration of aerosol particle (P) was used to calculate filter efficiency. The penetration of aerosol particle (P) was used to calculate filter efficiency. The penetration of aerosol particle (P) was used to calculate filter efficiency. The penetration of aerosol particle (P) was used to calculate filter efficiency.

\[
\eta = 1 - P = 1 - \frac{N_{\text{out}}}{N_{\text{in}}} \tag{3}
\]

\[
Q_f = \frac{\ln(1 - \eta)}{\Delta P} \tag{4}
\]

where \(P\), \(N_{\text{in}}\), \(N_{\text{out}}\), \(\Delta P\), and \(Q_f\) represented the penetration of aerosol particle, filtration efficiency, aerosol particle number at inlet space, aerosol particle number at outlet space, pressure drop across the filter (Pa), and filter quality (Pa\(^{-1}\)), respectively.

2.6. Bacterial filtration efficiency

This study aimed to apply the PI/PES nanofibrous membrane as face mask materials. Thus, the bacterial filtration efficiency (BFE) test was
Fig. 3. SEM and diameter distribution of nanofiber at different factors by the Taguchi method and parameters as shown in Table 1. (A) sample no.1; (B) sample no.2; (C) sample no.3; (D) sample no.4; (E) sample no.5; (F) sample no.6; (G) sample no.7; (H) sample no.8; (I) sample no.9.
conducted using a biological aerosol of Staphylococcus aureus. The test method followed the regulations in the ASTM Standards (ASTM F2101–01) of the Food and Drug Administration (FDA), US. The fibrous membrane with a filtration area of 49 cm$^2$ was clamped between a six-stage Andersen sampler and an aerosol chamber. Then, the Staphylococcus aureus aerosol was introduced into the chamber and drawn

Fig. 3. (continued).
through the fibrous membrane utilizing a vacuum, which was attached to the six-stage Andersen sampler at a sampling flow rate of 29.3 liter/min. The respective average counts of the positive control group and the negative control group with an average particle size of 3.2 µm were controlled at 2061 CFU and 0 CFU, respectively. BFE was calculated by comparing the average colony-forming units with and without the test filter. The calculation process is depicted in Eq. 5.

$$BFE(\%) = \frac{CFU_i - CFU_0}{CFU_i} \times 100\%$$

where BFE, CFU, and CFU₀ represented the bacterial filtration efficiency (%), the average colony-forming units (the bacteria-containing aerosol) without the test filter, and the average colony-forming units with the test filter, respectively.

### 2.7. Cytotoxicity assay

The objective of the tests was to use renal tubular cells (NRK-52E) for cytotoxicity assay to identify the cytotoxic effects of the materials and the medical device. In the blank, positive control, negative control, and PI/PES sample tests, as per ISO 10993–5, the NRK-52E cells were incubated for exactly 24 h. The morphology of the NRK-52E cell was evaluated, and the survival rate was calculated.

### 3. Results and discussion

#### 3.1. Functional groups of nanofibrous membrane

The material traits are based on their structure and morphology. FTIR is a useful instrument for analyzing the molecular structure of polymers and compounds. Fig. 4 depicts the FTIR spectrum of the PI/PES nanofibrous membrane. The specific peaks of PI and PES are separately shown in the spectrum. The specific peak of PI is depicted at a wavelength of 3064 cm⁻¹, which is also a peak of aromatic compounds, and other peaks of C-H, C–O, C-N, C-N-C, and C-O-C are shown in wavelengths of 2958, 1776, 1375, 1295, and 1243 cm⁻¹. Furthermore, the specific peak of PES is shown at a wavelength of 1577 cm⁻¹, which is also a peak of the benzene ring, and other peaks of C-O and C-H are depicted at wavelengths 1482 and 1150. Moreover, the PI/PES spectrum shows the specific peaks of PI and PES separately, so the PI/PES compound acquires both properties of PI and PES. Therefore, the compound produced by electrospinning can individually retain the properties of various samples, and PI and PES do not react while forming the PI/PES compound.

### Table 1

| Sample | Ratio of PI/PES | Flow rate (mL/hr) | Voltage (kV) | Basis weight (g/m²) | y1 | y2 | y3 | y4 | y5 | S/N | diameter (nm) |
|--------|-----------------|-------------------|-------------|---------------------|----|----|----|----|----|-----|---------------|
| 1      | 25:75           | 0.10              | 17.5        | 0.0275              | 0.47 | 0.55 | 0.50 | 0.44 | 0.45 | 6.28 | 478 ± 102     |
| 2      | 25:75           | 0.15              | 20.0        | 0.0825              | 0.39 | 0.45 | 0.46 | 0.55 | 0.50 | 6.51 | 478 ± 105     |
| 3      | 25:75           | 0.20              | 22.5        | 0.1625              | 0.49 | 0.46 | 0.53 | 0.57 | 0.50 | 5.86 | 507 ± 107     |
| 4      | 50:50           | 0.10              | 20.0        | 0.1625              | 0.50 | 0.48 | 0.50 | 0.44 | 0.45 | 6.50 | 471 ± 64      |
| 5      | 50:50           | 0.15              | 22.5        | 0.0275              | 0.56 | 0.55 | 0.58 | 0.59 | 0.60 | 3.74 | 564 ± 64      |
| 6      | 50:50           | 0.20              | 17.5        | 0.0825              | 0.60 | 0.59 | 0.58 | 0.59 | 0.60 | 4.54 | 592 ± 65      |
| 7      | 75:25           | 0.10              | 22.5        | 0.0825              | 0.67 | 0.69 | 0.63 | 0.64 | 0.66 | 3.63 | 644 ± 109     |
| 8      | 75:25           | 0.15              | 17.5        | 0.1625              | 0.55 | 0.58 | 0.55 | 0.54 | 0.56 | 5.12 | 555 ± 73      |
| 9      | 75:25           | 0.20              | 20.0        | 0.0275              | 0.60 | 0.59 | 0.61 | 0.56 | 0.56 | 4.67 | 585 ± 67      |

*The repeat experiments of factor influence were also done at the same time to obtain the optimal test conditions, as shown as y1, y2, y3, y4 and y5.
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3.2. Diameter results at different experimental conditions by the Taguchi method (smaller the better)

Four parameters, namely the ratio of PI and PES, flow rate, voltage, and basis weight, were applied to the Taguchi method, including nine experiments using an orthogonal array $L_{9}(3^4)$ to produce a highly efficient PI/PES nanofibrous membrane. Each parameter contains three levels, including the ratio of PI and PES (25:75, 50:50, and 75:25), flow rate (0.10 mL/hr, 0.15 mL/hr, and 0.20 mL/hr), voltage (17.5 kV, 20 kV, and 22.5 kV), and basis weight (0.0275 g/m$^2$, 0.0825 g/m$^2$, and 0.1625 g/m$^2$). $S/N$ is an important factor in the calculation of the Taguchi method, which indicates the benefits and drawbacks of the analyzed index. Meanwhile, a higher $S/N$ ratio indicates better quality of the analyzed index. If a fibrous membrane’s diameter is small, its filter efficiency is great. Thus, smaller-the-better was used to analyze the diameter of a fibrous membrane. Nine sets of experimental conditions were used to obtain the optimal diameter size, as shown in Table 1.

Table 1 shows the distribution of the diameter of a fibrous membrane at four variances using the equation for smaller-the-better. The optimal experimental conditions for the best diameter of 471 nm are the 50:50 ratio of PI and PES, 0.10 mL/hr flow rate, 22.5 kV voltage, and 0.1625 g/m$^2$ basis weight. According to the result in Table 2, the factor influence order arranges the ratio of PI and PES, voltage, basis weight, and flow rate because each $S/N$ values are 1.75, 1.48, 0.93, and 0.45. This finding means that the ratio of PI and PES is the most influencing factor for the diameter of the fibrous membrane, followed by voltage, basis weight, and flow rate.

Fig. 3 shows that the diameter of the fibrous membrane increases with the enhancement of the ratio of PI and PES because the low ratio of PI and PES only generates lesser viscosity of the electrospinning solution that loosens molecular linking, resulting in droplets being attached to the fibrous membrane. When solution viscosity increases, no droplets are attached to the fibrous membrane. High solution viscosity represents high solution concentration, and high solution concentration causes a high degree of entanglement between molecular linking, increasing the fibrous membrane’s diameter.

3.3. Factor influence on the filter efficiency of a nanofibrous membrane

3.3.1. Factor influencing the ratio of PI/PES

Polymer concentration is a critical factor in nanofibrous formation during the electrospinning process. Hence, five ratios of the PI/PES solution were used to test the optimal ratio of PI/PES for nanofibrous formation. Fig. 5A, Fig. 5B, and Fig. 5C show the influence of the ratio of

![Fig. 5.](image-url)
The viscosity value is 186 cP while the ratio of PI/PES is 0:100; viscosity becomes 3374 cP if the ratio of PI/PES is adjusted to 100:0. Solution conductivity and fiber diameter also increase with the enhancement of PI concentration. This finding means that PI concentration clearly affects viscosity and conductivity. However, the maximum filter efficiency is 86.88 % when the ratio of PI/PES is adjusted to 50:50.

A lesser viscosity and solution conductivity (PI concentration ≤ 25 %) loosen molecular linking during the electrospinning process, resulting in an unstable emitting flow rate of electrospinning and droplets formation. Fig. 6A and Fig. 6B show the same result as Fig. 5C, where droplets are attached to fiber, and the pore between fibers is too large to decrease the filter efficiency and fiber diameter. Further, higher solution conductivity varies the stability of the electrospinning solution, resulting in a wide range of diameter distribution on fibrous formation. Viscosity consequently increases over 2200 cp (PI concentration ≥ 75 %) because of the high degree of entanglement between molecular linking caused by the tractive force of the electronic field. Further, the emitting flow rate of electrospinning is also influenced, generating a bigger fiber diameter, as depicted in Fig. 6D and Fig. 6E. Consequently, when the ratio of PI/PES is adjusted to 50:50, the filter efficiency and filter quality reach the maximum value of 86.88 % and 2.07 Pa$^{-1}$, respectively. Simultaneously, the fiber diameter inclines to a middle value of 533 nm without droplets on the fiber (Fig. 6C).

Furthermore, there is more discussion on the filtering mechanism of a fibrous membrane with various PI/PES ratios in Fig. 5D. When the ratio of PI/PES is 0:100, there is droplet formation without any fiber silk, which shows a particle condition that cannot block aerosol particles (Fig. 6A). Penetration efficiency increases sharply, while particle sizes range from 50 to 200 nm and reach the maximum value of 83 %. As a result, the membrane with a ratio of PI/PES (0:100) can barely filter aerosol particles. Droplets and fiber form when the ratio of PI/PES is adjusted to 25:75 (Fig. 6B), resulting in a uniform distribution of the fiber diameter and the pore and influencing filter efficiency. Penetration efficiency reaches around 30 %, while particle sizes range from 200 to

| Voltage (kV) | Conductivity (μS) | Penetration efficiency (%) | Filter efficiency (%) | Pressure drop (Pa) | Filter quality (Pa$^{-1}$) |
|-------------|-------------------|----------------------------|-----------------------|-------------------|--------------------------|
| 15.0        | 1.30              | 0.27 ± 0.06                | 73.47 ± 5.69          | 1.31 ± 0.57       | 1.13 ± 0.43              |
| 17.5        | 1.93              | 0.26 ± 0.06                | 74.28 ± 5.65          | 1.31 ± 0.57       | 1.13 ± 0.27              |
| 20.0        | 2.50              | 0.18 ± 0.003               | 82.05 ± 0.29          | 0.98 ± 0.14       | 1.75 ± 0.02              |
| 22.5        | 3.03              | 0.13 ± 0.01                | 86.88 ± 0.47          | 0.98 ± 0.04       | 2.07 ± 0.04              |
| 25.0        | 3.71              | 0.15 ± 0.02                | 84.82 ± 1.51          | 1.14 ± 0.28       | 1.72 ± 0.42              |

Fig. 6. Various morphology pictures at five ratios of PI/PES. (A)0:100 (B)25:75 (C)50:50 (D)75:25(E)100:0.
500 nm. When the ratio of PI/PES is adjusted to 100:0, the fiber diameter and pore approach the maximum value (Fig. 6E). Penetration efficiency increases sharply when the ratio of PI/PES is 0:100. Most aerosol particles can pass through this fiber membrane, with the particle size ranging from 50 to 200 nm. Penetration efficiency reaches the minimum value when the ratio of PI/PES is adjusted to 50:50. There is only 20% penetration efficiency if the particle size ranges from 200 to 400 nm.

3.3.2. Factor of voltage

Table 3 depicts that lesser filter qualities occur at the conditions of 15 and 17.5 kV than at the conditions of 20, 22.5, and 25 kV. The optimal filter quality reaches 2.07 Pa⁻¹ at the condition of 22.5 kV. Increased voltage can enhance electrical density that improves the strength of the tractive force on the electrospinning solution, resulting in smaller diameter fiber formation. However, when voltage is adjusted to 25 kV, the strength of the tractive force becomes too high, causing a uniform fiber formation and decreasing the filter quality.

Fig. 7A shows that penetration efficiencies increase vividly at the conditions of 15 and 17.5 kV while particle sizes range from 60 to 500 nm. Thus, filter efficiency at the conditions of 15 and 17.5 kV is much lower than in other conditions. When voltage is adjusted above 20 kV, filter efficiency can reach above 80% because voltage over 20 kV

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**Fig. 7. Penetration efficiency: (A) different voltage; (B) different basis weights.**
provides enough strength to the tractive force on the electrospinning solution, resulting in a stable fiber formation. In addition, penetration efficiency reaches below 40%, while particle sizes range from 30 to 500 nm. Thus, filter efficiency remains above 80% at conditions of 20, 22.5, and 25 kV.

3.3.3. Factor of basis weight
The thickness of the fiber membrane enlarges with the increase of the basis weight. To quantitatively characterize the air filter performance of the basis weights at the ratio of 50:50 PI and PES, 0.15 mL/hr flow rate, and 22.5 kV voltage, the penetration efficiency, filtration efficiency, pressure loss, and filter quality were investigated for the aerosol particles with the size ranging from 10 to 500 nm, as shown in Fig. 7B and Fig. 8. Fig. 7B shows that the exceptional interception ratio against 100-nm airborne COVID-19 was over 99%, and less than 5% penetration efficiency occurs while particle sizes range from 100 to 500.

Fig. 8 depicts that all filter efficiencies reach 99% at various basis weights, and the thickest fiber membrane (0.1625 m²/g basis weight) exhibits the highest filtration efficiency of 99.74% with a pressure loss of 3.27 Pa and filter quality of 1.96 Pa⁻¹ for micrometer and nanometer-sized particles. Furthermore, filter quality decreases with the increase of the basis weights. Because the membrane’s mass per unit area (basis weight) increases accordingly with the basis weight, most aerosol particles can be blocked. However, the enhancement of the basis weight increased pressure loss, and the filter quality decreased positively with pressure loss. The thinnest fiber membrane (0.0275 m²/g basis weight) displays high filtration efficiency of 99.54%, a low-pressure loss of 0.98 Pa, and a high filter quality of 5.56 Pa⁻¹ for micrometer and nanometer-sized particles. The NaCl method measures particles with sizes between 10 nm and 10 µm, with N95 masks receiving a penetration of no more than 5% and a pressure loss of 99.64 Pa (Forouzandeh et al., 2021).

Table 4 depicts that each BFE of the three samples is 99.7%, 93.0%, and 98.3%, and the average value reaches 97.0%, matching the filter efficiency standard for medical face masks released from speaking, coughing, and sneezing. According to the requirement of medical/surgical masks (≥95.0% filtration) in the ASTM F2101–01 standard, the PI/PES fibrous membrane can be applied as a material for creating medical face masks. In filtering bioaerosol particles with a size diameter of 0.6–3 µm released from speaking, coughing, and sneezing, surgical or medical masks must obtain a BFE of at least 95% (Forouzandeh et al., 2021).

Furthermore, air exchange pressure (pressure loss) was tested to determine the airflow resistance and breathability of a mask. The more breathable the mask is, the lower will the airflow resistance be. Air exchange pressure is an important factor for breathing while wearing a mask. Thus, this study employed the ASTM F2101–01 to test the air

![Fig. 8. Effect of basis weights on filter efficiency and filter quality.](image)

| Sample | BFE (%) | Pressure loss (mm H₂O/cm²) |
|--------|---------|----------------------------|
| 1      | 99.7    | 0.04                       |
| 2      | 93.0    | 0.06                       |
| 3      | 98.3    | 0.06                       |
| 5      | –       | 0.04                       |
| 6      | –       | 0.02                       |
| Average| 97.0    | 0.05                       |

The standard value for medical masks ≥95.0 ≤5

3.4. Bacterial filtration efficiency and air exchange pressure
BFE measures how well a medical face mask can filter out bacteria when exposed to a Staphylococcus aureus-containing aerosol at the sampling flow rate of 29.3 liter/min and filtration area of 49 cm². Table 4 depicts that each BFE of the three samples is 99.7%, 93.0%, and 98.3%, and the average value reaches 97.0%, matching the filter efficiency standard for medical face masks for effectively removing aerosols released from speaking, coughing, and sneezing. According to the requirement of medical/surgical masks (≥95.0% filtration) in the ASTM F2101–01 standard, the PI/PES fibrous membrane can be applied as a material for creating medical face masks. In filtering bioaerosol particles with a size diameter of 0.6–3 µm released from speaking, coughing, and sneezing, surgical or medical masks must obtain a BFE of at least 95% (Forouzandeh et al., 2021).

Furthermore, air exchange pressure (pressure loss) was tested to determine the airflow resistance and breathability of a mask. The more breathable the mask is, the lower will the airflow resistance be. Air exchange pressure is an important factor for breathing while wearing a mask. Thus, this study employed the ASTM F2101–01 to test the air
The average value of pressure loss was 0.05 mmHg exchange pressure of the PI/PES fiber membrane. Table 4 shows the filtration performances of different membranes. The filtration performances of different membranes.

**Table 4**
The filtration performances of different membranes.

| Filters type | Flow rate (velocity) | Basis weight (g/m²) | Filtration efficiency ( %) | Pressure loss (Pa) | QF (Pa⁻¹) | Cytotoxicity | Reference |
|--------------|----------------------|---------------------|----------------------------|--------------------|----------|-------------|----------|
| PI/PES nanofiber membrane | 2 L/min | 0.0275 | PM0.1–0.5: 99.74 | 0.98 | 1.96 | Non-cytotoxic | This Study |
| N95 Masks (USA NIOSH Standard) | 85 L/min | – | PM0.3: ≥ 95 | 99.64 | – | – | [Forouzandeh et al. (2021)] |
| Level 1 Medical face mask (ASTM F2100) | – | – | PM0.1–5: ≥ 95 | 49.0 | – | – | [ASTM 2020] |
| Level 2&3 Medical face mask (ASTM F2100) | – | – | PM0.1–5: ≥ 96 | 58.8 | – | – | [ASTM 2020] |
| PA6 @Ag | 32 L/min | 28 | PM0.3–0.5: 97.98 | 31 | 0.13 | Toxic (slightly) | [Ju et al. (2021)] |
| CS/PVA@SiO₂-Ag NPs nanofiber membranes | 32 L/min | 6.2 | 96.6 | 305.67 | 0.055 | Non-cytotoxic | [Zhu et al. (2019)] |
| Gelatin/β-Cyclodextrin electrospinning membrane | 20 L/min | 1 | PM0.3: 97 | 148 | 0.029 | – | [Kadam et al. (2021)] |
| Soy protein electrospinning membrane | 32 L/min | 4.21 | PM0.3: 95.39 | 138 | 0.022 | – | [Jiang et al. (2018)] |
| Protein electrospinning membrane | 4 L/min | – | PM0.3: 98.61 | 198 | – | – | [Souzandeh et al. (2017)] |
| PAN/β-CD | 0.06 m/s | – | PM0.3: 95.5 | 112 | 0.027 | – | [Kadam et al. (2018)] |
| PVDF hollow fibers | 0.6 L/min | – | PM0.3: 99.99 | 2096 | 109 | – | [Wang et al. (2018)] |
| Electrospun zein membrane | 5.33 cm/s | 3.9 | PM0.3: 99.00 | 109 | 0.026 | – | [You et al. (2005)] |
| PS/PAN/PSS | 0.053 m/s | – | PM0.3: 99.96 | 54 | 0.1449 | Toxic (slightly) | [Cai et al. (2020)] |
| PVDF/DOPS/F-SiO₂ electrospinning membrane | 8.3 L/min | 4.65 | PM0.3: 99.78 | 16 | 0.382 | Non-cytotoxic | [Dong et al. (2022)] |
| PMIA/PV electrospinning membrane | 32 L/min | 0.12 | PM0.3: 99.984 | < 68 | 0.489 | – | [Zhang et al. (2019)] |

The pressure loss of the PI/PES fiber membrane. Table 4 shows that the average value of pressure loss was 0.05 mmHg exchange pressure at the penetration area of 12.57 cm² and a sampling flow rate of 8.0 liter/min, while the standard value for medical masks was set at 5 mmHg/cm². Hence, the pressure loss of the PI/PES membrane was 1/100 folds of the value of medical masks. The result confirms that the PI/PES membrane was still easy and comfortable to breathe in and out after filtering out bacteria in the air. Therefore, the PI/PES membrane acquired not only high filter efficiency of bioaerosol and nano-aerosol but also achieved ultra-low pressure loss, compared with the standard value for medical masks.

**3.5. Cell viability evaluation**

An ideal medical/surgical mask should not only exhibit excellent filter performance but also have no harmful effects on the human body (Kang et al., 2022; Zhao et al., 2020). Thus, cytotoxicity assays were conducted to confirm the potentially toxic and harmful effects of the PI/PES fiber membranes against NRK-52E cells. The obtained NRK-52E cell viability was taken as the assessment index for the biocompatibility evaluation of the materials. Fig. 9 exhibits the phase-contrast photographs of the cell viability. After the cultures in the experiments within 24 h were exposed to the blank control, positive control (dime-thylsulfoxide, DMSO), negative control (polyethylene, PE), and PI/PES fiber membranes, the cell viability achieved 100 %, 68 %, 93 %, and 107 %, respectively. This favorable result suggested that the cell metabolism was not affected by PI/PES fiber membranes, implying that PI/PES fiber membranes do not have cytotoxicity.

**3.6. Comparative analysis of dressings filtration performance**

According to an earlier published report (Anon, 2020), the filtration efficiency and pressure loss of level 1-medical face mask (ASTM F2100) is 95 % and 49 Pa, respectively. Table 5 also showed the comparison of different membranes (Zhang et al., 2016, 2019; Hu et al., 2022; Ju et al., 2021; Zhu et al., 2019; Kadam et al., 2021, 2018; Jiang et al., 2018; Souzandeh et al., 2017; Wang et al., 2018, 2015; Cai et al., 2020; Dong et al., 2022), indicating that the filtration efficiencies of the majority of membranes were better than that of level 1-medical face masks. Except for the PI/PES nanofiber membrane in this study, the pressure loss of the PA6 @Ag (Ju et al., 2021) and the PVDF/DOPS/F-SiO₂ electrospinning...
membranes (Dong et al., 2022) was still inappropriate and unsatisfactory for level 1-medical face masks. Although the membranes exhibited remarkable filtration efficiency, they are still not breathable and easily generate remarkable filtration efficiency, they are still not breathable and easily generate no effect on cytotoxicity. However, the viability of most membranes is still inappropriate and unidentifiable to be used in medical face masks, as they could only fit the respirator or air filter with applied pressure by pumping.

4. Conclusions

Four factors, including the ratio of PI and PES, flow rate, voltage, and the basis weight, were employed by the Taguchi experimental design for their nanoﬁber diameter to evaluate the optimum values of the P1/PES electrospinning nanofibers. The S/N analysis demonstrated that the ratio of P1/PES was the most experimental parameter of influence on the nanofiber diameter. A uniformly distributed and smooth PI/PES nanofiber with 471 nm was successfully synthesized at the optimal conditions of a 50:50 PI to PES ratio, a 0.10 mL/hr flow rate, a 22.5 kV voltage, and a 0.1625 g/m² basis weight. The thickest fiber membrane (0.1625 g/m² basis weight) displays the highest filtration efficiency of 99.74% with the fiber filter of 3.27 Pa−1, effectively filtering UPFs from combustion emission and the average size of COVID-19. The PI/PES membrane was further conducted with a ﬁltration test at the level of medical mask requirement by referring to the ASTM F2101−01 regulation. Furthermore, the PI/PES membrane was also conducted with an air exchange pressure test for medical face masks following ASTM F2101−01. The results showed that the PI/PES membrane required 100 folds of pressure-loss-efficiency than the regular medical mask. The results of cytotoxicity assays conﬁrmed no harmful effects of the P1/PES ﬁber membranes on the human body. Therefore, the nano-sized PI/PES membrane required a potential advantage to create a medical face mask with high nano−virus−aerosol ﬁltration and ultra−low pressure loss.

Declaration of Competing Interest

The authors declare that they have no known competing ﬁnancial interests or personal relationships that could have appeared to inﬂuence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jpsyche.2022.09.052.

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