Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Preparation of a composite coating film via vapor induced phase separation for air purification and real-time bacteria photocatalytic inactivation

Chengtang Zhong, Xiaopeng Xiong*

Department of Materials Science and Engineering, College of Materials, Xiamen University, Xiamen 361005, China

ARTICLE INFO

Keywords:
- Porous coating film
- Vapor-induced phase separation
- Super-hydrophobicity
- Photocatalytic inactivation
- Air purification

ABSTRACT

Infectious diseases resulted from transmitting of bacteria or virus like COVID-19 via air-borne droplets have brought severe threat to human beings worldwide. Cutting the spreading paths to obtain clean air is one of the promising strategies to prevent people from such dangerous diseases. In this work, we have employed a strategy of spray coating in combination with vapor induced phase separation to prepare a composite coating film to fulfill that purpose. A stable mixture suspension containing micelles of block copolymer of poly(styrene-block-butadiene-block-styrene) and TiO$_2$ nanoparticles was sprayed onto stainless steel mesh to evaporate solvent in non-solvent vapor atmospheres. A water vapor atmosphere and an ethanol vapor atmosphere were in turn employed to improve the mechanical strength of the obtained coating film. The porous microstructure, the porosity, and the superhydrophobicity of the coating film were carefully characterized and analyzed. The air pressure-drop of the coating film was determined to be lower than 100 Pa, indicating a high air permeability. Moreover, a foggy air containing $E.\ coli$ was pressed through the coating film via a home-made apparatus to simulate the air purification system, where $E.\ coli$ contained air-borne droplets were intercepted by the film matrix in a physical manner, and the bacteria was photocatalytically inactivated at the meantime. A filtration efficiency of 99.7% and a 99.6% efficiency of real-time photocatalytic inactivation of $E.\ coli$ demonstrate the promising potential of the coating film.

1. Introduction

People are facing more and more serious air-pollution challenges. For example, the lately occurred COVID-19 epidemic has brought tremendous disaster to human being [1–3]. Transmitting of COVID-19 is reported to be mainly via air-borne droplets, which can suspend in air for at least 3 h [4]. Therefore, cutting the spreading paths of air-borne droplets containing contaminants such as infectious virus and bacteria to obtain clean air is one of the promising strategies to keep people safe and healthy [5,6].

Interception of solid contaminants in air can be realized by membrane filtration [7,8], which has advantages such as high efficiency, energy saving, and facile application in a massive scale. In order to effectively block the contaminants in air, proper pore dimension is required for the membrane [9]. A relatively high porosity is also important for the air purification efficiency. The nanofiber membrane fabricated via electrospinning of polymer solution is often employed for air purification [10–14]. For example, Bortolassi et al. [14] have prepared an electrospun silver/polyacrylonitrile nanofiber membrane, which had a porosity of about 96% to exhibit high filtration efficiency for solid particles (9–300 nm) in the air and to display excellent antibacterial activity against Escherichia coli ($E.\ coli$). If a membrane possessed a superhydrophobic surface as well as proper porous structure, foggy droplets in addition to the solid contaminants could be more readily intercepted.

If the blocked contaminants were degraded, or the reproduction of the intercepted virus and bacteria was suppressed, their threat could be reduced further. A large number of nanomaterials and composites have been reported to provide decontamination functions [15]. Among them, nano-TiO$_2$ has attracted special attention based on its high surface-to-volume ratio and excellent photocatalytic behavior [16]. Upon illumination, nano-TiO$_2$ absorbs high-energy photons to excite electrons to the conduction band, which induces generation of reactive oxygen species (ROS), such as HO•, O$_2$ ••, etc. [17] Those ROS can oxidize and destroy the microbial cell wall [18]. Therefore, nano-TiO$_2$ especially anatase TiO$_2$ has been widely employed for decontamination [19,20] and for bacteria/virus inactivation [21–26]. For example, Zacarias et al. [27] have successfully prepared a photocatalytic reactor filled with TiO$_2$-
coated glass rings, and found the concentration of the *Bacillus subtilis* spores retained by the coated glass rings was reduced by almost 55% under UV light illumination, indicating extraordinary photocatalytic inactivation of nano-TiO$_2$ on bacteria.

In our previous work, superhydrophobic membranes have been successfully prepared through a vapor-induced phase separation (VIPS) strategy, and the high porosity of over 70% and the mean pore diameter about 500 nm provide the membranes with high air permeability and interception of saccharomycetes [28–30]. In this work, it is aimed to take the advantages of such membranes and of the nano-TiO$_2$ to prepare a superhydrophobic composite film. The superhydrophobic film could readily block air-borne droplets containing bacteria and/or virus, and the matrix of the film could intercept contaminants, while the nano-TiO$_2$ could inactivate bacteria and/or virus in real-time, so that the composite film was able to be used for air purification. For that purpose, an inexpensive commercial block copolymer of poly(styrene-butadiene-styrene) (SBS) was dissolved in a non-toxic solvent of ethyl acetate (EA) to obtain a micelle solution, in which TiO$_2$ nanoparticles were then evenly dispersed. The mixture slurry was sprayed onto stainless steel mesh in a non-solvent vapor atmosphere to evaporate solvent. After the VIPS process, a composite coating film has thus been prepared, and the preparation has been carefully optimized. A foggy air containing bacteria of *E. coli* was pressed through the coating film via a home-made apparatus to simulate the air purification system. Our results of a filtration efficiency of 99.7% and a 99.6% efficiency of real-time photocatalytic inactivation of *E. coli* demonstrate the promising potential of the coating film in the field of air purification.

2. Experimental section

2.1. Materials

Star-shaped four-arm poly(styrene-block-butadiene-block-styrene) (SBS) was dissolved in a non-toxic solvent of ethyl acetate (EA) to obtain a micelle solution, in which TiO$_2$ nanoparticles were then evenly dispersed. The mixture slurry was sprayed onto stainless steel mesh in a non-solvent vapor atmosphere to evaporate solvent. After the VIPS process, a composite coating film has thus been prepared, and the preparation has been carefully optimized. A foggy air containing bacteria of *E. coli* was pressed through the coating film via a home-made apparatus to simulate the air purification system. Our results of a filtration efficiency of 99.7% and a 99.6% efficiency of real-time photocatalytic inactivation of *E. coli* demonstrate the promising potential of the coating film in the field of air purification.

2.2. Coating preparation

The polymer SBS was dissolved in EA under stirring at 40 °C to obtain a light blue micelle solution [28] with a polymer concentration of 10 mg/mL. After the solution was cooled to room temperature, desired amount of P25 was added, and sonicated for 30 min to obtain an even slurry. Preparation of the coating film was carried out in a sealed glove box, which was located in an air-conditioned room with the temperature fixed at 26 ± 1 °C. First, the glove box was dried with anhydrous calcium chloride so that the relative humidity in the box was kept to be lower than 45%. After that, sufficient non-solvent of liquid EtOH stored in a beaker was positioned in the glove box for 24 h in advance in order to keep a saturated non-solvent vapor atmosphere. A commercial air spray gun (Morita spray gun, F-3, Auarita, Taizhou, China) was employed for the coating film preparation. The working pressure of the spray gun was 0.2 MPa, and the distance between the spray gun and the substrate was 20 cm. In each preparation, 10 mL of the above obtained mixture slurry was vertically sprayed onto the stainless steel mesh with an area of 36 cm$^2$. A solid white coating on the substrate was obtained within 10 min. The prepared coating films were coded as Wx or Ex, where W represented the coating films prepared in water vapor atmosphere, and E indicated the coating films prepared in ethanol vapor atmosphere, while x meant the percentage of P25 in the coating film. Moreover, a coating film prepared in water vapor atmosphere was further covered with another layer of coating, which was fabricated through the above-mentioned process in ethanol vapor atmosphere. Thus obtained coating film was coded as WEx, where x is also the percentage content of P25 in the composite coating film. The preparation conditions of the coating films are listed in Table 1.

2.3. Characterizations and measurements

The coating films were sputter-coated with Au nanoparticles (~2 nm) by an ion sputtering (LDM-1500SX, Yonglin, China), and then observed with a field emission scanning electron microscope (FE-SEM, SU-70, Hitachi, Japan).

The method of n-butanol adsorption [32] was used to measure the porosity of the coating films. In each measurement, 6 cm$^2$ coating film was soaked in n-butanol for 1 h, and the coating film was weighed before and after wetting. The porosity (Pr, %) was calculated using the following equation:

$$Pr(\%) = \frac{(W_2 - W_1)/\rho_B + (W_1 - W_3)/\rho_B + W_4/\rho_A) \times 100}{(W_2 - W_1)/\rho_B}$$

where $W_1$ and $W_2$ are the masses of the dry and the wet coating film, $W_3$ is the mass of the 6 cm$^2$ stainless mesh, and $W_4$ is that of P25 in the 6 cm$^2$ coating film, while $\rho_A$, $\rho_B$, and $\rho_C$ are the densities of n-butanol, SBS [33] and P25, respectively.

Water contact angles of the coating films were measured with a video optical contact angle meter (DSA20, Krüss, Germany) under ambient condition. The coating film was fixed on the plate carefully, and a 3 μL water droplet was dropped on the surface to measure its contact angle (CA, °). Three independent measurements were carried out on different parts of the same sample, and were averaged to obtain the CA.

Abrasion resistance of the coating films were checked with a sandpaper-abrasion method according to the literature method [29,34]. The coating film was fixed on the glass sheet with the polymer layer facing up, and then inverted and touched with 1000 cc sandpaper. After that, the coating film surface was longitudinally and transversely (10 cm for each direction) abraded by the sandpaper under a weight of 100 g, respectively, which was defined as 1 cycle. Water contact angle for the abraded surface was measured after each cycle.

2.4. Air purification

A coating film was fixed on a YGB461G air permeability tester

| Table 1 Preparation conditions of the coating films and their porosities (%) |
|-----------------|-----------------|-----------------|
| Coating film    | Atmosphere      | P25 content (wt%) | Pr (%)   |
| W10             | Water           | 10              | 78.4 ± 1.1 |
| W20             | Water           | 20              | 77.7 ± 2.8 |
| W30             | Water           | 30              | 75.1 ± 1.9 |
| W40             | Water           | 40              | 72.8 ± 2.1 |
| E10             | Ethanol         | 10              | 99.7 ± 1.4 |
| E20             | Ethanol         | 20              | 90.3 ± 1.2 |
| E30             | Ethanol         | 30              | 88.5 ± 1.0 |
| E40             | Ethanol         | 40              | 86.4 ± 1.2 |
| WE10            | Water → ethanol | 10              | 99.2 ± 1.6 |
| WE20            | Water → ethanol | 20              | 88.7 ± 1.9 |
| WE30            | Water → ethanol | 30              | 87.6 ± 0.6 |
| WE40            | Water → ethanol | 40              | 84.2 ± 0.9 |
(Darong, China), and the effective area for air permeation was 20 cm². The air permeability was determined by measuring the pressure drop between the air-inlet and the air-out sides, when pressing air through the coating film under a velocity of 6.8 cm/s, according to the standard of EN ISO 9237-1995.

Air purification was performed using a homemade apparatus, as schematically demonstrated in Fig. 1. E. coli was diluted with PBS buffer to have a concentration of 10⁶ CFU. Then it was nebulized using an ultrasonic atomizer to simulate polluted air, which was pumped to be filtered by the coating film under UV light. The effective area of the coating film for the filtration was 50.24 cm². After the purification was continued for 1 h, the inner wall of the vessel at the air-out side was rinsed with PBS buffer for 3 times. The collected solution was dropped on glass slide, stained with Gram stain, dried and observed under a microscope (MO, CL-S, Nikon, Japan) [28,35]. Moreover, the surface of the coating film was rinsed for 3 times with 10 mL PBS buffer, and 50 μL of the collected solution was cultured in an incubator at 37 °C for 24 h via the plate coating method [36,37]. The photocatalytic inactivation effect of the coating film was evaluated by calculating number of E. coli colonies.

3. Results and discussion

3.1. Microstructures and properties

Our previous results [28,29] demonstrate that casting the micelle solution of the block copolymer of SBS in an organic non-solvent of ethanol to evaporate solvent will accelerate the vapor induced phase separation process, so that the obtained film exhibits nodular morphology to display porous microstructure and superhydrophobicity. In this work, it is aimed to expand the functions of such films.

The inexpensive thermoplastic elastomer of SBS was dissolved in a non-toxic solvent of EA to form a micelle solution, and then a commercial TiO₂ nanoparticle of P25 was dispersed in the solution. It has been found that the mixture slurries with P25 contents (P25 percentage in the whole solid) of 10%, 20%, 30% and 40% were stable within 24 h. However, visible sedimentation of TiO₂ nanoparticles was found when the P25 content was 50% in the mixture slurry. Therefore, the stable suspensions were sprayed onto stainless steel mesh in a water vapor atmosphere or in an ethanol vapor atmosphere, respectively. The SEM images of the obtained coating films are shown in Fig. 2. The pure polymer coating film prepared in water vapor atmosphere displayed a macroporous structure (Fig. 2A), and that prepared in ethanol vapor atmosphere revealed nodular morphology (Fig. 2E). The rest SEM images indicated that introduction of TiO₂ nanoparticles did not change the morphologies fundamentally. The composite coating films prepared in water vapor atmosphere showed still macroporous structure, while those prepared in ethanol vapor atmosphere remained nodular morphology. However, it is noticed the presence of nanoparticles and their even distribution in the composite coating films. Comparing the SEM images of the composite coating films would find that, more TiO₂ nanoparticles were wrapped in the film matrix prepared in water vapor atmosphere, while more TiO₂ nanoparticles were exposed in those prepared in ethanol vapor atmosphere. When the P25 content was higher, more TiO₂ nanoparticles were exposed in the matrix of the composite coating film. This is understood that water is a strong non-solvent to solidify the sprayed tiny droplets of mixture slurry very quickly to wrap the TiO₂ nanoparticles. Whereas, ethanol is a much weaker non-solvent than water, which would solidify the slurry droplets much slower during the VIPS process of coating film preparation, so that TiO₂ nanoparticles could readily diffuse to the surface of the nodular matrix before the matrix was completely solidified.

Fig. 3 compares the contact angles (CA, °) of the coating films. It can be seen that the CA increased with the P25 content for both types of coating films. When the coating film was prepared in water vapor atmosphere, the CA increased from 139.1 ± 1.0° for the neat polymer film to 150.7 ± 0.8° for the film with 40% P25 content. While it increased from 148.3 ± 0.1° to 153.4 ± 0.8° for the coating films prepared in ethanol vapor atmosphere. Moreover, the CA for the coating film prepared in ethanol vapor atmosphere was always higher than that prepared in water vapor atmosphere, when the P25 content was identical. Both the increase of CA with P25 content and the higher CA for the coating film prepared in ethanol vapor atmosphere suggest rougher surface, which is consistent with the aforementioned SEM observations.

The coating films prepared in ethanol vapor atmosphere were found to detach from the stainless steel mesh occasionally, while those prepared in water vapor atmosphere attached the stainless steel mesh firmly. This phenomenon suggests that the coating films prepared in ethanol vapor atmosphere were not facile for application though with higher hydrophobicity. In order to take advantages of the both coating
films, a coating film obtained in water vapor atmosphere in advance was sprayed with another layer of coating film in ethanol vapor atmosphere, using the same initial mixture slurry. In this way, the solvent contained in the latter sprayed mixture slurry could dissolve or swell some parts of the former coating film, so that the two layers could be glued together firmly. Thus obtained composite coating films, denoted as WE\textsubscript{x}, were found to be mechanically strong, which was checked by abrasion resistance test.

Fig. 4 shows the CA changes for the coating films of E30 and of WE30 with abrasion cycle. For the coating film prepared in ethanol vapor atmosphere, the CA decreased from the initial of 152.6 ± 0.7° to 132.0 ± 0.8° after 10 cycles of abrasion, and some parts of the coating film were found broken even by the naked eyes. However, for the composite coating film of WE30 prepared in turn under water vapor atmosphere and then under ethanol vapor atmosphere, the initial CA was 151.4 ± 0.9° and retained over 150° after two abrasion cycles. No visible broken part was found for the coating film even after 10 cycles of abrasion, and its CA remained over 140°, meaning improvement in abrasion resistance, i.e. improvement in mechanical strength of the coating film.

The microstructures of WE30 before and after 10 cycles of sandpaper-abrasion test are displayed in Fig. 5. It can be seen that WE30 (Fig. 5A) still exhibited the same nodular structure as that of E30 (Fig. 2G), suggesting that the underneath substrate (stainless steel mesh or coating film prepared in water vapor atmosphere) had limited effect.

Fig. 2. SEM images of the coating films respectively prepared in water (left column) and in ethanol (right column) atmospheres, with the TiO\textsubscript{2} nanoparticle contents of 0 (A and E), 20% (B and F), 30% (C and G), and 40% (D and H).
on the morphology of the coating fabricated in ethanol vapor atmosphere. The enlarged part of Fig. 5A shows that the latter sprayed layer has been steadily bound to the former coating, evidencing the above discussion. After 10 cycles of sandpaper-abrasion, major part of the nodular structure remained (Fig. 5B), so that the sandpaper-abrasion treated coating film retained a high CA of greater than 140°. Those results clearly indicated that the two-step preparation could largely improve the abrasion resistance of the coating film to satisfy the mechanical strength for application.

In addition to the superhydrophobicity and the satisfactory mechanical strength, the porosity of the coating film is also of key importance to its air filtration performance [38]. Table 1 summarizes the porosity of the coating films. The porosities of the coating films prepared in water vapor atmosphere were below 80%, while they are greater than 85% for those prepared in ethanol vapor atmosphere. The porosity decreased with P25 content for both types of coating films, which could be attributed to the filling of TiO$_2$ nanoparticles in the matrix of the coating film. For the composite films prepared through the above mentioned two-step process, there was a slight decrease in porosity when compared with that with identical P25 content prepared in ethanol vapor atmosphere, which could be due to the layer with lower porosity prepared in water vapor atmosphere.

3.2. Air permeation

The highly porous coating film with relatively large pore dimension has promising potential in the field of air purification [39]. For air purification, high air permeability, i.e. low pressure drop between the air-inlet side and the air-out side of a coating film is preferred, which can increase the air purification efficiency while reduce the energy consumption. The coating films with P25 content of 30% such as W30, E30 and WE30 were chosen for that purpose, due to their relatively high porosities and high content of TiO$_2$ nanoparticles, the latter of which was expected to photocatalytically inactivate the blocked bacteria or virus during air purification. Fig. 6 shows the results of the air permeability tests for the three coating films, and some literature results [40–42] are also displayed for comparison. It is surprising to notice the extremely low air pressure drops for the coating films of under the standard of EN ISO 9237-1995 at an air velocity of 6.8 cm/s. The air pressure drops were 55.3 ± 2.8 Pa for W30, 91.0 ± 2.8 Pa for E30, and 85.2 ± 3.2 Pa for WE30, respectively. It can be seen that the air drop for the composite coating film of WE30 was even lower than that of the coating film prepared in ethanol vapor atmosphere, which could be due to the macroporous structure of the coating layer prepared in water vapor atmosphere. Moreover, the air drops of the coating films reported in this work were much lower than those of the films reported previously [40–42], suggesting their potential in air purification field.

3.3. Air purification

Since the composite coating film prepared in two-step process exhibited improved mechanical strength, satisfactory superhydrophobicity and excellent air permeability, it was chosen to test its air purification performance. A composite coating film was set in the homemade air-purification apparatus, as schematically shown in Fig. 1, for that purpose. An E. coli solution was nebulized to simulate polluted air, and was pumped to be filtrated by the coating film. After 1 h purification process, the inner wall of the vessel at the air-out side and the surface of the coating film at the air-in side were rinsed with PBS buffer for 3 times, and the collected solutions were observed under a microscope, respectively. Fig. 7 shows the OM images of the collected solutions. The air purification performance of the coating films was

---

**Fig. 3.** Contact angles of the coating films with different content of P25. Error bars represent a standard deviation of 3 parallel measurements.

**Fig. 4.** Dependences of CA on the sandpaper-abrasion test cycle for the coating films of E30 and WE30.

---

**Fig. 5.** SEM images of WE30 before (A) and after 10 cycles of sandpaper-abrasion test (B).
evaluated by comparing the number of colonies before and after filtration. The filtration efficiencies of *E. coli* using the composite coating films were similar to be about 99.7%, no matter the coating film contained TiO$_2$ nanoparticles or not, nor the filtration was carried out under or without UV light illumination. The excellent filtration efficiency of the composite coating films was mainly attributed to the porous nodular 3D-network structure (Fig. 2). This unique structure with hierarchical geometry displayed micron and submicron pores, which might be helpful for the blocking *E. coli* [43].

The solutions collected from the coating film surfaces were cultured to indicate the photocatalytic inactivation effect of the TiO$_2$ particles on *E. coli*. Fig. 8 shows the photographs of the cultured *E. coli*. For the coating film of WE0, there was still obvious reproduction of *E. coli* although the filtration was carried out under UV light irradiation. However, the reproduction of *E. coli* was markedly suppressed, when the coating film of WE30 was used for its filtration and UV light illumination was applied. Without UV illumination, the reproduction of *E. coli* was still markedly despite the coating film of WE30 containing 30% TiO$_2$ nanoparticles was used. It has been suggested that reactive oxygen species (ROS) such as OH$^\cdot$ and O$_2$$^{\cdot-}$ could be generated when TiO$_2$ nanoparticles were illuminated with UV light [17,44,45]. Those free radicals play a pivotal role on inactivation of bacteria, as they can actively participate in the oxidation of cellular components, membrane

---

**Fig. 6.** Pressure drops of the coating films at an air velocity of 6.8 cm/s. The results of three literature films are also shown for comparison.

**Fig. 7.** OM images of the solutions collected by rinsing the coating films (left column) and the inner wall of the vessel at the air-out side (right column), where the coating films and the conditions were WE0 with UV light illumination (A, a), WE30 with UV light illumination (B, b) and WE30 without UV light illumination (C, c), respectively.
4. Conclusion

Stable mixture suspension containing micelles of block copolymer of SBS and TiO₂ nanoparticles was sprayed onto stainless steel mesh in turn in a water vapor atmosphere and in an ethanol vapor atmosphere to evaporate solvent. In the two steps of vapor induced phase separation processes, the coating layer formed in the water vapor atmosphere could adhere to the stainless steel mesh solidly to provide a strong substrate, so that the later sprayed layer could firmly bond the former. A strong composite coating film has thus been successfully prepared, and the two-step fabrication process had limited effect on the porous microstructure and porosity of the obtained coating film, while its top-surface displayed almost identical superhydrophobicity as that of the film prepared only in ethanol vapor atmosphere. The highly porous coating film exhibited high air permeability with an air pressure-drop lower than 100 Pa. The superhydrophobic coating film was found to readily block E. coli contained in foggy drops, and its filtration efficiency was determined to reach 99.7%. Meanwhile, the TiO₂ nanoparticle contained coating film displayed 99.6% efficiency of photocatalytic inactivation of E. coli. Therefore, our work provide a mechanical strong and superhydrophobic composite coating film, exhibiting high air permeability, satisfactory bacterial filtration efficiency and excellent real-time photocatalytic inactivation performance, which may have promising potential in air purification field.

CRediT authorship contribution statement

Chengtang Zhong: Experimental investigation, Data curation, Writing - Original draft preparation. Xiaopeng Xiong: Conceptualization, Methodology, Supervision, Writing - Reviewing and Editing.

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.

Acknowledgements

The authors acknowledge the financial supports from the Fundamental Research Funds for the Central Universities of China (20720200040) and the Natural Science Foundation of China (51273166).

References

[1] Z. Niu, F. Liu, H. Yu, S. Wu, H. Xiang, Association between exposure to ambient air pollution and hospital admission, incidence, and mortality of stroke: an updated systematic review and meta-analysis of more than 23 million participants, Environ. Health Prev. 26 (2021) 15.
[2] J. Yang, B. Zhang, Air pollution and healthcare expenditure: implication for the benefit of air pollution control in China, Environ. Int. 120 (2018) 443–455.
[3] Y. Chang, China needs a tighter PM2.5 limit and a change in priorities, Environ. Sci. Technol. 46 (2012) 7069–7070.
[4] N. van Doremalen, T. Bushmaker, D.H. Morris, M.G. Holbrook, B. N. Williamson, A. Tamin, J.L. Harcourt, N.J. Thornburg, S.I. Gerber, J.O. Lloyd-Smith, E. de Wit, V.J. Munster, Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1, N. Engl. J. Med. 382 (2020) 1564–1567.
[5] C.I. Shan, M.L. Wei, H.A. Chio, Investigation of indoor air quality at residential homes in Hong Kong - case study, Atmos. Environ. 36 (2002) 225–237.
[6] E. Baures, O. Blanchard, F. Mercier, E. Surget, P. Le Cann, A. Rivier, J.P. Gangneux, A. Florentin, Indoor air quality in two French hospitals: measurement of chemical and microbiological contaminants, Sci. Total Environ. 642 (2018) 166–179.
[7] B. Wang, Q. Wang, Y. Wang, J. Di, S. Miao, J. Yu, Flexible multifunctional porous nanofibrous membranes for high-efficiency air filtration, ACS Appl. Mater. Interfaces 11 (2019) 43409–43415.
[8] P. Kapkova, M. Kormanda, Z. Kolka, J. Trol, M. Munzarova, P. Rysanek, Electrospun antimicrobial PVDF-DTAB nanofibrous membrane for air filtration: effect of DTAB on structure, morphology, adhesion, and antibacterial properties, Macromol. Mater. Eng. 303 (2018), 1700415.
[9] S. Zhang, H. Liu, J. Yu, W. Luo, B. Ding, Microwave structured polyamide-6 nanofiber/net membrane with embedded poly(m-phenylene isophthalamide) staple fibers for effective ultrafine particle filtration, J. Mater. Chem. A 4 (2016) 6419–6437.
[10] T. Lu, J. Cui, Q. Qu, Y. Wang, J. Zhang, R. Xiong, W. Ma, C. Huang, Multistructured electrospun nanofibers for air filtration: a review, ACS Appl. Mater. Interfaces 13 (2021) 22393–22313.
[11] A. Patanäik, V. Jacobs, R.D. Anandjiwala, Performance evaluation of electrospun nanofibers for air filtration: density-based and fiber diameter size-based, J. Membr. Sci. 352 (2010) 136–142.
[12] Y. Wang, W. Li, Y. Xia, X. Jiao, D. Chen, Electrospun flexible self-standing γ-alumina fibrous membranes and their potential as high-efficiency fine particulate filtration media, J. Mater. Chem. A 2 (2014) 15124–15131.
[13] A.C. Canalli Bortolassi, V.G. Guerra, M.L. Aguia, L. Sousan, D. Cornu, P. Miele, M. Bechelany, Composites based on nanoparticle and pan electrospun nanofiber membranes for air filtration and bacterial removal, Nanomaterials 9 (2019) 1740.
[14] A.C.C. Borrotillo, S. Nagazajan, B. de Araujo Lima, V.G. Guerra, M.L. Aguia, V. Hoon, L. Sousan, D. Cornu, P. Miele, M. Bechelany, Efficient nanoparticles removal and bactericidal action of electrospun nanofibers membranes for air filtration, Mater. Sci. Eng. C Mater. Biol. Appl. 102 (2021) 718–729.
[15] Y. Zhang, B. Wu, H. Xu, H. Liu, M. Wang, Y. He, B. Pan, Nanomaterials-enabled water and wastewater treatment, Nanolipid 3 (2016) 22–39.
[16] I. De Pasquale, C. Lo Porto, M. Dell’Edera, F. Petronella, A. Agostiano, M.L. Curri, R. Comparelli, Photocatalytic TiO₂-based nanostructured materials for microbial inactivation, Catalysts 10 (2020) 1392.
[17] U. Joost, K. Juganson, M. Vinapuu, M. Mortimer, A. Kahru, E. Nommitte, U. Joost, V. Kisand, A. Ivask, Photocatalytic antibacterial activity of nano-TiO₂ (anatase)-based thin films: effects on Escherichia coli cells and fatty acids, J. Photochem. Photobiol. B Biol. 142 (2015) 179–185.
[18] P.A. Reddy, P.V. Reddy, E. Kwon, K.H. Kim, T. Akter, S. Kalagara, Recent advances in photocatalytic treatment of pollutants in aqueous media, Environ. Int. 91 (2016) 94–103.
[19] Y. He, G. Huang, C. An, J. Huang, P. Zhang, X. Chen, X. Xin, Reduction of Escherichia coli using ceramic disk filter decorated by nano-TiO₂: a low-cost solution for household water purification, Sci. Total Environ. 616–617 (2018) 1628–1637.
[20] F. Petronella, A. Truppi, C. Ingrosso, T. Placido, M. Striccoli, M.L. Curri, A. Agostano, R. Compitelli, Nanocomposite materials for photocatalytic degradation of pollutants, Catal. Today 281 (2017) 85–106.

[21] O. Carp, Photoinduced reactivity of titanium dioxide, Prog. Solid State Chem. 32 (2004) 33–177.

[22] A. Khezerlou, M. Alizadeh-Sani, M. Azizi-Lalabadi, A. Ehsani, Nanoparticles and their antimicrobial properties against pathogens including bacteria, fungi, parasites and viruses, Microb. Pathog. 123 (2018) 505–526.

[23] M. Miyauchi, H. Irie, M. Liu, X. Qiu, H. Yu, K. Sunada, K. Hashimoto, Visible-light-sensitive photocatalytic nanocluster-grafted titanium dioxide for indoor environmental remediation, J. Phys. Chem. Lett. 7 (2016) 75–84.

[24] N. Yao, K. Lun Yeung, Investigation of the performance of TiO\textsubscript{2} photocatalytic coatings, Chem. Eng. J. 167 (2011) 13–21.

[25] M. Sansotera, S. Geran Malek Kheyli, A. Baggioli, C.L. Bianchi, M.P. Pedeferri, M. V. Diamanti, W. Navarrini, Absorption and photocatalytic degradation of VOCs by perfluorinated ionomeric coating with TiO\textsubscript{2} nanopowders for air purification, Chem. Eng. J. 361 (2019) 885–896.

[26] J.H. Martinez-Montelongo, I.E. Medina-Ramirez, Y. Romo-Lozano, J.A. Zapien, Development of a sustainable photocatalytic process for air purification, Chemosphere 257 (2020), 127236.

[27] S.M. Zacarias, S. Firola, A. Marassero, M.E. Vizuara, O.M. Alfano, M.L. Satuf, Photocatalytic inactivation of bioaerosols in a fixed-bed reactor with TiO\textsubscript{2}-coated glass rings, Photochem. Photobiol. Sci. 18 (2019) 884–890.

[28] Q. Ke, Y. Liao, M. Lin, S. Lin, H. Du, S. Yao, X. Xiong, A superhydrophobic film with high water vapor transmission prepared from block copolymer micelle solution via VIPS method, J. Polym. Res. 22 (2015) 213.

[29] J. Meng, S. Lin, X. Xiong, Preparation of breathable and super-hydrophobic coating film via spray coating in combination with vapor-induced phase separation, Prog. Org. Coat. 107 (2017) 29–36.

[30] Q. Ke, Y. Liao, S. Yao, L. Song, X. Xiong, A three-dimensional TiO\textsubscript{2}/graphene porous composite with nano-carbon deposition for supercapacitor, J. Mater. Sci. 51 (2015) 2008–2016.

[31] X.P. Xiong, J. Eckelt, B.A. Wolf, Z.J. Zhang, L.N. Zhang, Continuous spin fractionation and characterization by size-exclusion chromatography for styrene-butadiene block copolymers, J. Chromatogr. A 1110 (2006) 53–60.

[32] C. Wang, W. Shen, J. Lu, S. Guo, Graphene oxide doped poly(vinylidene fluoride-co-hexafluoropropylene) gel electrolyte for lithium ion battery, Ionics 23 (2017) 2045–2053.

[33] X. Xiong, J. Eckelt, L. Zhang, B.A. Wolf, Thermodynamics of block copolymer solutions as compared with the corresponding homo-polymers: experiment and theory, Macromolecules 42 (2009) 8398–8405.

[34] Y. Lu, S. Sathasivam, J.L. Song, C.R. Crick, C.J. Carmalt, I.P. Parkin, Robust self-cleaning surfaces that function when exposed to either air or oil, Science 347 (2015) 1132–1135.

[35] W. Zheng, R. Tiina, A.G. Sergey, L.G.-H. Rafa, W. Klaus, Effect of sampling time and air humidity on the bioefficiency of filter samplers for bioaerosol collection, J. Aerosol. Sci. 32 (2001) 661–674.

[36] M.B. Fisher, D.A. Keane, P. Fernández-Ibáñez, J. Colreavy, S.J. Hinder, K. G. Mcguigan, S.C. Pillai, Nitrogen and copper doped solar light active TiO\textsubscript{2} photocatalysts for water decontamination, Appl. Catal. B Environ. 130 (2013) 8–13.

[37] F. Aziz, M. El Ackaby, K. Aziz, N. Ousazzani, L. Mandi, M.N. Ghazzal, Nanocomposite fiber based on natural material for water decontamination under visible light irradiation, Nanomaterials 10 (2020) 1192.

[38] C. Liu, P.C. Hsu, H.W. Lee, M. Ye, G. Zheng, N. Liu, W. Li, Y. Cui, Transparent air filter for high-efficiency PM2.5 capture, Nat. Commun. 6 (2015) 6205.

[39] K. Xu, J. Deng, R. Lin, H. Zhang, Q. Ke, C. Huang, Surface fibrillation of para-aramid nonwoven as a multi-functional air filter with ultralow pressure drop, J. Mater. Chem. A 8 (2020) 22269–22275.

[40] S.-M. Ji, A.P. Tiwari, H.J. Oh, H.-Y. Kim, ZnO/Ag nanoparticles incorporated multifunctional parallel side by side nanofibers for air filtration with enhanced removing organic contaminants and antibacterial properties, Colloids Surf. A Physicochem. Eng. Asp. 621 (2021), 126564.

[41] H. Zhang, Y. Xie, Y. Song, X. Qin, Preparation of high-temperature resistant poly(m-phenylene isophthalamide)/polyacrylonitrile composite nanofibers membrane for air filtration, Colloids Surf. A Physicochem. Eng. Asp. 624 (2021), 126831.

[42] D.S. de Almeida, L.D. Martins, E.C. Muniz, A.P. Rudke, R. Squizzato, A. Beal, P.R. de Souza, D.P.F. Bonfim, M.L. Aguiar, M.L. Gimenes, Biodegradable CA-CPB porous ceramics with 3D reticular architecture and efficient flow-through filtration towards high-temperature particulate matter capture, Chem. Eng. J. 362 (2019) 504–512.

[43] J. Liu, B. Ren, Y. Wang, Y. Lu, W. Wang, Y. Chen, J. Yang, Y. Huang, Hierarchical porous ceramics with 3D reticular architecture and efficient flow-through filtration towards high-temperature particulate matter capture, Chem. Eng. J. 362 (2019) 84–90.

[44] Y. Lin, J. Li, S. Ma, G. Liu, K. Yang, M. Tong, D. Lin, Toxicity of TiO\textsubscript{2} nanoparticles to Escherichia coli: effects of particle size, crystal phase and water chemistry, PLoS One 9 (2014), e110247.

[45] P.V. Laxma Reddy, B. Kavitha, P.A. Kumar Reddy, K.H. Kim, TiO\textsubscript{2}-based photocatalytic disinfection of microbes in aqueous media: a review, Environ. Res. 124 (2017) 296–303.