Multifunctional filter membrane for face mask using bacterial cellulose for highly efficient particulate matter removal

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Abstract Particulate matter (PM) pollution and SARS-CoV-2 (COVID-19) have brought severe threats to public health. High level of PM serves as a carrier of COVID-19 which is a global pandemic. This study fabricated filter membrane for face mask using bacterial cellulose and fingerroot extract (BC–FT) via immersion technique. The surface area, pore volume and pore size of BC were analyzed by Brunauer–Emmett–Teller. The physiochemical properties of the membrane were analyzed by scanning electron microscopy, Fourier transform infrared spectroscopy and X-ray diffractometer. The crystallinity decreased from 63.7% in pure BC to 52.4% in BC–FT filter membrane. Young’s modulus increased from 1277.02 MPa in pure BC to 2251.17 MPa in BC–FT filter membrane. The filter membrane showed excellent PM 0.1 removal efficiency of 99.83% and antimicrobial activity against Staphylococcus aureus and Escherichia coli. The fabricated membrane is excellent to prevent inhalation of PM2.5 and COVID-19 respiratory droplet.

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Introduction

Air pollution has become a major concern in the world due to the various harmful health effects in humans and animals (Manisalidis et al. 2020). One of the main pollutants that poses serious health threat is particulate matter. Particulate matter (PM) “is a heterogeneous mixture of suspended liquid droplets and solid particles in the air with various size, shape, and chemical features” (Maleki et al. 2021). PM contains various substances including metals, elemental and organic carbon, sulfates, and nitrates (Maleki et al. 2021). There are two kinds of PM namely PM 10 and PM 2.5. The PM 10 is an inhalable particle with diameter less than or equal to 10 μm, while PM 2.5 is a pollutant that has diameter less than or equal to 2.5 μm (Zhang et al. 2019). The PM 2.5 is more dangerous than PM 10 because it can invade the deepest parts of the lungs and easily reach the bloodstream due to the small size of the particles (Manisalidis et al. 2020). Some reported health effects for inhaling PM 2.5 include respiratory and cardiovascular morbidity such as chronic obstructive pulmonary disease.

Keywords  Bacterial cellulose · COVID-19 · Face mask · Filter membrane · Fingerroot extract · Particulate matter
that of commercial mask (64.00 ± 1.50%) with fiber diameter of 590 ± 180 nm had better filtration efficiency (92.00 ± 1.00%) than filter membrane with fiber diameter of 0.3 μm was reported to have lower efficiency (Cao et al. 2019). The removal efficiency of face mask (Zangmeister et al. 2020).

The most important part of face mask is the filter membrane. The filtration efficiency of face mask is affected by fiber diameter of the filter membrane. Fiber diameter at the nanometer scale is more effective than the one at the micrometer scale, due to large surface area for capturing particles. The filtration efficiency of polycrylonitrile (PAN) filter membrane with diameter of 0.3 μm was reported to have lower efficiency (90.0%) when compared to 77 nm fiber diameter filter membrane with 99.26% filtration efficiency (Cao et al. 2019). The removal efficiency of filter membrane with fiber diameter of 590 ± 180 nm had better filtration efficiency (92.00 ± 1.00%) than that of commercial mask (64.00 ± 1.50%) with fiber diameter of 3.9 ± 1.6 μm (Tan et al. 2019). One major challenge of these filter membranes is that they are made from synthetic fibers that are difficult to degrade. The PM pollutants couple with the recent global Covid-19 pandemic have contributed to the rise in waste from used face mask. About 468.9 tons of medical wastes including face masks are generated every day (Sangkhram 2020), most of which are non-biodegradable and contain toxic chemicals that poses environmental and health problems (Sullivan et al. 2021). Elimination methods such as incineration may lead to global warming. Herein, this study used biodegradable bacterial cellulose, which is skin friendly, non-allergic, eco-friendly and sustainable as a filter membrane for face mask.

Bacterial cellulose (BC) is a biodegradable natural cellulose with diameter of fibers ranging 20 to 100 nm (Manoukian et al. 2019). It is also known as microbial cellulose produced by several types of acetate acid bacteria, including Komagatzeibacter xylinus. BC has specific properties such as high water-holding capacity due to its hydrophilic nature, high tensile strength, smaller fiber diameter with thickness of 3–4 nm and relatively less expensive to produce. The fibers are orderly arranged with high surface area, non-toxic and biocompatible (Manoukian et al. 2019; Torgbo and Sukyai 2018). Using BC as filter membrane for face mask will result in better filtration efficiency than commercial membrane due to high surface area, nano fiber diameter and high hydrophilicity.

Heat and humidity build up from breathing when wearing face mask. This results in optimal conditions for the growth of microorganisms. Also, when a patient wearing face mask coughs or sneezes it causes an accumulation of microorganisms on the mask. Similarly, the person wearing the mask near a patient (for instance Covid-19 patient) who sneeze may contract pathogens from the patient. Bacterial and fungal contamination has been reported on the inside and outside areas of used face masks, with higher contamination on outside areas (Luksamijarulkul et al. 2014). Therefore, this research used fingerroot extract to address this problem. Fingerroot (Boesenbergia rotunda) belong to the Zingiberaceae family and it is a traditional medicinal plant native to Southeast Asia and Indo-China (Ongwisepaiboon and Jiraungkoorskul 2017). Fingerroot also serves as food ingredient in daily food intake due to its biological and nutritional properties. Its phytochemical components
include essential oils, flavonoids, boesenbergin, kra-chaizin, panduratin A, panduratin B and pinostrobin (Ongwisepaiboon and Jiraungkoorskul 2017). The phytochemical components are known to possess several biological activities including antibacterial, antiviral and wound healing properties. Studies have shown good antibacterial activity against microorganisms that are commonly involved in hospital-acquired infections such as *Staphylococcus aureus* and *Escherichia coli* and against acne-inducing bacteria such as *Propionibacterium acnes* (Mazlan et al. 2016; Rahman et al. 2016; Zainin et al. 2013). A study has also shown that its phytochemical component exerts inhibitory effect against COVID-19 (Kanjanasirirat et al. 2020). In this study, an eco-friendly and inexpensive standard green solvent dimethyl sulfoxide (DMSO) was used to fabricate the fingerroot extract and BC filter membrane. DMSO is nontoxic and recyclable when compared to traditional solvents. Therefore, it has been used by previous studies to fabricate membrane (Xie et al. 2019).

The recent challenges of PM and COVID-19 pandemic have caused rising global demand for face masks and shortage of the raw materials for their production. The rising environmental challenges with used face mask, require fabrication of efficient and eco-friendly filter membrane. This study fabricated filter membrane for face mask with high removal efficiency using sustainable and biodegradable BC and fingerroot extract as an antimicrobial agent. The results presented can answer the question on whether BC can be used as filter membrane of face mask for efficient removal of PMs.

**Experimental section**

**Materials and chemicals**

*Komagataeibacter xylinus* (TISTR No.975) was purchased from the Thailand Institute of Scientific and Technological Research, Pathum Thani, Thailand. Coconut water was purchased from the local market. Fingerroot extract powder was purchased from AP operations Co., Ltd. (Thailand). Acetic acid (CH₃COOH), ammonium sulfate ((NH₄)₂SO₄) and sodium hydroxide (NaOH), were purchased from Ajax Finechem Pty., Ltd. (New Zealand). Dimethyl sulfoxide (CH₃SOCH₃) was purchased from Loba Chemie Pvt. Ltd. (India). All other chemicals were of analytical grade and used without further purification.

The BC was prepared following a previous method (Torgbo and Sukyai 2019) with modifications. Basically, the culture medium was prepared by mixing 90 mL of coconut water with 5% (w/v) sucrose and 2.5% (w/v) ammonium sulfate, followed by sterilization at 100 °C. After sterilization, the medium was cooled to room temperature and the pH was adjusted to 4.5 with 5% (v/v) glacial acetic acid and 10% (v/v) of inoculum (*Komagataeibacter xylinus*) was inoculated. Microbial cultures were incubated at room temperature for 7 days under static condition. After incubation, the BC pellicles were collected and boiled in deionized (DI) water to remove the residual medium and other impurities. BC pellicles were then boiled in 1% (w/v) NaOH solution for 1 h to remove the cells and boiled in DI water until the pH of the water became neutral (pH 7). The purified BC was frozen at −20 °C for at least 24 h before lyophilized.

**Determination of minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC)**

The MIC and MBC of fingerroot extract were determined in 96-well microplates using broth microdilution method (Sunthornvarabhas et al. 2020). Mueller–Hinton broth was used as diluent for *Staphylococcus aureus* and *Escherichia coli*. The positive control composed of diluent and nutrient broth, while the negative control contained only bacteria strains. Microplates were inoculated at 37 °C for 24 h. To determine the MBC, 10 µL of bacterial suspension was removed from each well after overnight growth, (before adding the resazurin working solution) and spread onto Mueller–Hinton agar prior to incubation at 37 °C for 24 h. The MBC was defined as the lowest concentration of fingerroot extract at which 99.9% of the inoculated microorganisms were killed (Sukatta et al. 2021).
Preparation of BC with fingerroot extract filter membrane

The fingerroot extract (3% w/v) was dissolved in 100 mL dimethyl sulfoxide (DMSO). The freeze-dried BC (7 cm × 11 cm) was soaked in the fingerroot solution and shaken at 200 rpm using mechanical shaker at room temperature for 24 h. Thereafter, the BC membrane was rinsed with deionized water to remove unbound particles as well as excess DMSO and frozen at −20 °C for 24 h before freeze dried. The freeze-dried BC with fingerroot extract filter membrane (BC–FT filter membrane) was pressed with manually designed (5 cm × 10 cm, with 0.5 cm interval between needles) 3D sterilized needle grid to create pores. The amount of extract in BC–FT membrane was determined by the difference in weight of BC before and after addition of the extract (BC–FT). The process is summarized in Fig. 1.

Characterization

Scanning electron microscopy

Surface morphologies of pure BC and BC–FT filter membrane were examined using a scanning electron microscope (FEI Quanta 450, Czech Republic) at an accelerating voltage of 15–20 kV.

Porous size and porosity measurement by Brunauer–Emmett–Teller (BET)

The surface area, pore volume and pore size of pure BC membrane were analyzed by nitrogen adsorption and desorption at 200 °C. The various parameters were calculated using Micromeritics ASAP 2020 V3.00 software, Brunauer–Emmett–Teller (BET) equation and Barrett–Joyner–Halenda (BJH) method.
Fourier transform infrared (FTIR) spectroscopy

The chemical interaction and functional groups of pure BC and BC–FT filter membrane were analyzed using Fourier transform infrared spectrometer (Bruker model Tensor 27, USA) at room temperature. Pure BC and BC–FT filter membrane were analyzed by ATR mode. The fingerroot extract was blended with potassium bromide (KBr) powder and compressed to form a disc and analyzed by KBr method. The spectra were recorded in the transmittance mode with a resolution of 4 cm⁻¹ in the range from 500 to 4000 cm⁻¹.

X-ray diffraction (XRD)

The crystallinity and characteristic fingerprint of pure BC and fingerroot extract in BC–FT filter membrane were measured using an x-ray diffractometer (Bruker D8 Advance, Germany) using Cu-Kα radiation (λ = 1.54 Å) at 40 kV. The samples were scanned in 2θ angles from 5° to 50° with a scanning rate of 5°/min. Briefly, the sample was mounted in deep well sample holder made of polymethyl methacrylate (PMMA), packed well by glass slide and put into the sample stage. In the diffractometer, X-rays produced by the tube passed through primary optical component and irradiated the sample in the air environment, which was diffracted by the sample phases to pass through secondary optical component containing anti-scatter slit to ensure that no air scatter reach the detector. The individual crystalline peaks were extracted by peak-fitting process from the diffraction intensity profiles, with a maximum intensity >8,000 counts. A peak fitting program (OriginPro; www.originlab.com) was used, assuming pseudo-Voigt function for each peak and a broad peak ascribed to the amorphous contribution. After subtracting the background to ensure a stable baseline fitting and reduce fitting error, the pattern was deconvoluted into crystalline and amorphous contribution. The crystallinity index (CrI) was calculated by dividing the total area of main peaks of crystalline cellulose by the total peaks area (all crystalline plus amorphous peaks) according to Eq. 1.

\[
\text{Crystallinity Index (CrI)} = \frac{\text{Integrated area of all the crystalline peaks}}{\text{Integrated area of all the crystalline and amorphous peaks}} \times 100
\]

| Parameter          | BC–FD | BC–HP |
|--------------------|-------|-------|
| BET surface area (m²/g) | 69.915 | 20.016 |
| Pore volume (cm³/g) | 0.270 | 0.046 |
| Pore size (nm)     | 13.984 | 8.137 |

Mechanical property measurements

The tensile stress and Young’s modulus of pure BC and the filter membrane were determined according to ASTM D882-02 standard using universal testing machine (Shimadzu model AGS5kN, Japan) fitted with a 500 N load cell, with crosshead speed of 20 mm/min and 20 mm distance between clamps. The samples were cut into 10×50 mm strips with replicates. The results were presented as an averaged for each sample.

Removal efficiency measurement

The removal efficiency of BC filter membrane and commercial membrane were determined by filtering polystyrene latex particles with diameter of 0.1 μm according to ASTM F2299-03 standard using TSI’s Automated Filter Tester 3160. The BC filter membrane was cut spherically with diameter of 5.02 cm as the middle layer in commercial outer and inner layers of face mask before been tested. The efficiency (η) was calculated using Eq. 2 (Tan et al. 2019):

\[
\eta = 1 - \frac{C_{\text{downstream}}}{C_{\text{upstream}}}
\]

where \( C_{\text{upstream}} \) is the concentration of particulate matter (PM0.1) taken before filtration and \( C_{\text{downstream}} \) is the concentration of particulate matter taken after filtration.

Agar disc diffusion

The antimicrobial activity of BC with fingerroot was examined using the agar disc diffusion method by Chollakup et al. (2020) with modification. Briefly,

Table 1  Surface area, pore volume and pore size of pure BC dried by freeze dry (BC–FD) and hydraulic press (BC–HP) method
bacteria were incubated on the nutrient agar plates at 35 °C for 24 h and then inoculated into NaCl (0.85% w/v) to obtain the inoculum suspension with the turbidity equivalent to McFarland No. 0.5 (108 CFU/mL). Staphylococcus aureus and Escherichia coli were inoculated on Mueller–Hinton agar. After that, the BC–FT filter membrane was cut into a circle (1 cm diameter) and placed on inoculated agar plates. The plates were then incubated at 37 °C for 24 h.

Statistical analysis

The data collected were subjected to one-way analysis of variance (ANOVA) using GenStat software 12th edition. The experiments were performed with \( n = 3 \) replicates and data presented as the average of three replicates. Bonferroni test was used to evaluate the differences between groups; \( p \) value < 0.05 was considered significant.

Results and discussion

Brunauer–Emmett–Teller (BET) analysis of BC membrane

The surface area, pore volume and pore size of pure BC dried by freeze drying and hydraulic press were analyzed by Brunauer–Emmett–Teller (BET) equation and Barrett–Joyner–Halenda (BJH) method, to determine which drying process is most appropriate. The result in Table 1 shows the surface area, pore volume and pore size of pure BC dried by freeze dry method is higher than hydraulic press. The freeze-dried BC (BC-FD) has surface area, pore volume and pore size of 69.915 m\(^2\)/g, 0.270 cm\(^3\)/g and 13.984 nm, respectively. This implies that freeze drying method is more appropriate for drying BC to fabricate the filter membrane. Higher surface area means higher area to capture PM, while higher pore size and pore volume means higher breathability, because air can pass through the pores with ease than the one with less pore size and volume. Nonetheless, BC dried by both methods have pore size in nano scale which is good for fabricating filter membrane, as PM cannot pass through it Zhang et al. (2020).

Morphology of pure BC and BC–FT filter membrane

The surface properties of pure BC and BC–FT filter membrane were observed using SEM. The SEM images of the sample are shown in Fig. 2. The pure BC shows characteristic morphology of cellulose with porous and interwoven fibrils networks (Tsai et al. 2018). After immersion in fingerroot solution, BC–FT filter membrane shows some changes in the surface architecture and porous networks. The cellulose fibrils (Fig. 2b) were covered by small particles of fingerroot extract. The amount of fingerroot extract on the BC membrane was estimated as 162.9 mg (5.43% of fingerroot extract). This confirmed successful impregnation of fingerroot extract into BC membrane. The porous network of pure BC provides an ideal environment for penetration of the extract.

![Fig. 2](image-url)
under ex-situ shaking and attachment via physical and chemical interaction. This justifies the fabrication of low-cost filter membrane from BC and plant-based bioactive material for face mask.

FTIR analysis of pure BC and BC–FT filter membrane

The chemical functional groups of pure BC and BC–FT filter membrane were characterized using FTIR spectroscopy. FTIR spectra of pure BC and BC–FT filter membrane in Fig. 3 shows that, the BC–FT have same peak with pure BC. The O–H stretching vibration of hydroxyl group of cellulose
was found at 3348 cm\(^{-1}\). The peaks at 2895 cm\(^{-1}\), 1639 cm\(^{-1}\), 1526 cm\(^{-1}\) and 1160 cm\(^{-1}\) represented the stretching vibration of C–H group, stretching vibration of C=O group, symmetric bending of CH\(_2\) and antisymmetric bridge stretching of 1,4-\(\beta\)-d-glucoside, respectively (Wang et al. 2017). The new absorption peaks observe in BC–FT at 1015 cm\(^{-1}\), 984 cm\(^{-1}\) and 950 cm\(^{-1}\) referred to C–H bending vibration from isoprenoids in fingerroot (Thummajitsakul and Silprasit 2021). The BC–FT shows stretching vibration in peak intensity of the various absorbance that are presence in pure BC. The stretched peak intensity and appearance of new peaks indicated the chemical interactions and bonding of fingerroot extract in BC matrices.

X-ray diffractogram of pure BC and BC–FT filter membrane

The crystallinity and characteristic fingerprints of pure BC and BC–FT filter membrane were measured using an X-ray diffractometer. Figure 4 shows the diffractogram of modeled individual peaks and fitted peaks of BC and BC–FT with their amorphous contributions (dotted lines). There were at least three peaks separated from the diffraction intensity profiles. The distinct peaks at \(\theta = 14.6^\circ, 16.9^\circ\) and \(22.7^\circ\) represents the diffraction planes of \((100), (010)\) and \((110)\), respectively, corresponding to the Miller indices of diffraction crystallographic planes of I\(\alpha\) cellulose (French 2014). The diffractogram presents slight difference in the crystallinity degree of the two samples. The sharp diffraction peaks with high intensity in pure BC indicate more organized crystals and higher crystallinity than in BC–FT. The loading of fingerroot extract results in a significant reduction of crystallinity from 63.7% of pure BC to 52.4% in the BC–FT membrane. The stiffness of the fibrils and ribbons of cellulose is imparted by its crystallinity. Higher crystallinity means stronger polymer chain, less flexibility and higher thermal stability. The lesser crystalline

![Stress–strain curve of pure BC and BC–FT filter membrane](image)

**Fig. 5** Stress–strain curve of pure BC and BC–FT filter membrane

| Sample   | Tensile strength (MPa) | Elongation (%) | Young’s modulus (MPa) |
|----------|------------------------|----------------|-----------------------|
| Pure BC  | 159.74 ± 2.38\(^a\)    | 11.91 ± 0.46\(^a\) | 1277.02 ± 6.43\(^a\)  |
| BC–FT    | 243.21 ± 3.09\(^b\)    | 10.19 ± 0.41\(^b\) | 2251.17 ± 9.46\(^b\) |

Values are presented as mean ± standard deviation. Values with different letters (\(^a,b\)) within a column indicate significant different (\(p < 0.05\)).
peak areas and CrI of BC–FT shows that, the BC–FT filter membrane will easily degrade when disposed of than pure BC (Torgbo and Sukyai 2020). The addition of extract to BC possibly caused decreased in crystallinity due to the amorphous nature of the extract. The lower crystallinity was associated with easier and faster degradation process due to the transformation of crystallinity region into amorphous region (Torgbo and Sukyai 2020).

Mechanical properties of pure BC and BC–FT filter membrane

The mechanical properties of pure BC and BC–FT filter membrane were measured using tensile test. The results show highly significant difference between the samples. The addition of fingerroot extract to the BC resulted in an increased tensile strength of 243.21 MPa which is higher than pure BC of 159.74 MPa as shown in Table 2. Young’s modulus of pure BC and BC–FT filter membrane were 1277.02 MPa and 2251.17 MPa, respectively. It could be deduced that fingerroot extract improved the mechanical properties of BC by binding to the matrices. Figure 5 shows the representative stress-strain curves of pure BC and BC–FT filter membrane. The percentage elongation of pure BC and BC–FT filter membrane were 13.85% and 11.90%, which means that the elasticity of pure BC is higher than BC–FT.

Removal efficiency of BC–FT filter membrane

The removal efficiency of commercial membrane and BC–FT filter membrane was determined by filtering polystyrene latex (PSL) particles with diameter of 0.1 μm according to ASTM F2299-03 standard. In Fig. 6, the BC–FT filter membrane shows excellent removal efficiency of 99.83 ± 0.38% which is significantly higher than the pure BC and commercial membrane of 95.37 ± 0.014% and 93.23 ± 0.23%. The commercial membrane is made of polypropylene, a widely used polymer for synthetic fibers production. The polypropylene is mostly obtained through polymerization of propylene with or without other alpha olefin monomers, at high temperature cracking of petroleum hydrocarbons and propane. It is resistant to environmental stress, thus contributing to it longevity and environmental pollution (Koerner and Koerner 2018). The excellent performance of the fabricated
filter membrane may be due to the fiber diameter of BC and incorporation of the plant extract. The BC have diameter in nano scale, while the commercial membrane fibers have diameter in micro scale. The nano scale fibers have more surface area than micro scale diameter fibers. It has been acknowledged that the removal efficiency of filter membrane depends on the surface area. Thus, the removal efficiency in general, increased with increases in surface area (Chen et al. 2019). The plant derived compounds are reported to have very strong chelating activity of various ions, and can chelate compounds containing carbonyl, hydroxyls and catechol group (Makarov et al. 2014). These mechanisms explain the ability of fingerroot extract to enhance adsorption of PSL particles onto the surface of BC–FT membrane. Also, BC–FT filter membrane is made up of abundant O–H group which may induce interactions between the PSL particles and BC fibers (Zhang et al. 2019). The BC–FT filter membrane shows higher removal efficiency than those reported earlier with different materials (Al-Attabi et al. 2018; Cao et al. 2019; Chen et al. 2019; Tan et al. 2019). The high efficiency of the filter membrane in filtering 0.1 μm particles means it can effectively filter respiratory droplets which are noted for the transmission of Covid-19.

Antimicrobial activity of fingerroot extract and BC–FT filter membrane

The antibacterial activity of the extract was investigated to determine the minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC). The result in Table 3 shows the extract exhibited strong inhibitory and bactericidal activities on S. aureus with the MIC and MBC values of < 0.05 mg/mL and < 0.05 mg/mL, respectively. However, higher concentration was required against E. coli with MIC and MBC values of 6.4 mg/mL and 12.8 mg/mL, respectively. The differences in the sensitivity between the bacteria strains may be due to the variation in their cell wall structure. E. coli is gram negative bacteria with thin peptidoglycan cell wall and outer membrane that contain lipopolysaccharide. It also has periplasmic space between cytoplasmic membrane and thin outer membrane where lactamase enzyme is secreted as resistance mechanism against antimicrobial agent (Elisha et al. 2017), compared with S. aureus (gram positive bacteria) which cell wall has only peptidoglycan layer. Thus, it requires higher concentration of the extract to inhibit E. coli than S. aureus. The antimicrobial activity of BC–FT filter membrane was determined and the result shows no inhibition zone (clear zone) around the BC–FT disc. However, it killed the bacteria cells that were in close contact with the disc (clear zone under the disc as shown in Fig. S1). The inability of the test sample to show clear zone does not discount the effectiveness of the fingerroot extract in the membrane. It could probably be as a result of some limitations of agar disc diffusion test. The test requires migration of antimicrobial agent into the nutrient agar. The inability of the active compound to migrate/diffuse into the agar and lack of proclivity or incompatibility of antimicrobial agent with the agar, could cause none visual zone. One of the major phytochemicals in B. rotunda with antimicrobial activity is essential oils, which is hydrophobic in nature (Ait-Ouazzou et al. 2011), this could not easily migrate in the media to cause clear zone inhibition (Leontiev et al. 2018). The active compounds in the filter membrane caused death of cells that came in contact with the membrane by interacting directly with the bacterial cell membrane, enzymes and proteins, disrupted the integrity of the membrane and cell wall, and inhibit the biosynthesis of amino acids (Li et al. 2019; Mostafa et al. 2018).

### Table 3 Minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) of fingerroot extract

| Tested bacteria                   | MIC (mg/mL) | MBC (mg/mL) |
|----------------------------------|-------------|-------------|
| Staphylococcus aureus (TISTR 746)| <0.05 ± 0.00| <0.05 ± 0.0 |
| Escherichia coli (TISTR 117)     | 6.4 ± 0.00  | 12.8 ± 0.00 |

Conclusions

In this work, novel BC–FT filter membrane for highly efficient air filtration with antimicrobial properties was successfully fabricated. BC–FT filter membrane is highly effective in removing PM0.1 with 99.83%
removal efficiency, which is better than that of commercial membrane. Fingerroot extract used for the filter membrane inhibited and killed S. aureus and E. coli. at minimum concentration of 0.05 and 12.8 mg/mL, respectively. BC–FT filter membrane also killed the tested bacteria strains attached to the filter membrane. The membrane demonstrated good mechanical properties and low crystallinity index. The BC–FT can be applied as a filter membrane for face mask to curtail the hazards of PM2.5 and COVID-19 infection by reducing risk of direct and indirect exposure to viral particles in respiratory droplets.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human/animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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