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Historical Perspective

Fabrication of air filters with advanced filtration performance for removal of viral aerosols and control the spread of COVID-19

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ABSTRACT

COVID-19 is caused via the SARS-CoV-2 virus, a lipid-based enveloped virus with spike-like projections. At present, the global epidemic of COVID-19 continues and waves of SARS-CoV-2, the mutant Delta and Omicron variant which are associated with enhanced transmissibility and evasion to vaccine-induced immunity have increased hospitalization and mortality, the biggest challenge we face is whether we will be able to overcome this virus? On the other side, warm seasons and heat have increased the need for proper ventilation systems to trap contaminants containing the virus. Besides, heat and sweating accelerate the growth of microorganisms. For example, medical staff that is in the front line use masks for a long time, and their facial sweat causes microbes to grow on the mask. Nowadays, efficient air filters with anti-viral and antimicrobial properties have received a lot of attention, and are used to make ventilation systems or medical masks. A wide range of materials plays an important role in the production of efficient air filters. For example, metals, metal oxides, or antimicrobial metal species that have anti-viral and antimicrobial properties, including Ag, ZnO, TiO_2, CuO, and Cu played a role in this regard. Carbon nanomaterials such as carbon nanotubes, graphene, or derivatives have also shown their role well. In addition, natural materials such as biopolymers such as alginate, and herbal extracts are employed to prepare effective air filters. In this review, we summarized the utilization of diverse materials in the preparation of efficient air filters to apply in the preparation of medical masks and ventilation systems. In the first part, the employing metal and metal oxides is examined, and the second part summarizes the application of carbon materials for the fabrication of air filters. After examination of the performance of natural materials, challenges and progress visions are discussed.

1. Introduction

Presently, one of the main concerns of humans is the very fast spreading of COVID-19. Due to the epidemic of COVID-19, the importance of aerosols and their role in SARS-CoV-2 transmission and air quality is studied and discussed. This virus is transmitted primarily through droplets caused by sneezing, coughing, speaking, singing, and inhalation. According to the published results, the aerosols containing SARS-CoV-2 were detected about 5 m away from an infected patient [1–9]. Besides, the effects of this virus on the environment over time are very destructive. This acute respiratory syndrome is associated with airborne transmission. Actually, particulate air pollution is a global environmental issue and continuous exposure to these particles creates irreparable risks. According to the results, the air in areas such as patients' rooms and the hospital environment contains the SARS-CoV-2 virus. The main air pollutants include microscale airborne particles (particulate matter 2.5, as well as particulate matter 10), gaseous hazards in form of an aerosol (include SO_2, CO, NO_2, O_3), which studies have shown to be produced by steel and iron factories, power plants, cement industries, and the transportation and burning system of fossil fuels. There is a complete link between these atmospheric hazards and the SARS-CoV-2 virus. Humid air and the presence of moisture in the atmosphere are directly related to the formation of aerosols [10–14]. As shown in Fig. 1, humid climates increase the likelihood of airborne particles adhering to the virus and increase mortality. Therefore, Southeast Asian countries such as India are more exposed to deadly infectious diseases. The sources and routes of transmission of this new virus indoor in-house air pollution and outdoor ambient air are shown in this figure. As a result, it can be said that due to human interventions and air pollution, air quality is gradually deteriorating, which causes more

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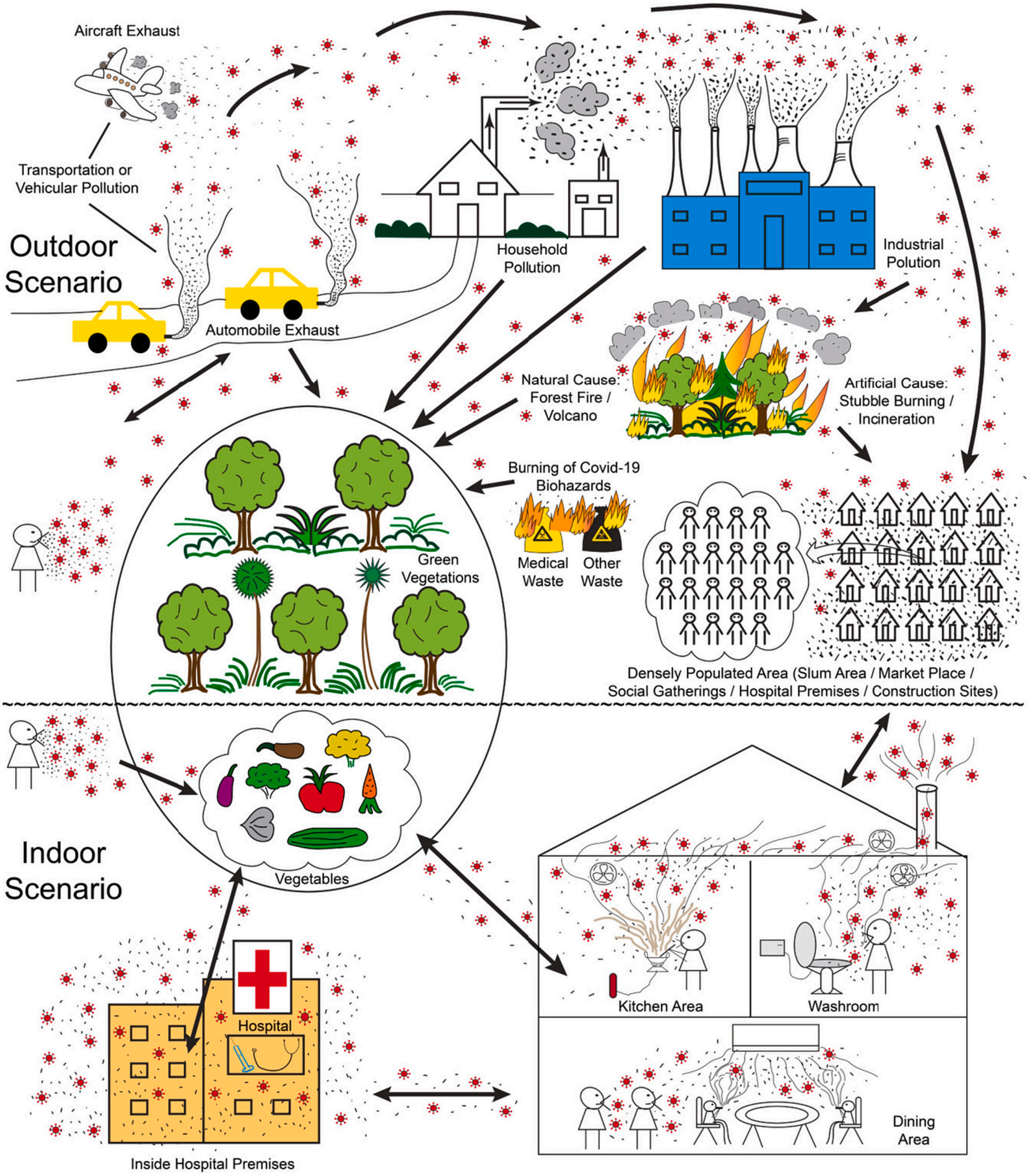

Fig. 1. Sources and pathways of transmission of novel coronavirus through several routes of air medium containing solid particulate matters, gaseous hazards in form of aerosol leading to indoor in-house air pollution and outdoor ambient air pollution are depicted (Reprinted with permission from [14], Copyright 2021 Elsevier).

deaths [14].

Particulate matter, which includes liquid as well as solid droplets, creates from sources such as forest fires, vehicle exhaust, smokestacks, road dust, windblown soil, and so on. Particulate matter 2.5 or particles with aerodynamic diameters lower than 2.5 μm, can penetrate the circulatory system and pose serious risks, and inhaling them is dangerous. An environmental study has shown that prolonged exposure to these particles increases mortality due to COVID-19. In fact, particles with high surface-to-volume ratios can absorb the virus-containing SARS-CoV-2 and spread viral infection [15–17].

As the COVID-19 outbreak continues, people prefer to be more at home this summer and less likely to travel to crowded areas. Air conditioning is essential for homes, offices, gyms, hospitals, warehouses or laboratories, and vehicles. Disinfecting and cleaning these areas to reduce contamination including the SARS-CoV-2 virus is critical. Since SARS-CoV-2 has been reported to be transmitted through the air, for this reason, air filters with anti-viral and antimicrobial properties are expanding. These filters play an effective role in reducing virus

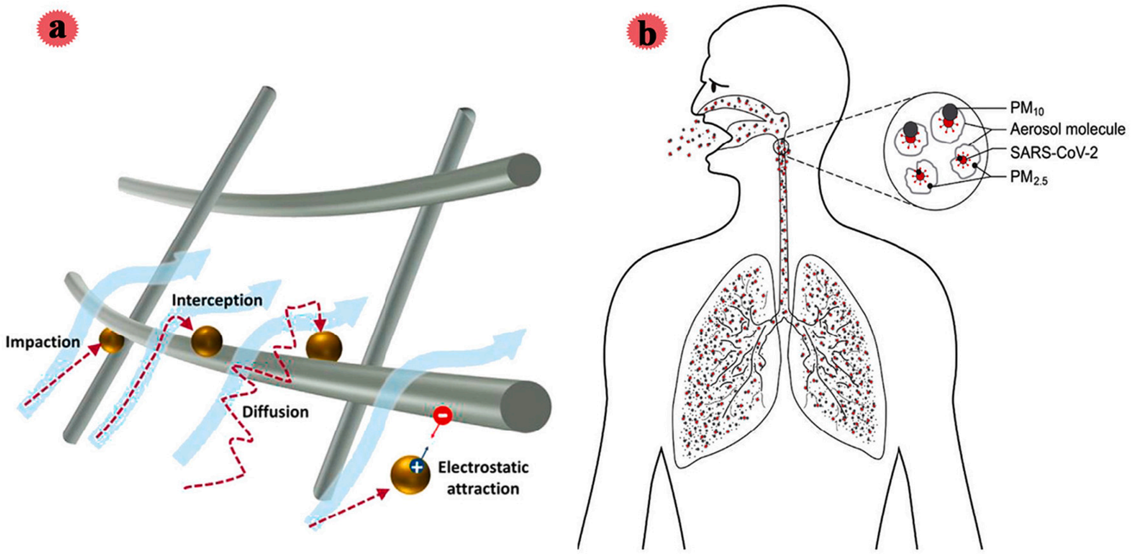

Fig. 2. a: Four types of particulates filtration mechanisms. The representative PM filtration mechanisms: impaction, interception, diffusion, electrostatic attraction, b: Viral load adhered to the surface of aerosol particulates severely affecting human respiratory tract and system (Reprinted with permission from [12,14], Copyright 2021 Elsevier).

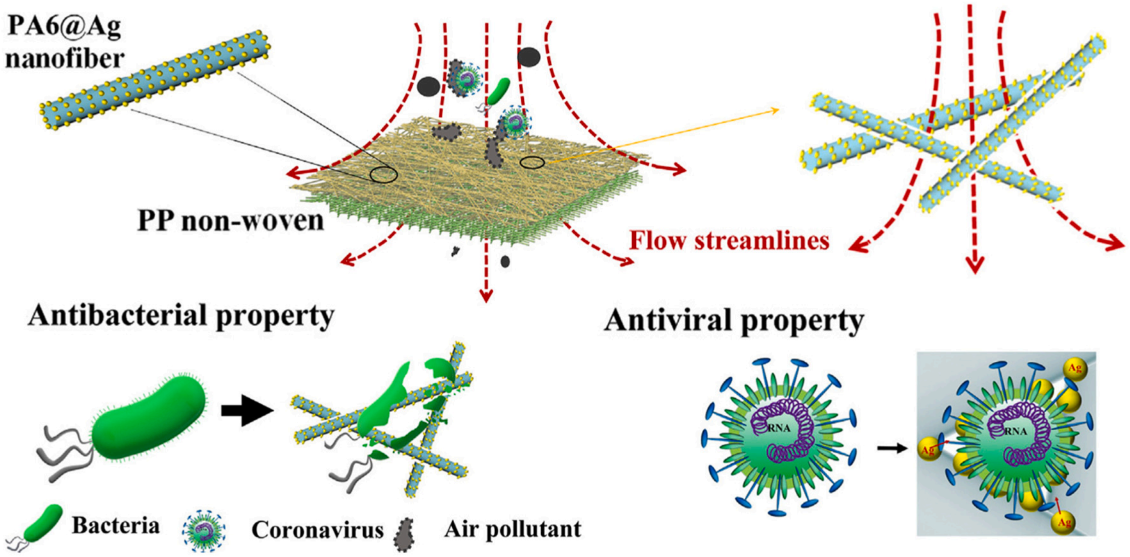

Fig. 3. Schematics showing PA6@Ag ENM as an air filter membrane with antibacterial and antiviral property (Reprinted with permission from [25], Copyright 2021 Elsevier).

transmission. Closed spaces with poor ventilation are a risk factor for the spread of COVID-19. So, recently, the outbreak of the virus has made everyone think about air quality and the provision of proper air filtration systems. Besides, to protect general health, air filters based on electrospun nano-fibers that have antimicrobial properties have been expanded and can be used to provide proper ventilation systems and masks [18–22].

Particulate matter filtration can be done through several mechanisms: sieving, gravity settling, inertial impaction, interception, diffusion, and electrostatic attraction (Fig. 2). For gaseous pollutants, it is based on physisorption (based on weak Vander Waals force), and chemisorption (strong connection among pollutant and the filter material) [12,14–16].

Today, high-performance and efficient air filters are made using polymer nano-fibers as well as nanomaterials that have anti-viral and antimicrobial features such as metals, metal oxides, biopolymers, and carbon-based nanomaterials like graphene and carbon nanotubes [15,16,21,23,24]. In this review, we summarized the utilization of diverse materials in the preparation of efficient air filters to apply in the preparation of medical masks and ventilation systems. In the first part, the employing of metal and metal oxides is examined and the second part summarizes the application of carbon materials for fabrication air filters. After examination of biopolymers or other green materials, challenges and progress visions are discussed.

2. The performance of metals, metallic oxide, and metal ions for fabrication of antimicrobial air filters

2.1. Ag nanoparticles

Recently, the outbreak of epidemic diseases such as COVID-19 has accelerated the finding and improvement of air filters with anti-viral as

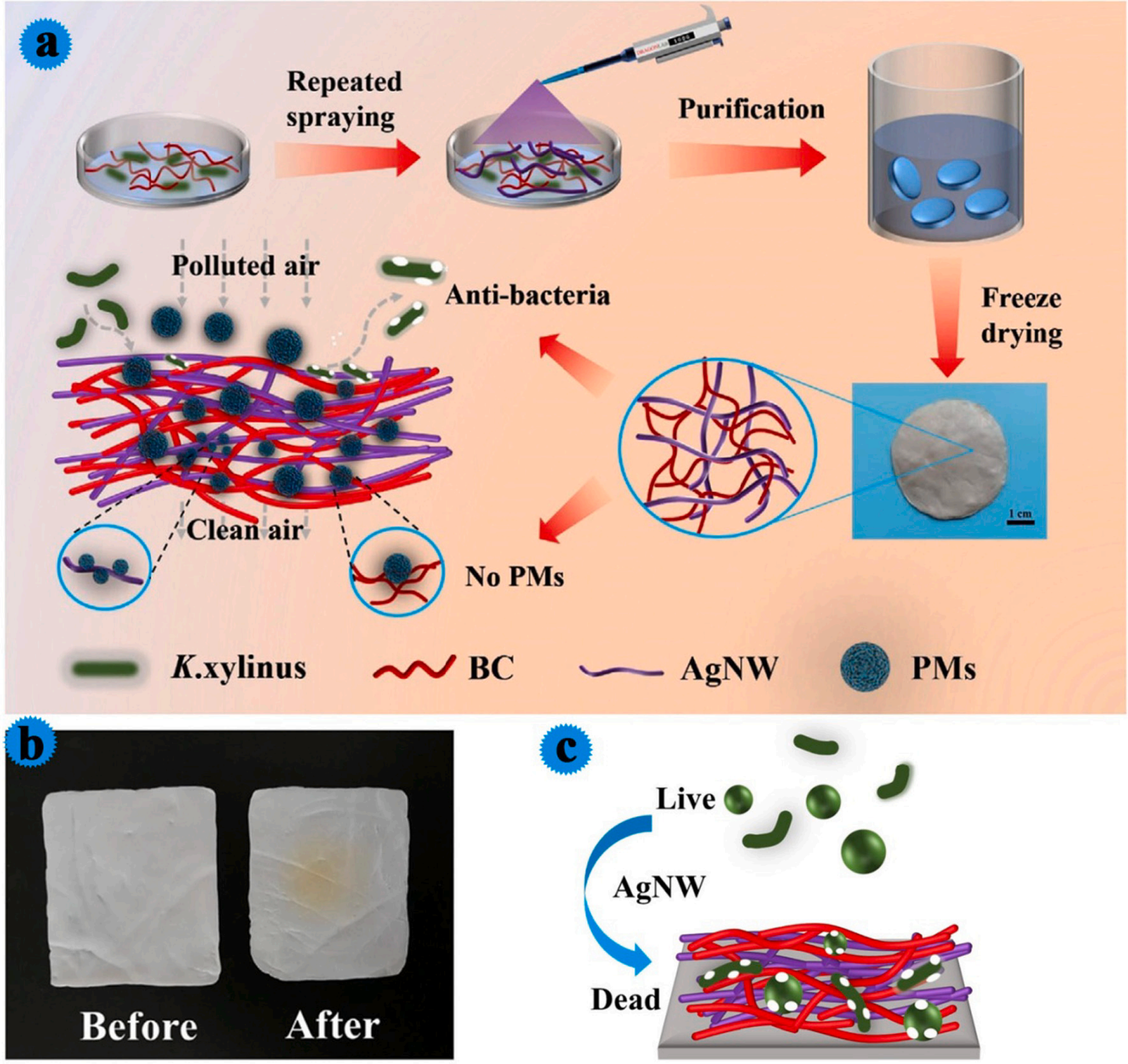

Fig. 4. a: Schematic illustration of the preparation of BC/AgNW filter with antibacterial activity for highly efficient PMs removal, b: The photographs of the BC air filter paper before and after filtration test, c: Schematic illustration the as-prepared air filter paper for anti-bacteria. The filter material can effectively kill bacteria (Reprinted with permission from [34], Copyright 2021 Wiley).

well as antimicrobial features to deal with infections and so, for health protection. Considering the latest outcomes from diverse research, SARS-CoV-2 is transmitted through aerosols/droplets in the air. Aerosols generally are available in two dimension range: sub and super-micron regions, which are in 0.25 to 1.0 μm, and > 2.5 μm ranges, respectively. Besides, based on published reports, particulate matter 2.5 carries viruses, bacteria, as well as organic pollutants. Indeed, they are suspended in the atmosphere for the long-term and enter the human body through respiration, and cause irreparable danger. Accordingly, medical masks, as well as ventilator systems, must have a suitable filter for the elimination of nano-aerosols or ultrafine submicron particles. Nanotechnology plays a good role in this regard. Metallic nanoparticles including Ag (silver) with inhibitory performance and bactericidal action could be a good choice for preparation air filters. In this regard, Ju et al. reported a suited approach for the fabrication of a highly efficient air filter with anti-viral and antibacterial performance simultaneously [25]. For this aim, via electrospinning process, a membrane of polyamide 6 nano-fibrous was manufactured on polypropylene matrix (nonwoven), and after that, through impregnation technique (immersion polyamide6/polypropylene membrane in Ag solution), Ag nanoparticles were assembled on nano-fiber (Fig. 3). In fact, by hydrogen bond, nanofibers were anchored with Ag. The product showed a multilevel structure with a bumpy nano-rough surface, high surface area, and fine diameter that improved the capture capacity and the nanoparticles inactivated viruses and bacteria. The fabricated membrane showed low-pressure drop (31 Pa), high (99.99%) filtration efficacy and great performance for the removal of multiple aerosol pollutants. The antimicrobial and anti-viral performances were examined for *E. coli* and *S. aureus*, and PDCoV (Porcine Delta-coronavirus as positive-sense RNA virus). The prepared membrane was fixed air conditioner, and the outcomes showed an outstanding air purification act.

Heating, Ventilating and Air Conditioning (HVAC) systems reduce microorganism's circulation and air-transmission of disease. These efficient systems capture and inactivate virus-rich aerosols, creating a safe indoor air environment and protecting humans from danger. In this regard, in order to prevent the spread of airborne diseases such as influenza, cold, current pandemic COVID-19, which arise from air-transmitted pathogens like fungi, bacteria, and viruses, Balagna et al. developed anti-viral air filters by using nanocomposite coating. By the co-sputtering method, Ag nano-clusters/SiO_2 hybrid coating was placed on glass, and metallic air filters [26]. The resulted air filters were tested for human respiratory viruses including FluVA (influenza virus type A), RSV (respiratory syncytial virus), as well as HRV (human rhinovirus). Considering the outcomes from anti-viral tests, the resultant air filters,

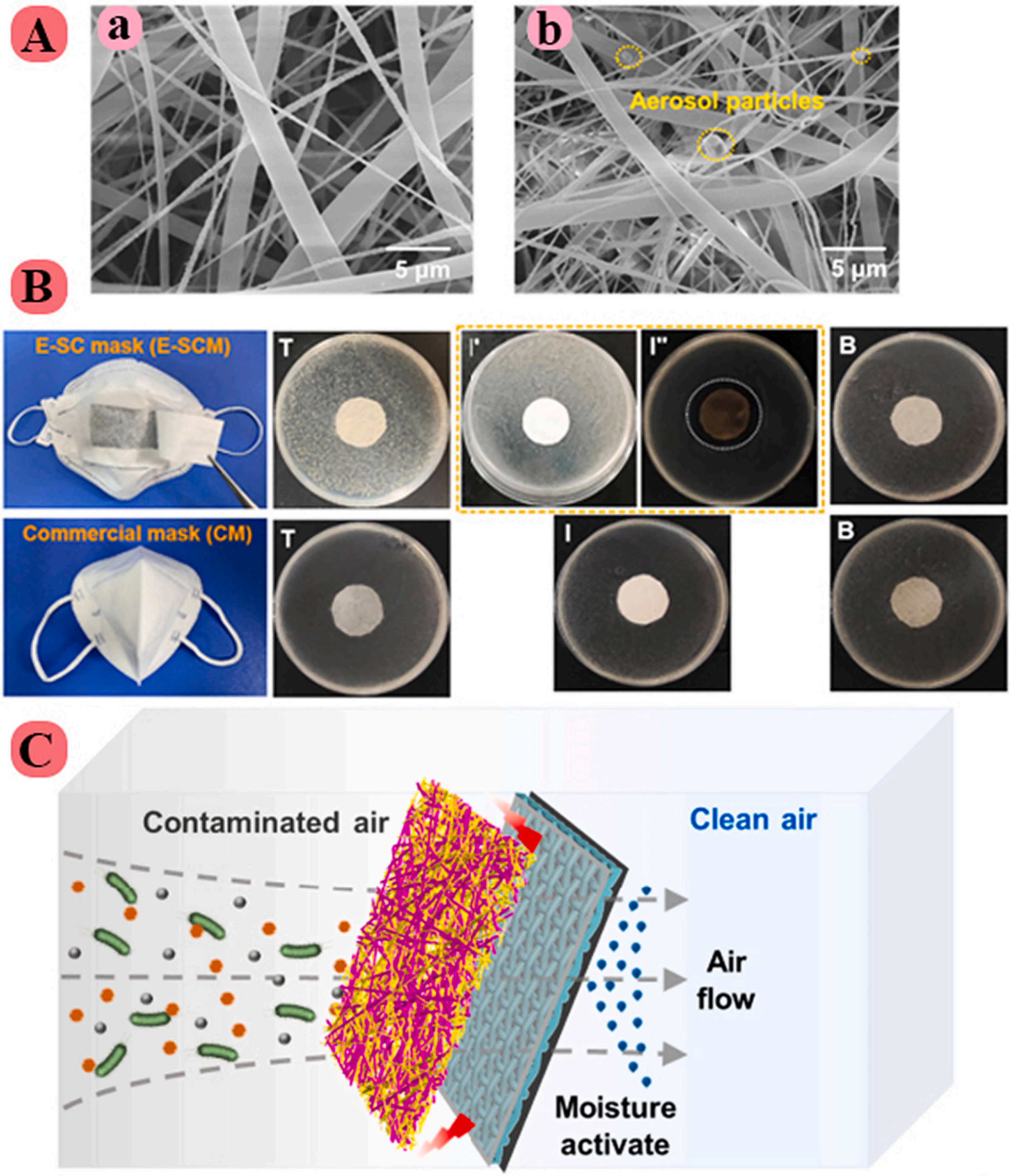

Fig. 5. A: SEM images of the PVDF/PS1/2 membrane (a) before and (b) after filtration, B: Antibacterial performance comparison between *E*-Ag/Zn@cotton fabric-based mask (E-SCM) and commercial mask (CM, N95 medical protective mask),C: Schematic representation of the air cleaning system (Reprinted with permission from [36], Copyright 2022 Elsevier).

composite coating showed strong virucidal activity against FluVA and RSV, but no anti-viral performance against the HRV.

In another study, an anti-viral filter based on nano-Ag/TiO_2-chitosan was prepared for removal of viral aerosols, the precaution of airborne viruses' transmission, and reducing infection [27]. By photochemical deposition technique, nano-Ag^0/TiO_2-chitosan was synthesized, then, the anti-viral ability of it was evaluated using filtration experiments and MS2 plaque reduction assay. Indeed, the MS2 bacteriophage was employed as an airborne virus. The fabricated filter removed >93% of airborne MS2 particles and proficiently deactivated >95% of the MS2 in 20 min. Based on the prediction of the Wells–Riley model, this filter could decrease infection probability from 99% to 34.6%. Also, after one week of continuous operation, anti-viral efficiency was 50%.

Haeng Joe and co-workers fabricated an air filter with anti-viral activity by employing nano-SiO_2/Ag particles (anti-viral particles). In this study, SiO_2 and Ag nanoparticles were prepared, and then, the surface of SiO_2 nanoparticles was coated with Ag. After that, SiO_2/Ag was coated on an air filter [28]. The filtration efficacy, as well as the anti-viral performance of the prepared filter, was estimated toward aerosolized MS2 virus particles in a continuous airflow condition. With increasing SiO_2/Ag coating levels, the pressure drop, filtration efficacy, as well as anti-viral effectiveness were increased. In a similar study, Ag

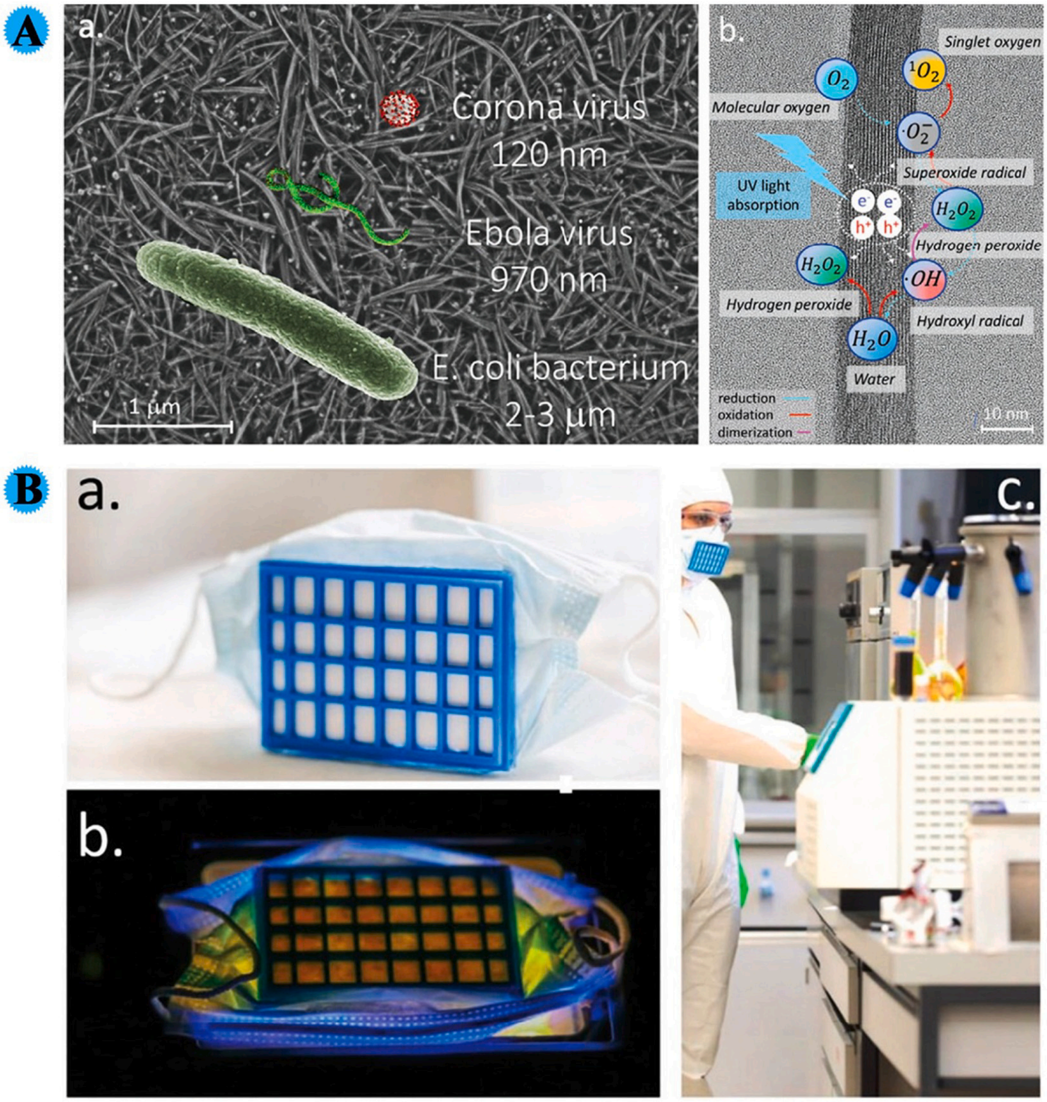

Fig. 6. A: a) The SEM image of the surface of the TiO_2NWs filter overlapped with the schematic representations of the example germs to be filtered out. b) Schematic illustration of photocatalytical processes leading to ROS generation at the humid surface of TiO_2NWs. The resulting photogenerated ROS inactivate all the microbial targets in its proximity, B: The reusable protective mask designed around the TiO_2NWs-based filter paper. a) Photo of the mask prototype in which the TiO_2NWs filter paper is attached to a 3D-printed plastic frame. b) Photo of the mask prototype during its disinfection under 365 nm UV illumination. The filtered germs are inactivated by ROS, formed in the photocatalytic reaction on the surface of the filter material. c) Photo of the reusable protective mask prototype in real conditions (courtesy of Swoxid S.A.) (Reprinted with permission from [38], Copyright 2020 Wiley).

nanoparticles were prepared with about 11 nm size by spark discharge generation method [29]. Then, anti-viral Ag nanoparticles were covered on the air filter. The anti-viral performance toward aerosolized virus, filtration efficacy, and also, pressure drop were examined with dust loading. With dust loading, anti-viral ability decreased, and filtration efficiency increased. Using a mathematical model, both experimentally and mathematically examinations of anti-viral capability were performed. Also, in another work, for evaluation of air filter anti-viral proficiency, a safe platform was developed for airborne aerosolized infectious viruses. Ag nanoparticles were manufactured by a lab-made spark discharge generation method. Then, they were covered on HEPA (high-efficiency particulate air) filters. Also, between air-liquid media, a mathematical connection of anti-viral efficacies was reported. By many kinds of virus species including infectious virus, a broadly available method was revealed [30].

Although a common way to clean the air is to use air filters, microorganisms can survive on the filter surface. Therefore, antimicrobial coatings for these filters kill microorganisms. In a study, through a high-volume flow atomizer, an anti-viral air filter was developed based on the covering of anti-viral nanoparticles on commercial air filters, which this process had a rate of 8.5 times compared to the conventional ones. Aerosolized SiO_2-Ag nanoparticles were covered on filters without effect on pressure drop. The performances of the air filter (anti-viral action and filtration efficacy) were studied by aerosolized MS2 virus. The resulted filter showed ~92% anti-viral efficiency [31].

Till now, diverse antimicrobial agents including ZnO, Ag, CuO, and TiO_2 have been inserted into fibers to enhance antimicrobial performances. Fan et al. developed a multifunctional air filter zein nanofibers-Ag@paper towel inspired by a “tug-of-war” repulsion force [32]. For this aim, Ag@paper towel substrate was manufactured by in-situ reduction. Also, zein nano-fibers as an upper layer were fabricated through electrospinning a zein Pickering emulsion on a particularly planned collector. In this study, Ag nanoparticles provided an effective antimicrobial performance and the substrate with an anisotropic electric field for achievement aligned, stretched, and thinner nano-fibers compared to that without Ag. Indeed, the filtration behavior of the fabricated filter

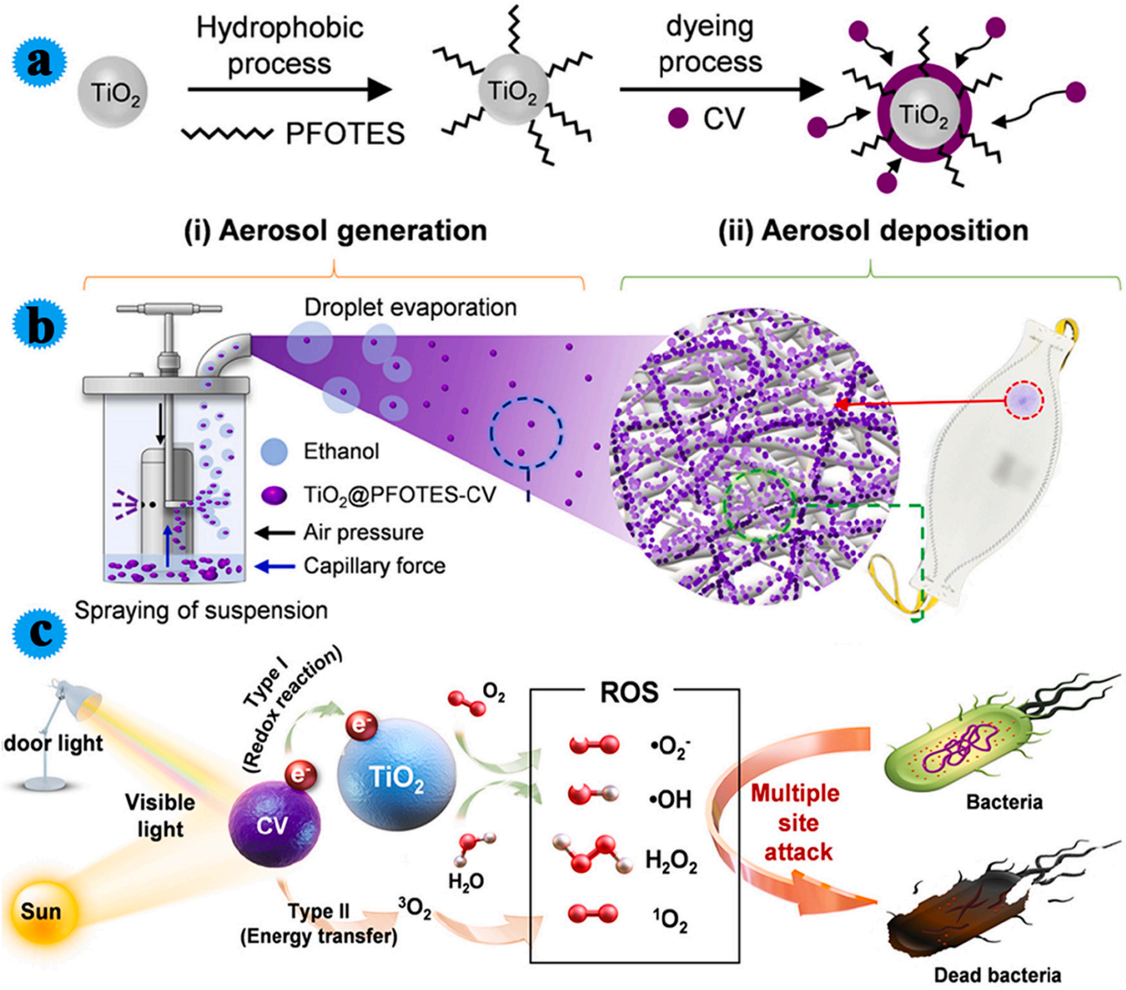

Fig. 7. a: Schematic illustration of the synthesis of TiO_2@ PFOTES-CV nanoparticles (NPs),b: Schematic diagram of the aerosol deposition process for the VLA antimicrobial air filter, c: Schematic of the VLA inactivation mechanisms based on the production of ROS and $^1O_2$. (Reprinted with permission from [40], Copyright 2021 American Chemical Society).

was enhanced after using Ag particles. Overall, the achieved air filter with outstanding filtration action, hydrophobic behavior, antimicrobial, and mechanical features displayed great removal efficiency (99.30%) for particulate matter 0.3.

Shen et al. extracted keratin (the main constituent of wool fibrils) from coarse wool (goat wool) through a high-efficiency technique (using $Na_2S_2O_3$ mixed solution with 75.3% extraction rate) [33]. Indeed this wool has many features like large diameter, less bending, and better strength that cause difficulty to use in the textile. On the other side, keratin is bio-compatible, bio-degradable, hydrophilic material that has attracted wide consideration. After that, a composite nano-fiber air filter was prepared by an Ag-doped keratin/polyamide-6 with improved antibacterial and filtration behaviors by HCOOH as reductant/solvent. Keratin was a dopant with polyamide-6 and enhanced water–vapor transmission, and air filtration efficacy. Ag nanoparticles were synthesized (in-situ) in composite solution using $AgNO_3$ and formic acid. After the addition of Ag nanoparticles, the prepared composite showed strong antibacterial performance toward *E. coli* (99.10%) as well as *S. aureus* (99.62%). Bacterial filtration effectiveness toward *E. coli* and *S. aureus* were $> 95.6\%$ and $> 96.8\%$, respectively. These outcomes of the fabricated air filter showed great potential for preparation for comfortable and bio-protective filters.

Multifunctional air filters for effective removal of particulate matter, prevention of dangerous materials, and low respiratory resistance are required. Air filters based on bacterial cellulose (nano-fiber secreted through *Acetobacter xylinum*), capture particulate matters from airflow [34]. Nevertheless, the dense construction sacrifices air permeability. So, in an investigation, Ag nanowires were introduced into bacterial cellulose filter by in-situ cultivation technique and Ag nanowires/bacterial cellulose filter was prepared as can be observed in Fig. 4a. The insertion of Ag efficiently increased the porosity of bacterial cellulose, reduced pressure drop, and increased the air permeability. In addition, small particles were adsorbed on Ag nanowires via electrostatic adsorption and improved filtration efficiency for filter paper. Fig. 4b shows before and after filtration tests that revealed the effectiveness of this filter well. Furthermore, high-performance antibacterial potency was observed for filter due to Ag nanowires (Fig. 4c). The filtration efficiencies for the prepared composite filter for particulate matters 2.5 and particulate matter 10 were 99.7% and 99.8%, respectively and pressure drop was 123 Pa. the prepared fine long-term structural stable filter was promising for human health.

Blosi et al. developed poly(vinyl alcohol)/Ag electrospun nano-fibers as a biocidal filter to capture virus-size particles via electrospinning technology. Ag nanoparticles were inserted for improvement of the requirements: antimicrobial performance for inactivation of aerosolized microorganisms, high air filtration efficacy for capturing particles, low airflow resistance for breathability. The fabricated filter displayed 99.6% and 100% bacteria reductions toward *S. aureus* and *E. coli,* respectively. Pressure drop was in line with FFP1 and FFP2 masks. So, this filter showed potential for the production of indoor air purification

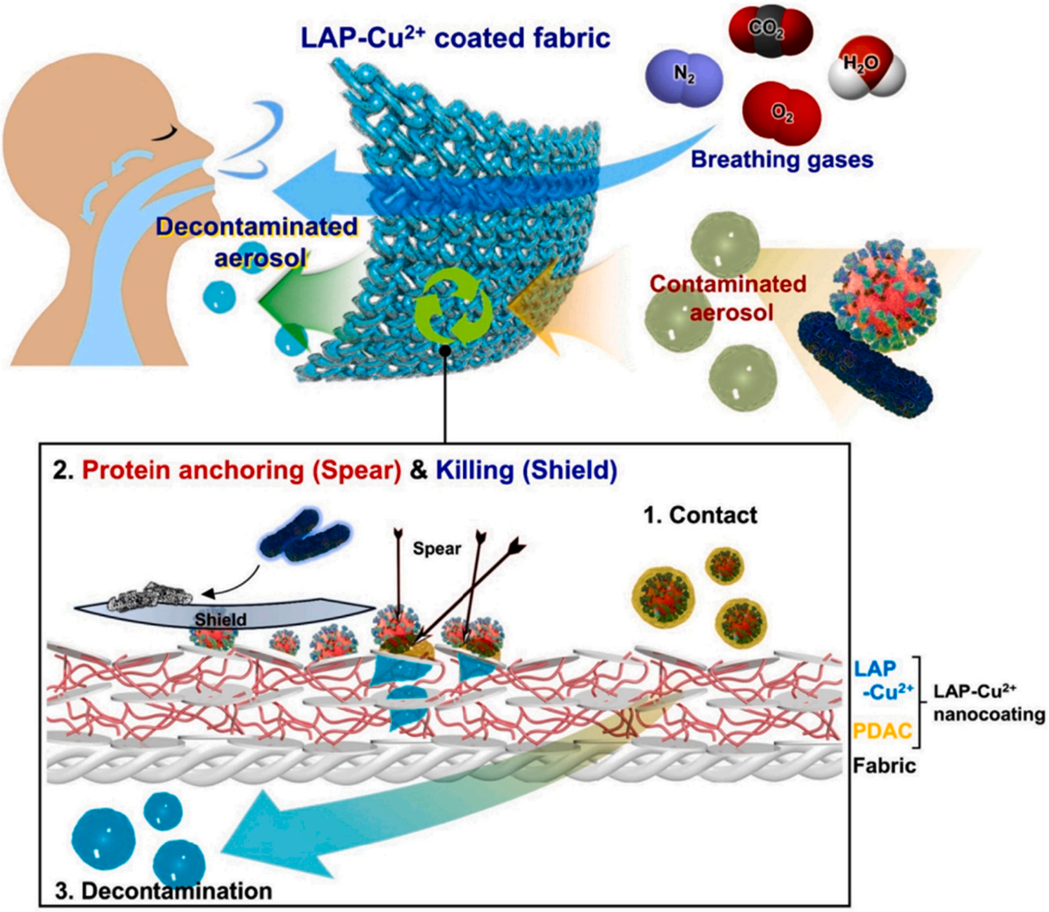

Fig. 8. Schematic illustration of 2 paradoxical effects on LAP-Cu^{2+}-coated fabric. When the contaminated aerosol containing bacterial or proteinaceous pathogens contacts the fabric, the LAP can trap the pathogens (Spear), and the Cu^{2+} ions kill the bacteria (Shield) over the nanocoating without interfering air and vapor transmission. Finally, the aerosol is decontaminated (Reprinted with permission from [43], Copyright 2021 Elsevier).

devices and facemasks [35].

For the development of antimicrobial face masks for public health protection., He et al. prepared an antimicrobial composite filter by employing Ag/Zn modified cotton and electrospun poly(vinylidene fluoride)/polystyrene nanofibers [36]. The good features of nanofibers like high porosity, low weight, small pore size filtration, and permeability performance were excellent. Besides, *E*-Ag/Zn@cotton fabric as the middle layer of face mask that was nao harmful to humans, provided strong structural stability as well as high proficiency contact sterilization function. The fabricated filter showed great filtration presentation to PM0.3 (99.1%, 79.2 Pa). Furthermore, in 20 min contact of the filter with *E. coli* and *S. aureus*, 99.64% and 98.75% of them were killed (Fig. 5).

2.2. TiO_2 nanoparticles

COVID-19's epidemic is an un-precedented crisis. In order to stop the SARS-CoV-2 spread, it is necessary to have air filters with antimicrobial properties to prepare masks and air conditioning systems. In air filters, bactericidal-virucidal surfaces show great potential uses. Photocatalytic materials-based air filters, which produce ROS (OH•, H_2O_2, $^1O_2$ O_2^{-}, and HO_2•) under UV light, powerfully deactivate airborne pathogens and also are reusable. Photocatalytic materials based on nano-TiO_2 represent a hopeful solution for these uses. Indeed, TiO_2 nanoparticles have outstanding photocatalytic behavior, so, they can be employed for the removal of pollutants [37]. Recently, TiO_2 nanowire-based filter papers have been developed and evaluated their performance. Through processing TiO_2 nano-wires into filter paper, the pore size of these filters can be tuned to effectively trap the pathogens with diverse sizes, comprising viruses (Corona and Ebola viruses) and bacteria (Fig. 6a). Nano-TiO_2 particles have many useful features for example high dielectric constant, which facilitates wetting the surface of filters through water or saliva droplets containing pathogens, so, this feature is significant for filtration materials. The preparation of ROS by TiO_2 can be observed in Fig. 6b. An example of this mask was prepared, which is shown in this figure. The fabricated anti-viral face masks based on TiO_2 with easily sterilizable and reusable features (more than 1000 times) can provide a strong prevention device against the SARS-CoV-2 [38].

Providing antimicrobial and anti-viral filters with high filtration performance and bio-degradability both protect people and reduce environmental waste and can also be sewn on fabric masks and reduces costs. On the other hand, long-term use of surgical masks, especially in hot areas, irritates the skin and even causes sweating and increased infection. Therefore, it is very important to prepare suitable masks. In order to prepare an inexpensive face mask filter with high filtration performance, Abbas et al. prepared a hybrid nano-fibrous layer with anti-viral and antimicrobial behavior by employing chitosan, poly(vinyl alcohol), and TiO_2 nano-tubes by electrospinning method, as the most versatile technique to prepare nano-fibers. The combinatorial filter layers were prepared via the integration of anti-viral and antimicrobial agents (TiO_2 nano-fillers) into polymeric electrospun nano-fibers of chitosan/poly(vinyl alcohol). In this filter, outer, middle, and inner composite layers were TiO_2/chitosan/poly(vinyl alcohol), chitosan/poly(vinyl alcohol), and silk/poly(vinyl alcohol) respectively. The outer layer acted as an antimicrobial and anti-viral agent, middle layer acted as a green pathogens inactivation layer and air filtration. The inner layer

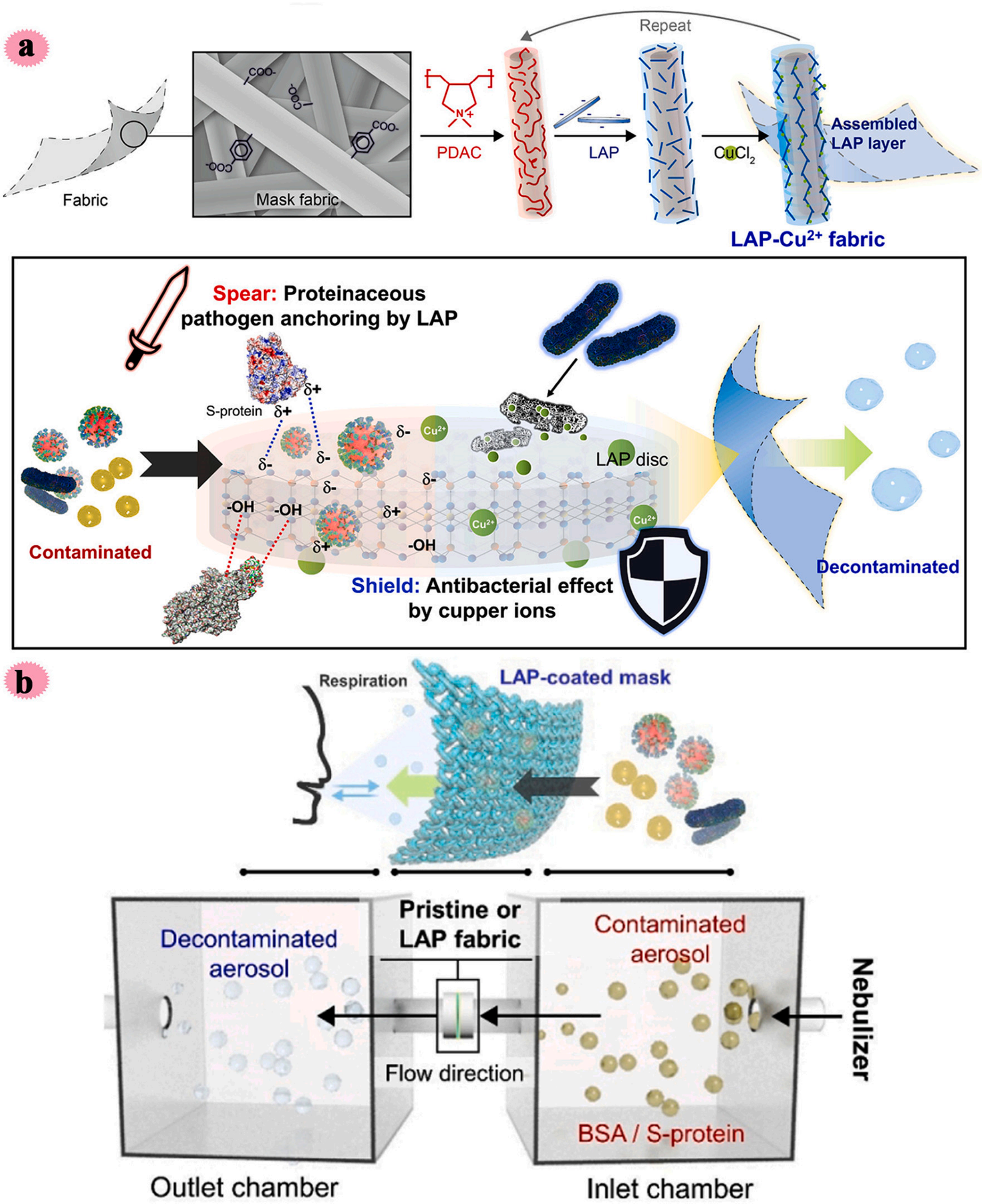

Fig. 9. a: Schematic illustration of the materials used for the proposed LbL coating. Due to the LAP and Cu ions, the two functions that attacking proteinaceous contaminants are adsorbed onto LAP (Spear) and bacterial are killed by Cu^{2+} ions (Shield) are co-existing on filter, b:Schematic illustration of the protein-containing aerosol nebulizer system used to measure the protein-trapping efficiency of the fabric. To mimic human respiration situation (top), experimental model using nebulizer is designated (bottom) (Reprinted with permission from [43], Copyright 2021 Elsevier).

improved the mechanical and heat dissipation properties and helped in the wearers' skin comfort. Furthermore, all materials were affordable and easy to fabricate and handle. The outcomes revealed high filtration efficiency, and the outer layer considerably reduced *S. aureus* bacteria (by 44.8%) due to the performance of TiO_2 and chitosan infectious [39].

Global public health is ready to suppress threats against airborne microorganisms or bioaerosols. These aerosols have caused the death of many people in different years for instance H1N1 influenza pandemic of 2009, MERS-CoV in 2012, COVID-19 in 2019. These highly contagious respiratory infections can be transmitted in the form of droplets produced by sneezing, coughing, talking, and airborne particles (which can attach to dust). The best way to control it is to use proper breathing masks. Improper use of the mask increases the prevalence of the disease. Long-term masks cause secondary bioaerosol spread because microorganisms survive on the surface of the filters. Recently, inactivation of these bioaerosol has been done through visible-light activated sterilization. In fact, the inactivation of microorganisms can be performed at any time and place through the photocatalytic process, which is a green process in the sun or indoor light. In this process, the production of ROS (strong germicidal agents) inactivates microorganisms by damaging cell

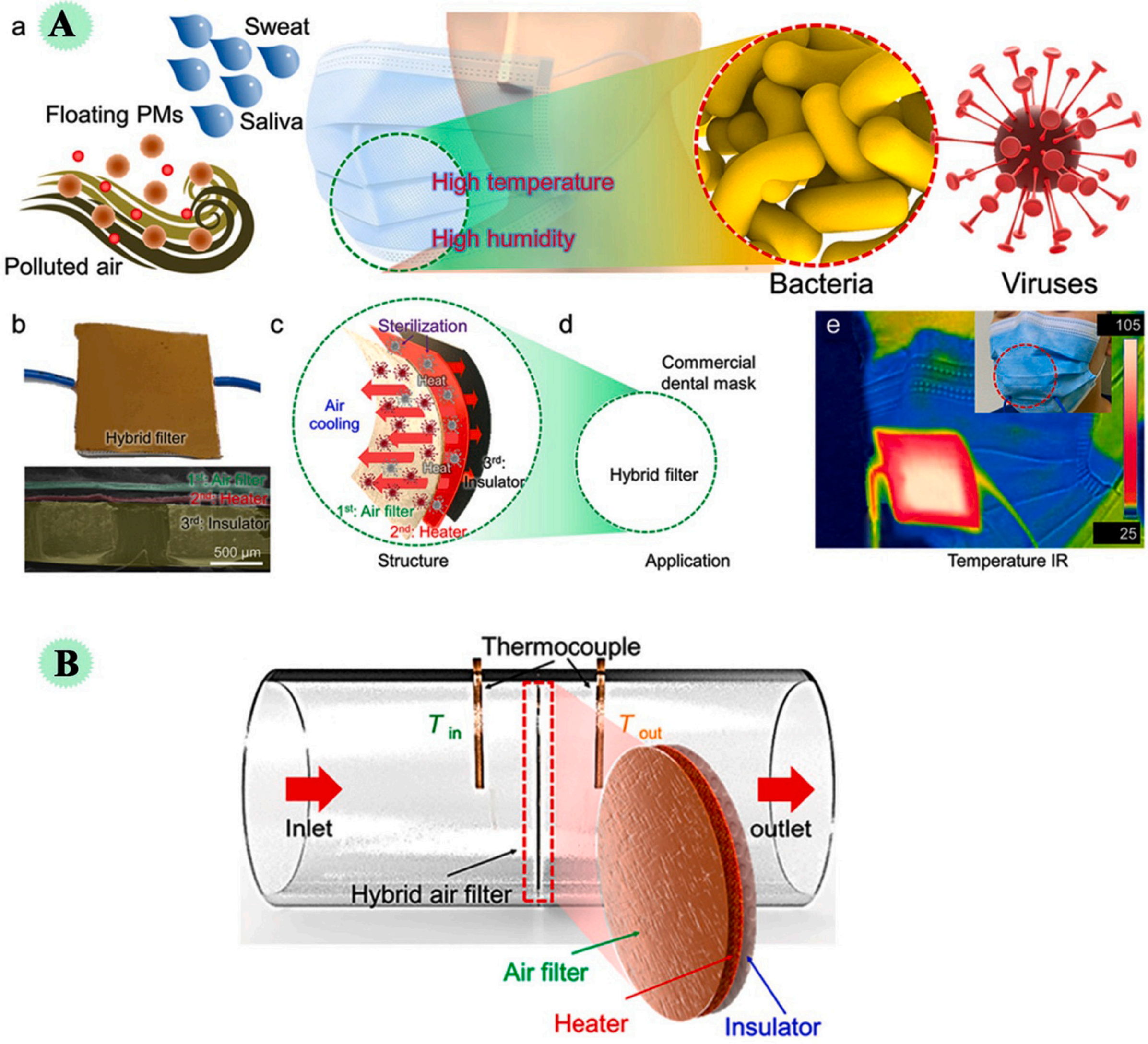

Fig. 10. (a) Schematic of the existing facemask that is not only exposed to PMs in air but also to bacteria and viruses from the saliva and sweat of humans. (b) Photograph and a cross-sectional SEM image of the hybrid air filter. Illustrations of (c) the multilayered structure of hybrid air filter composed of the air filtration, heating, and thermal insulation layers, and (d) the hybrid air filter that is installed inside of a commercial facemask. (e) Infrared image of the facemask equipped with the hybrid air filter, where the voltage of 3 V was applied to the thermal heating layer. The inset photograph is a real snapshot (Reprinted with permission from [44], Copyright 2021 American Chemical Society.

membranes and DNA. In 2021 for killing airborne microorganisms, Heo et al. introduced water-repellent visible-light activated antimicrobial nanostructure as an antimicrobial air filter. In this process, for preparation of 3D nanostructures, TiO_2, organic dye CV (crystal violet as visible-light sensitizer), and hydrophobic molecule PFOTES (1H,1H,2H,2H-perfluorooctyltriethoxysilane) were used for facilitating abandoned visible light from sunlight or indoor lights. The fabrication process of TiO_2@PFOTES-CV can be observed in Fig. 7a, in which PFOTES was bonded (covalently attachment) to TiO_2 nanoparticles, then, by incorporation of CV, the photocatalytic reaction of TiO_2 was enhanced to light. After that, TiO_2@PFOTES-CV was covered on fibers by a simple aerosol deposition process. Visible-light activated antimicrobial air filter was organized by aerosol deposition process by TiO_2@PFOTES-CV nanoparticles (Fig. 7b). Based on Fig. 7c, with flowing photoexcited electrons from CV to TiO_2, redox reaction (type I) was placed and ROS (O^{2-}, H_2O_2, and •OH) were produced. Also, CV molecules induced the generation of $^1O_2$ through energy transfer (type II). These active species from synergistic effects between TiO_2-CV cause the death of microorganisms. The fabricated antimicrobial air filters showed an effective inactivation rate against several bioaerosols (~99.98%) with ~99.9% filtration efficiency. Besides, the fabricated filter exhibited humidity resistance because of the hydrophobic barrier by PFOTES, showed potential usage of it in real environments for example damp, exhaled air, as well as rain [40].

2.3. Cu/CuO

Cu/CuO-based materials with great features including antibacterial and anti-viral features [41,42] are good candidates for the fabrication of efficient antimicrobial air filters. Also, Bioaerosols of infectious pollutants threaten human general health. In particular, the indoor environment provides the conditions for the transmission of viruses such as SARS-CoV-2 through the air. To prevent the spread of infection, indoor air purifiers or the use of masks with appropriate filters are essential. Since conventional filters can be contaminated by bioaerosols, better filter systems and self-sterilizing are needed. In 2021, Choi et al. prepared nano-coating by using laponite and Cu^{2+} ions in order to trap the proteinaceous pathogens and antibacterial influence and coated on

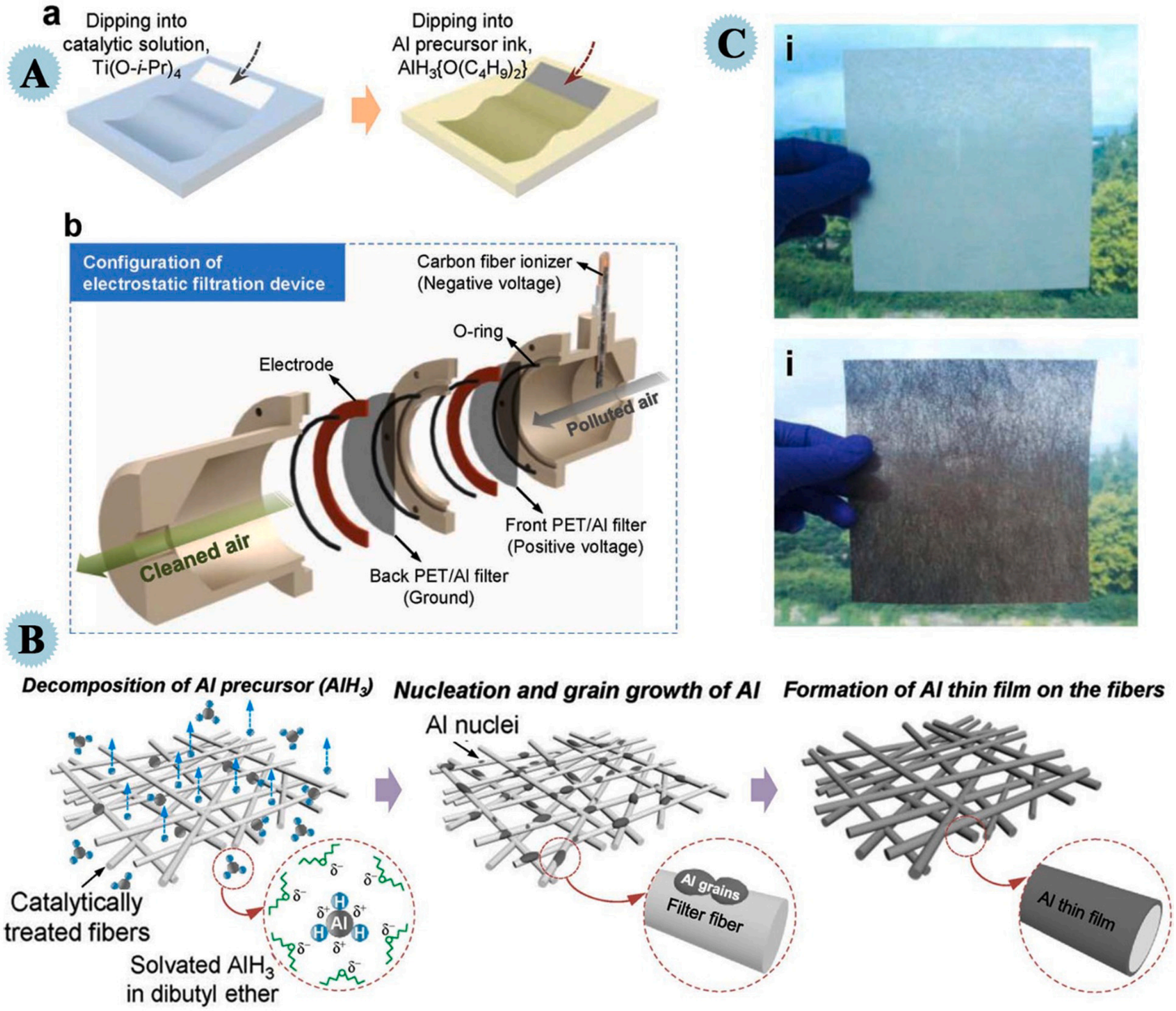

Fig. 11. A: (a) Diagram of the chemical solution process for conductive polyester/aluminum (PET/Al) filter fabrication. (b) Configuration of the electrostatic filtration device composed of a carbon fiber ionizer and two PET/Al filters. Electric fields are formed between the front filter and the ionizer as well as the back filter and the front filter. Inflowing particles are negatively charged by the ionizer, and are captured by Coulomb forces toward the front PET/Al filter. B: Schematic illustration of the formation mechanism of Al thin films on the filter fibers. C: Photograph of a 15 cm × 15 cm raw PET filter and Photograph of a 15 cm × 15 cm PET/Al filter (Reprinted with permission from [49], Copyright 2018 Elsevier).

fabric by layer-by-layer assembly method for effective air filtration [43]. Because of the robust interaction of laponite-protein, spike protein, as well as albumin, is trapped into the fabric. The blocking performance of the fabric coated with this nano-coating was about 10 times higher than that of ordinary fabric. Also, after using and washing, the function of this filter is maintained so it had reproducibility and stability. This coating also demonstrates strong antibacterial performance toward *S. aureus* and *P. aeruginosa* pathogens due to Cu^{2+} ions, which can be a suitable alternative to the air purifier and masks during the COVID-19 epidemic. The laponite-Cu^{2+} fabric showed 2 paradoxical “Spear and Shield” influences and decontaminated air (Fig. 8).

Based on Fig. 9a, negatively charged laponite was deposited on the fibers as nano-coating with positively charged poly(diallyldimethylammonium chloride) through electrostatic contact. Owing to the laponite and Cu$^{2+,}$ the two functions are adsorption onto laponite (Spear) and killing bacteria by Cu^{2+} ions (Shield). Also, Fig. 9b shows a protein-containing aerosol nebulizer system applied for the measurement of the protein-trapping efficacy of fabric. So, this self-sterilized nano-coating is good for fighting viral pandemics.

Recently, for preventing the spread of infection by bacteria/viruses and lethal diseases, nano-fiber-based filters have been broadly examined due to high strength, physicochemical stability, uniform distribution of fibers, and proper morphology. At present (outbreaks of COVID-19), particulate matter and airborne pollutants pose severe health risks. So, for anti-viral/antibacterial protections, Kim et al. developed a reusable hybrid air filter including three layers: air filtration, heating, and thermal insulation layers [44]. By electrospinning (house-made electrospinning setup) of polyacrylonitrile, an air filtration layer was prepared. The heating layer was prepared by using a Cu-electroplated microfiber mat owing to its ability to generate high-temperature heat. The thermal insulation layer was fabricated by Teflon mesh for preventing the direct transformation of heat from the heating layer to human skin or other contact surfaces. Studies have shown that the coronavirus is disabled by heat, so filters that can withstand temperatures above 100 °C are considered. As shown in Fig. 10A, the face masks are exposed to viruses and bacteria. Also, the three-layer filter prepared in this study can be seen in this figure. In the prepared filter, the air filtration layer captured bacteria, viruses, and airborne particulate matter particles (less than 1.0 μm). The heating layer with approximately 150 °C heat sterilized and eradicated the viruses and bacteria. And Teflon layer prevented direct transferring heat to the human skin. Fig. 10B shows cylindrical filtration setup by the resulted filter, in which Tin and Tout are front and back

Table 1
The performance of metals, metallic oxide, and metal ions for fabrication of antimicrobial air filters.

Ref	Results	Microorganism or pollutant	Materials
[25]	The fabricated membrane showed low-pressure drop (31 Pa), high (99.99%) filtration efficacy, and great performance for removal of multiple aerosol pollutants.	*E. coli* and *S. aureus*	Polyamide6/ polypropylene/Ag
[26]	Strong virucidal activity against FluVA and RSV	FluVA (influenza virus type A), RSV (respiratory syncytial virus), as well as HRV (human rhinovirus)	Ag nano-clusters/SiO_2 hybrid
[27]	The fabricated filter removed >93% of airborne MS2 particles and proficiently deactivated >95% of the MS2 in 20 min.	MS2 bacteriophage	Nano-Ag/TiO_2-chitosan
[28]	With increasing SiO_2/Ag coating levels, the pressure drop, filtration efficacy, as well as anti-viral effectiveness were increased.	MS2 bacteriophage	SiO_2/Ag
[31]	~92% anti-viral efficiency	aerosolized MS2 virus	SiO_2-Ag
[32]	Great removal efficiency (99.30%)	Particulate matter 0.3	Zein nanofibers-Ag@paper towel
[33]	Performance toward *E. coli* (99.10%) as well as *S. aureus* (99.62%)	*E. coli* and *S. aureus*	Keratin/Ag
[34]	The filtration efficiencies for the prepared composite filter for particulate matters 2.5 and particulate matter 10 were 99.7% and 99.8%, respectively	Particulate matters 2.5 and 10	Bacterial cellulose/Ag
[35]	The fabricated filter displayed 99.6% and 100% bacteria reductions toward *S. aureus* and *E. coli*, respectively.	*S. aureus* and *E. coli*	Poly(vinyl alcohol)/Ag electrospun nano-fibers
[36]	99.64 and 98.75% of *Escherichia coli* and *Staphylococcus aureus* were killed	*Escherichia coli and Staphylococcus aureus*	Ag/Zn@cotton fabric
[38]	The fabricated anti-viral face masks based on TiO_2 with easily sterilizable and reusable features (more than 1000 times) can provide a strong prevention device against the SARS-CoV-2	Corona and Ebola viruses	TiO_2 nanowire-based filter papers
[39]	High filtration efficiency, and reduced *S. aureus* bacteria	*S. aureus*	TiO_2/chitosan/poly (vinyl alcohol)
[40]	The fabricated antimicrobial air filters showed an effective inactivation rate against several bioaerosols (~99.98%) with ~99.9% filtration efficiency	Diverse microorganisms	TiO_2@PFOTES-CV
[43]	The blocking performance of the fabric coated with this nano-coat was about 10 times higher than that of ordinary fabric	*S. aureus* and *P. aeruginosa* pathogens	Laponite and Cu^{2+} ions
[44]	The heating layer with approximately 150 °C heat sterilized and eradicated the viruses and bacteria.	Bacteria/viruses	Polyacrylonitrile/ Cu
[45]	>75% decrease in virus amount	SARS-CoV-2	Cu thin on polypropylene filter
[46]	It showed excellent antimicrobial feature	*E. coli*, and *B. subtilis.*	Polyacrylonitrile/CuO
[47]	Superior efficiency of air-filtration performance was >99.99%	*E. coli* and *B. subtilis*	Poly(vinyl alcohol), konjac glucomannan, and ZnO nanoparticles
[48]	High filtration efficiency	*S. aureus* and *E. coli*	Polyacrylonitrile/ ZnO nanoparticles
[49]	High-efficiency rate (~99.99%) were captured on the fabricated filter	*E. coli* and *S. epidermidis*	Al nano-grains on the polyester fibers

temperatures. The outcomes showed great potential for anti-viral protection.

In another study, for preparation filter face mask with SARS-CoV-2 anti-viral capability, Jung et al. [45] deposited Cu thin film (20 nm) on polypropylene filter surrounding a KF94 face mask via vacuum coating process for trapping bioaerosols and preventing secondary transmission. The adhesion of Cu thin film on fibers surface was enhanced by oxygen ion beam pretreatment, so Cu_2O and CuO were formed on fiber without deformation in construction. The filtration efficiency of coated mask for paraffin oil and NaCl particles was 91.6 ± 0.83% and 95.1 ± 1.32%, respectively. The anti-viral performance of the Cu-coated filters was examined via exposing Vero cells to the mask surface after 1 h of contact with the SARS-CoV-2 virus. The SARS-CoV-2 nucleocapsid immunofluorescence outcomes and Real-time PCR showed a decrease (>75%) in virus amount.

In another work, CuO nanoparticles were chosen as an antibacterial agent for antimicrobial breath mask uses [46]. Via electrospinning process, polyacrylonitrile/CuO nano-fibers were prepared. Morphological examinations showed the uniform dispersion of CuO. Besides, after the addition of 1.00% CuO nanoparticles, tensile strength and antimicrobial activity significantly improved. Based on the breathability test results, the air permeability of nano-fibers was enhanced via adding CuO. The achieved results such as good mechanical, structural, antimicrobial, and thermal properties, air permeability, and breathability showed the significant potential of polyacrylonitrile/CuO for antimicrobial breath masks.

2.4. ZnO nanoparticles

For efficient air filtration, Lv et al. prepared nano-fiber membranes based on poly(vinyl alcohol), konjac glucomannan, and ZnO nanoparticles as bio-compatible and bio-degradable materials via green electrospinning as well as thermal crosslinking. Konjac glucomannan is a polysaccharide with good physical and chemical features like respectable water absorption ability, bioactivity, and film-forming behavior. On the other side, ZnO is a bio-compatible metal oxide with

Table 2
The role of carbon-based nanomaterials for fabrication of effective air filters.

Ref	Results	Microorganism or pollutant	Materials
[52]	The presence of Ag nanoparticles and graphene oxide fillers improved the bactericidal properties, adsorptive as well as mechanical stability.	*S. aureus* and *E. coli*	Graphene oxide/Ag nanoparticles/ polyacrylonitrile
[53]	After exposing the polyacrylonitrile/ graphene oxide filter in a medium with ~460 μg m-3 concentration of particulate matter 2.5, removal efficiency was 99.6%. After 100 h, the removal efficiency maintained 99.1%, which showed exceptional sorption ability and long-term stability.	Particulate matter 2.5	Polyacrylonitrile and graphene oxide
[54]	The prepared air filter membrane exposed brilliant mechanical strength, significant thermal stability (300 °C), high (99.5%) filtration efficacy, and low (92 Pa) pressure drop.	Particulate matter 2.5	Polyacrylonitrile/ graphene oxide/ polyimide
[55]	Great self-sterilization performance	Bacteria, microorganisms, and aerosols	Laser-induced graphene
[56]	Resultant filter disclosed improved antimicrobial performance and protection	Airborne pathogens	Ultra-thin graphene oxide /polydopamine hybrid on polypropylene surface
[57]	98.2% filtration efficiency	SARS-CoV-2	Functionalized graphene
[58]	Improved filtration effectiveness and antimicrobial performance	*S. epidermidis and E. coli*	Ag-coated CNT nano-hybrid
[59]	Enhanced specific surface area, improved filtration efficiency by 0.64% and high air permeability	Virus	Multi-walled CNTs and phenol-formaldehyde in cellulose fibers
[60]	The prepared air filter showed 99.999% filtration efficiency, while low-pressure drop was maintained	Virus	CNT on porous polyester

antibacterial and photocatalytic actions for air filtration. In this study, thermal crosslinking considerably enhanced the mechanical features as well as water resistance. ZnO improved the filtration efficiency endowed the fabricated membrane with antibacterial and photocatalytic actions. Achieved nano-fibrous membranes showed effectual air-filtration performance (efficiency was superior, >99.99%) and antibacterial activity against *E. coli* and *B. subtilis* [47].

For generating nano-fiber-based filters, electrospinning is a developing technology. Compared to the conventional filters, these nanofibrous materials show important morphological benefits like small pore size, nano-scale fiber, great surface area, as well as respectable mechanical features. In a recent study, via electrospinning process, antimicrobial polyacrylonitrile nano-fibers, as efficient aerosol filtration materials to employ in respirators were developed by Pardo-Figuerez et al. These nano-fibers were deposited on spun-bond polypropylene. ZnO nanoparticles were incorporated in nano-fibers in the form of the nanocomposite. ZnO was well distributed in the fibers did not reduce filtration proficiency, and improved the breathing resistance. High filtration efficiency was observed for the fabricated antimicrobial nanofilters. These filters showed the potential for use in personal protective equipment (masks) [48].

2.5. Al nanoparticles

In order to high effectiveness in capturing and inactivation of airborne microorganisms, simultaneously, Choi et al. introduced a reusable bi-functional polyethylene terephthalate/aluminum air filter. Microorganisms (*E. coli* and *Staphylococcus epidermidis*) with a high-efficiency rate (~99.99%) were captured on the fabricated filter through the electrostatic attractions with no losing pressure drop. After growing Al nano-grains on the polyester fibers, antimicrobial performance toward airborne bacterial bioaerosols enhanced (*E. coli* ~94.8% and *S. epidermidis*~96.9%) because of the surface roughness as well as reinforced hydrophobicity of the resulted filter. In addition, the antimicrobial and capturing behaviors were maintained after washing, which showed the reusability. For the preparation of poly(ethylene terephthalate)/aluminum air filter, a non-woven filter of polyester was applied as a backbone membrane. Chemical solution procedure was two-step: 1: by using ($Ti(Oi\text{-}Pr)_4$), catalytic treatment of poly(ethylene terephthalate) was performed 2: treated filter was immersed into $AlH_3\{O(C_4H_9)_2\}$ as Al precursor ink, so, conductive Al layers were created on the filter at ambient temperature. The poly(ethylene terephthalate)/aluminum air filter showed excessive potential to employ in energy-efficient systems for bioaerosol control in indoor locations. Air-cleaning devices were prepared in this study, which can be observed in Fig. 11A. A carbon fiber ionizer was placed in a device to charge bioaerosols along with 2 conductive filters of poly(ethylene terephthalate)/aluminum for capturing microorganisms. Also, Photographs of pure poly(ethylene terephthalate) and poly(ethylene terephthalate)/aluminum air filters are shown in this fig. [49].

We have provided an overview of the utilization of metal/metal oxide-based materials with antimicrobial behavior for designing efficient air filters to capture and kill microorganisms. As summarized in Table 1, metals like Ag, Al, and metal oxides such as CuO, ZnO, TiO_2 have been shown an important role in this regard. These materials are good candidates for developing anti-viral filters to control the COVID-19 pandemic.

3. The role of carbon-based nanomaterials for fabrication of effective air filters

Carbon-based nanomaterials such as graphene oxide and carbon nanotubes (CNTs) with great features like unique construction, outstanding mechanical/chemical stability, and antimicrobial performance [50,51] have been employed broadly in fabrication air filters which Table 2 shows many of them. The following are some of their applications in this regard.

3.1. Graphene-based materials

In a recent investigation, graphene oxide/Ag nanoparticles were impregnated into polyacrylonitrile nano-fibers to develop antibacterial air filters for the removal of airborne pollutants including microbes, aerosols, as well as particulate matters. For this aim, graphene oxide was ultrasonicated in dimethylformamide, for breaking the larger sheets of graphene oxide, then, $AgNO_3$ was added and mixed polyacrylonitrile/ dimethylformamide solution. $AgNO_3$ was reduced to Ag using dimethylformamide reducing agent. Finally, using the electrospinning process (10–16 kV and flow rate at 0.45 mL/h), nano-fibers were prepared and collected on a metallic collector, and a composite nano-fibrous membrane was fabricated with improved bactericidal and thermal

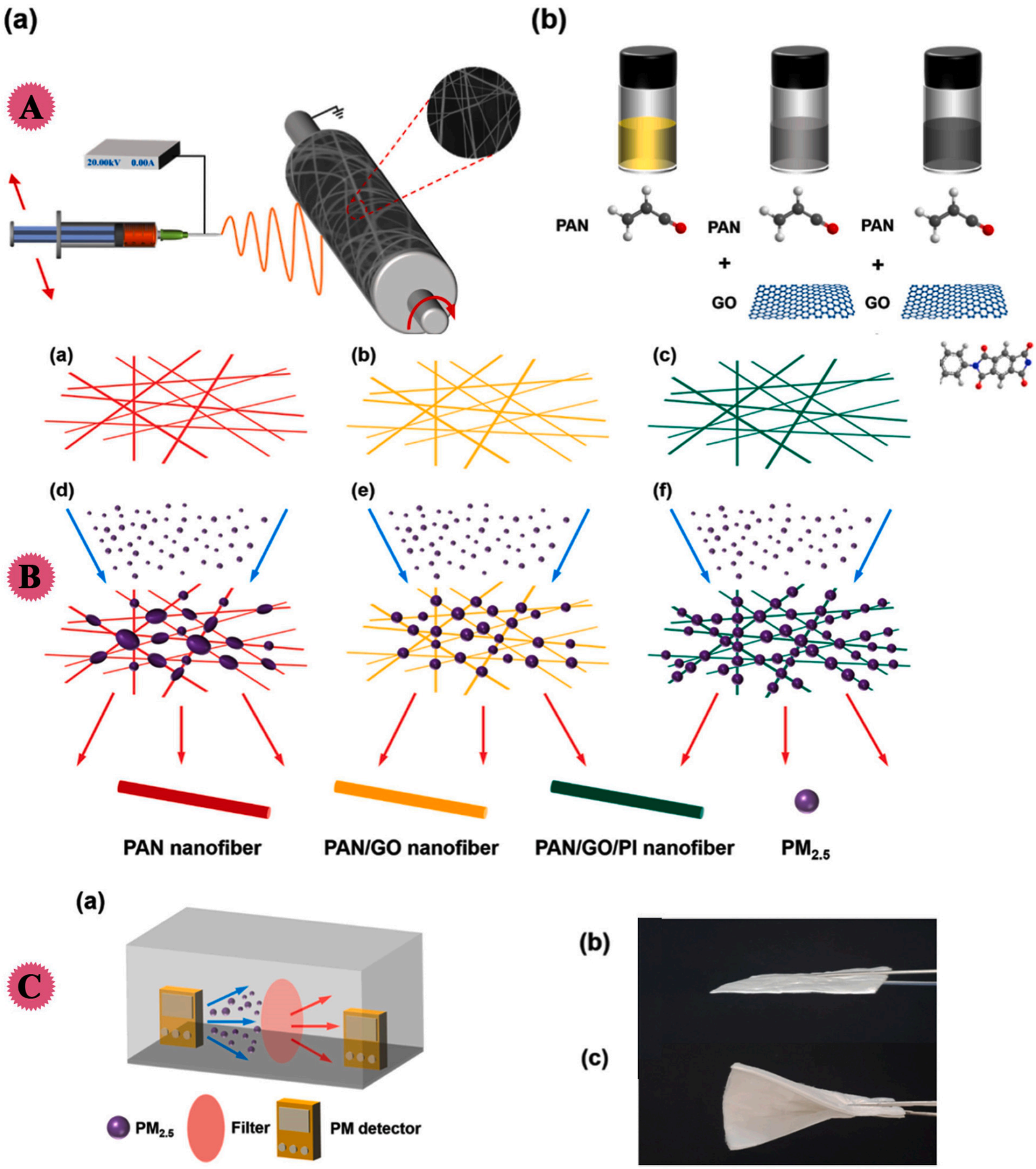

Fig. 12. A: (a) Fabrication process of electrospinning nanofibers. (b) Components of electrospinning solutions B: Illustration of nanofibers before and after adsorption of (a and d) PAN nanofibers, (b and e) PAN/GO nanofibers, and (c and f) PAN/GO/PI-6 nanofibers, . C: (a) Schematic diagram of the equipment in the purification process and demonstration of the rigidity of the PAN/GO/PI nanofibrous membranes. (b,c) Demonstration of the flexibility of the PAN/GO/PI nanofibrous membranes (Reprinted with permission from [54], Copyright 2021 Elsevier).

features and developed surface chemistry. The filtration performance of the fabricated air filter was studied by a filtration setup employing cigarette smoke and incense stick. Antibacterial behavior was tested toward *E. coli* and *S. aureus* and the outcomes from disc diffusion assay showed efficient bactericidal performance toward bacterial strains (~19 and ~18 mm inhibition zone for *S. aureus* and *E. coli*). The presence of Ag nanoparticles and graphene oxide fillers improved the bactericidal properties, adsorptive as well as mechanical stability. The prepared antimicrobial air filter could be utilized as an anti-pollutant commercial mask for remediation of airborne pollutants in hospitals or industries [52].

In order to provide air filters with high stability and efficiency as well as low cost, Zhang et al. introduced novel nano-fibers by using polyacrylonitrile and graphene oxide for capturing particulate matter 2.5 (particles with an aerodynamic diameter < 2.5 μm, which is hazardous to human health) pollutants. These airborne pollutants have a large surface area and can load with pathogenic materials and imperil universal health. Indeed, graphene oxide-containing membranes have been revealed the enhanced adsorption rate for particulate matter 2.5, adsorption stability, and adsorption capacity. In this study, through

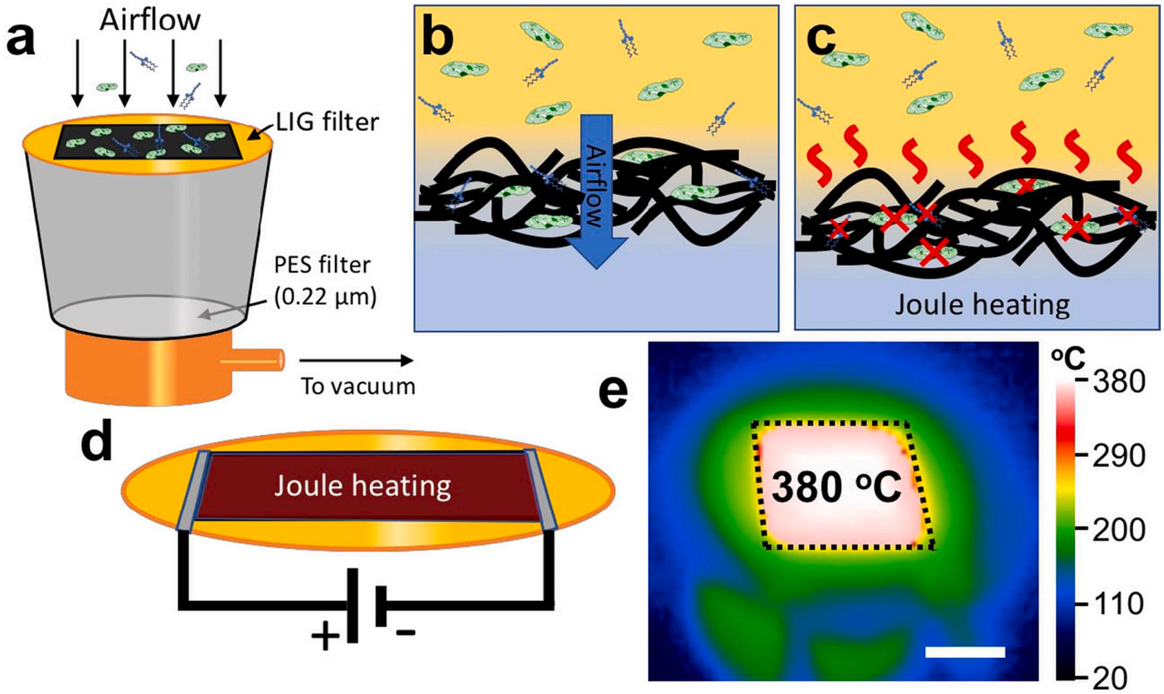

Fig. 13. Schematic of bacteria capture, along with subsequent sterilization and depyrogenation by Joule-heating. (a) Schematic of air filtration with the LIG filter mounted on a vacuum filtration system with a backing PES test filter. Bacteria and endotoxins are suggested by the picture. (b) Schematic of filtration followed by (c), sterilization and depyrogenation through Joule-heating. (d) Schematic of the Joule-heating setup in which a potential is applied across the filter for Jouleheating. (e) Infrared image of a LIG filter that is Joule-heated to 380 °**C**. The scalebar is 2 cm. The shape of the LIG filter is denoted by black dotted lines (Reprinted with permission from [55], Copyright 2019 American Chemical Society).

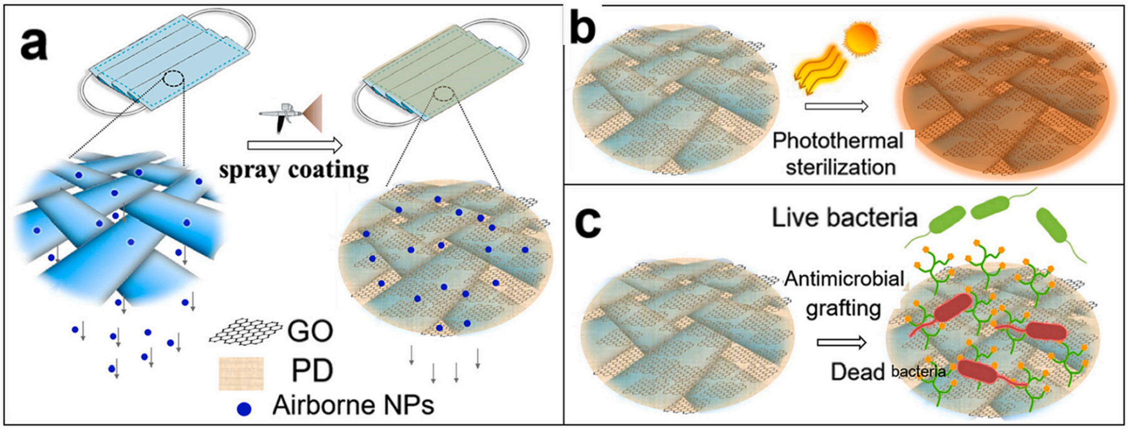

Fig. 14. Schematic of the ultrathin hybrid coating and its functionalities. (a) One-step spray-coating process of the GO-PD coating on filters or masks. The blue dots represent airborne nanoparticles. (b) Sterilization by light irradiation is achieved due to the photothermal effect of GO. (c) The ultrathin hybrid coating has enhanced antimicrobial property after grafting cationic polymer brushes (Reprinted with permission from [56], Copyright 2021 American Chemical Society). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

modest and versatile electrospinning techniques, nano-fibers were manufactured. The prepared filter showed high efficiency and capacity for adsorption and outstanding long-term elimination effectiveness for particulate matter 2.5. After exposing the polyacrylonitrile/graphene oxide filter in a medium with ~460 µg m-3 concentration of particulate matter 2.5, the removal efficiency was 99.6%. After 100 h, the removal efficiency maintained 99.1%, which showed exceptional sorption ability and long-term stability. As a result, the fabricated filter has the potential for preparation in large-scale production for using in air filtration media like masks for individuals. These filters can apply as window screens to remove particulate matter2.5 from outdoor and existing indoor and produce cleaner air [53].

In a similar study, an air filter membrane was developed using polyacrylonitrile/graphene oxide/polyimide by electrospinning process for high-efficiency capturing of particulate matter 2.5 (Fig. 12A). The prepared air filter membrane exposed brilliant mechanical strength, significant thermal stability (300 °C), high (99.5%) filtration efficacy, and low (92 Pa) pressure drop. These great performances are attributed to interactions of particulate matter 2.5 particles and nano-fibrous filters. Also, thermal stability was due to the unique molecular construction of polyimide components. Fig. 12B shows the filtration mechanism by three nano-fibers (polyacrylonitrile, polyacrylonitrile/graphene oxide, and polyacrylonitrile/graphene oxide/polyimide) which show diverse adsorption effects. Many factors are effective for filtration:

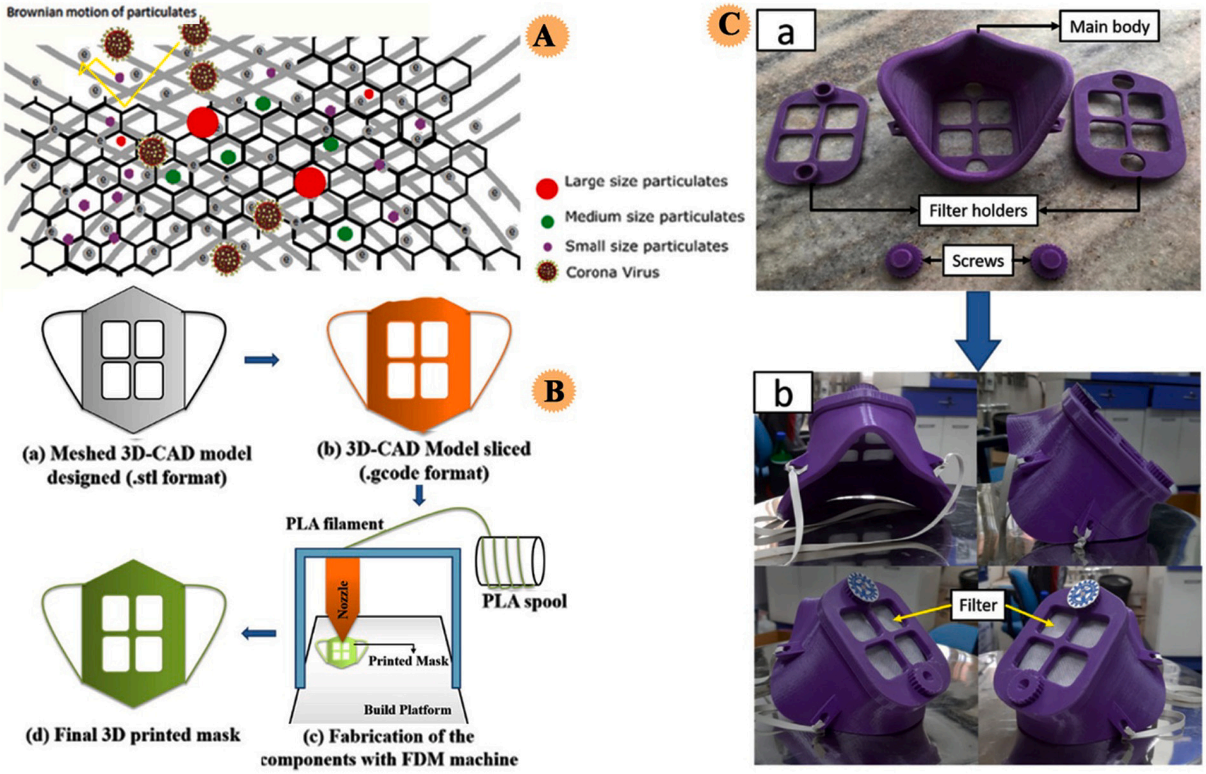

Fig. 15. A: Interaction of airborne virions and pollutant particulates with the electrostatically charged fibers of a graphene mask, B: A schematic representation for a) 3D-CAD model, b) slicing into g-code, c) 3D printer setup, and d) 3D printed mask prototype.C: Assembly of a 3D printed mask: a) various parts of 3D printed mask prototype and b) fabricated 3D printed mask with fG coated filters (Reprinted with permission from [57], Copyright 2021 Elsevier).

electrostatic adsorption, size screening, brownian diffusion, inertial impact, and gravity sinking. In polyacrylonitrile nano-fibers, pollutant particles (particulate matter 2.5 particles) accumulate asymmetrically in the nano-fibers and a small amount of them is seen in the middle of them (ellipsoid shape). Nitrile groups interact with polar functional groups of particles and adsorption takes place. In the polyacrylonitrile/graphene oxide, the particles are absorbed uniformly along the nano-fibers (spherical shape). And in the polyacrylonitrile/graphene oxide/polyimide, this absorption is even more uniform. This process is due to the addition of graphene oxide, which provides more hydrophilic groups to the fibers. These hydrophilic groups help absorb more moisture in the airflow (pollutant particles are usually liquid or solid aerosols). Moreover, polyimide also increases the adhesion of particles to the surface of the nano-fibers due to the large dipole moment (6.2D). To study the filtration efficiency, an adsorption device was used for capturing test. Based on Fig. 12C, through burning incense, particulate matter 2.5 particles were generated. By using a detector, the concentration difference of particles on both sides of the device was measured. Based on the outcomes, adsorption speed and filtration efficiency for polyacrylonitrile/graphene oxide/polyimide were higher than polyacrylonitrile, and polyacrylonitrile/graphene oxide fibers [54].

Infections in hospitals can be transmitted through airborne, droplet, aerosol, which is dangerous for employees and patients. So, in another study, a self-sterilizing filter based on laser-induced graphene was prepared to capture bacteria, microorganisms, and aerosols. Through a CO_2 laser cutter and photo-thermal conversion of a polyimide film, porous conductive graphene foam was made. The prepared filter showed electrical conductivity, which was suitable to be Joule-heated through electrical power dissipation. Via periodic Joule-heating mechanism, the captured microorganisms are annihilated using this thermally-stable filter (T: >300 °C). Porous graphene construction of laser-induced graphene with high (340 m^2g^{-1}) surface area as well as thermal stability provided suitable conditions for the capture and elimination of microorganisms. Fig. 13 displays the self-sterilization performance of the laser-induced graphene-based filter. This filter overcame the drawbacks of traditional ventilation and air conditioning filters [55].

The non-woven polypropylene filter shows restrictions in filtration effectiveness for uses as protective masks against airborne nanoparticles. Kasbe et al. proposed a simple, efficient, as well as inexpensive technique for functionalization of the polypropylene air filter with antimicrobial/photo-thermal features (Fig. 14). In this process, via spray-coating process, ultra-thin graphene oxide (2D layered materials)/polydopamine (bioadhesive polymer) hybrid coating was covered on polypropylene surface. The synergism in graphene oxide/polydopamine hybrid coating developed the filtration effectiveness of polypropylene filter by 20% (with minimal pressure drop). Besides, covering graphene oxide/polydopamine improved the negative charges (surface charges) and hydrophobicity for improving the performance of the filter. The photo-thermal feature of graphene oxide allowed a rapid increase in temperature of the filter by light irradiation to sterilize, easily. In addition, via chemically grafting of the hybrid surface with cationic polymer brushes, the resultant filter disclosed improved antimicrobial performance and protection toward airborne pathogens [56].

In 2021, Goswami et al. reported a simplistic development of an air filter based on graphene for the preparation 3D-printed mask for COVID-19 (Fig. 15B, C). In fact, functionalized graphene or derivatives are good candidates for air filters and modifying N95 masks owing to exceptional physicochemical features, antimicrobial and anti-viral properties, biocompatibility, and high surface-to-volume ratios (Fig. 15A). In addition, functionalized graphene with nano-sheet construction and negative charge provide anti-viral performance for the inactivation of the virus. COVID-19 virions have a positive charge; hence functionalized graphene (negatively charged) can interact with it through redox reaction, —H bonding, and electrostatic interactions. Then, the adsorbed virus on the functionalized graphene can be washed off. The fabricated anti-viral filter showed 98.2% filtration efficiency (and breathing

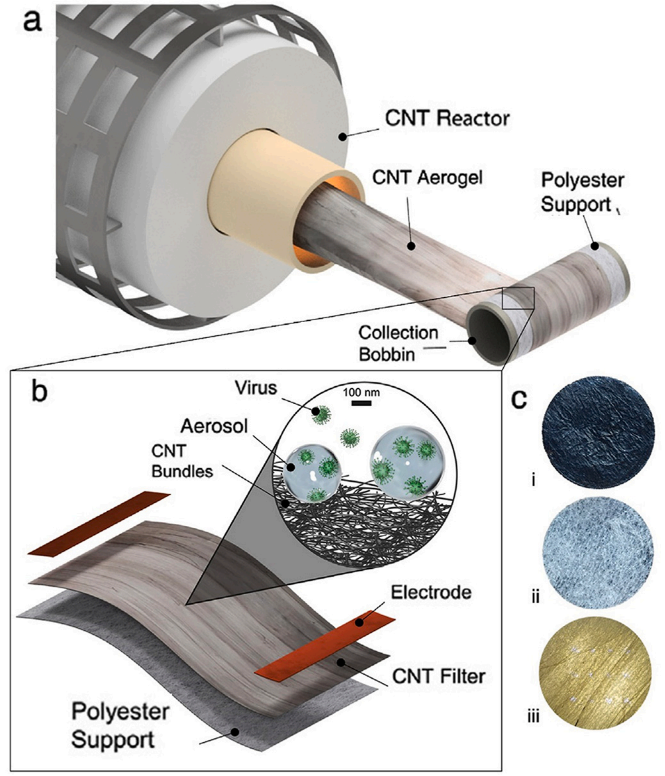

Fig. 16. The hybrid CNT filter. (a) The adapted direct spinning method using a collection bobbin covered with the polyester backing for the in-situ production of the CNT hybrid filter material. (b) An illustration showing the concept of the active hybrid CNT filter. The CNT filter can retain SARS-CoV-2 virions and aerosols containing them. The hybrid can be actively sterilized via resistive heating enabled by applying a potential between two electrodes. (c) Photographs showing (i) The upper layer of the hybrid that is made from a micrometer thin non-woven CNT mat. (ii) The lower layer is made from a porous polyester backing. (iii) The fine structure of the hybrid as revealed by a backlight (Reprinted with permission from [60], Copyright 2021 Elsevier).

resistance was 1.10 bar). The role of functionalized graphene-covered filters toward SARS-CoV-2 has many mechanisms including sharp-edge insertion (sharp edges of graphene physically damage the membrane of virus), cell entrapment, and oxidative stress (because of the imbalance of oxidation/antioxidation, graphene nano-sheets interfere with virus metabolism) [57].

3.2. CNTs-based materials

As mentioned before, for improving the quality of indoor air and providing public human health, antimicrobial air filtration has attracted broad consideration. Filters that do not have antimicrobial properties can improve air quality but, after a while, these filters generate a source of infection due to the deposition of microorganisms on the surface of the filters. Antimicrobial filters are very useful and inactivate microorganisms and minimize their number. Inorganic metals like Ag nanoparticles are widely used in the preparation of antimicrobial filters due to their performance against bacteria, fungi, and viruses. On the other side, CNTs with great features like mechanical and chemical stability, unique structure, and antibacterial ability are often interfaced with inorganic solids for preparation composites including mechanical, electrical, and optical features. In an investigation by Jung and coworkers, Ag-coated CNT nano-hybrid was prepared by aerosol nebulization and thermal evaporation/condensation processes [58]. The performance of this fabricated composite was examined for antimicrobial air filtration. The outcomes showed strong adhesion and homogeneous dispersion of Ag nanoparticles (<20 nm) to the surfaces of CNT. For antimicrobial filtration uses, the prepared hybrid (Ag/CNT) was put on the air filter's surface. After deposition of Ag/CNT on the air filter's surface, the antimicrobial performance of the filter toward bacterial bioaerosols was enhanced compared to deposition of Ag or CNT alone on the filter. CNTs enhanced the surface area of nano-Ag particles. Therefore, the filtration effectiveness of hybrid (Ag/CNTs) was higher than Ag-based filters. The antimicrobial performance (relative microbial viabilities) of hybrid-based filters against *S. epidermidis* and *E. coli* was ~32 and 13%, which was higher than Ag and CNTs.

Sun et al. designed antibacterial air filter paper with high filtration efficiency by using impregnation of antibacterial multi-walled CNTs (optimal concentration: 0.1%) and phenol-formaldehyde in cellulose fibers [59]. The outcomes showed the presence of CNTs on the surface and among the pores of fibers, so, the specific surface area of fibers was enhanced and the filtration efficiency improved by 0.64% and high air permeability was exhibited. Moreover, after the addition of phenol-formaldehyde, the mechanical features of the air filter were meaningfully improved. Considering the outcomes, the prepared air filter showed good potential for diverse applications.

A primary route of transmission of respiratory disease is exposure to virus-containing particles and droplets. Removal of these droplets is effective through anti-viral filtration. CNTs with the nano-sized structure are good candidates for the preparation of nano-fiber filters. Recently, an anti-viral air filter has been developed with the help of CNTs, which is mechanically supported by porous polyester (with ~100 mm sized holes) for enhancement the structural stability and filtration efficiency. For this aim, by a continuous facile procedure, CNT aerogels were spun on the support, and a bilayered hybrid is formed, as shown in Fig. 16: a thin CNT membrane on porous polyester with 0.4 mm thick. The prepared air filter showed 99.999% filtration efficiency (in 10 min at 26 air changes per hour), while a low-pressure drop was maintained. This air filter with electrically conductive feature could be flash heated to 130 °C in many seconds for complete inactivation of viral on filter surfaces such as betacoronavirus [60].

4. The role of biopolymers and other natural materials in the fabrication of air filters

As attractive alternatives to conventional synthetic materials, biopolymers including chitosan, alginate, soy, have been used for filtration applications comprising air filters for hospitals, homes, and cars (Fig. 17) [21]. These materials are naturally abundant, bio-degradable, tunable functionality as well as surface chemistry, and cheap. Till now, these materials have been used for the fight against COVID-19 [61,62]. Also, other natural materials such as plants and herbal extracts with antimicrobial features are good candidates for preparation efficient air filters. Table 3 shows a summary of many uses of these natural materials in this regard, and in the following many of them are expressed.

4.1. Chitosan

In a study, a versatile and scalable air filter was effectively invented through the electrospinning method. Bi-layer filter was prepared based on electrospun superhydrophobic fibers [poly(methylmethacrylate)/polydimethylsiloxane] as moisture ingression barrier and chitosan fibers with superhydrophobic nature for capturing efficacy of over 96% particulate matter [63]. Synergism of polar functional groups and small size of chitosan fibers ceased proficiently capturing particles. Indeed, chitosan fibers improved removal capability, and poly(methylmethacrylate)/polydimethylsiloxane acted as a blocker to prevent water from accumulating. Schematics of constructing the air filters, photographs, and filtration process can be observed in Fig. 18. Also, a schematic illustration of airflow pass and mechanism adsorption/desorption of particulate matter via the prepared filters can be seen in this figure. The attained filter showed great capture efficiency for particulate

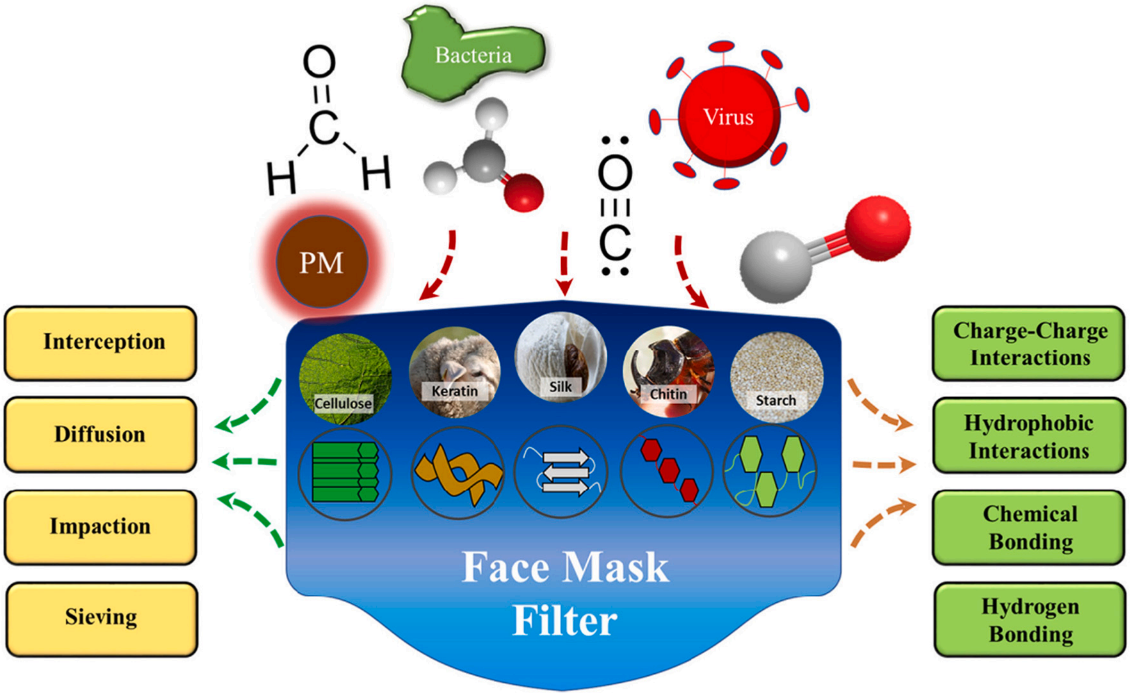

Fig. 17. Biopolymer-based filtration materials fabricated from a variety of protein and polysaccharide sources (inserted cellulose, keratin, silk, chitin, and starch photo credits: pixabay.com). These unique surface chemistries and diverse molecular interactions aid filtration of various contaminants, including particulate matter (PM), bacteria, viruses, and smoke pollutants (O—H, HCHO, and C═O) (Reprinted with permission from [21], Copyright 2021 American Chemical Society).

matters (particulate matter 2.5 > 98.0%, particulate matter10 > 98.4%), high flow rate (1.9 m s^{-1} after 1 h) a low (21 Pa) pressure drop. Furthermore, these filters with 54% optical transmittance could be employed in a hazardous environment for >100 h with maintained removal effectiveness. After five cleaning cycles, the filter showed high efficiency for the removal of particulate matter. Further, excellent antibacterial performance was observed owing to the chitosan constituent.

Zhang et al. employed chitosan and N-halamine compounds for the fabrication of multilayer structured filters with outstanding air filtration act as well as antibacterial behavior through sequential electrospinning. N-halamine is a biopolymer that was fabricated through free-radical copolymerization of ADMH (3-allyl-5,5-dimethylhydantoin) and NVF (N-Vinylformamide) [64]. Then, it was mixed with poly(vinyl alcohol) to prepare a middle layer of poly(vinyl alcohol)/P(ADMH-NVF. Poly (vinyl alcohol)/chitosan has placed on both sides of the middle layer and a multilayer network was obtained (Fig. 19). The fabricated multilayer electrospun nano-fibrous structure showed 99.3% filtration efficacy for NaCl, and 99.4% for DEHS aerosol (Diisooctyl sebacate). In addition, high tensile strength (6.1 MPa) and low-pressure drop were achieved. Outstanding antibacterial performance toward *E. coli* and *S. aureus* was observed.

Hsu et al. evaluated the inactivation ability of bioaerosols by chitosan-coated antimicrobial filters [65]. In this study, chitosan as an antimicrobial agent has coated on polypropylene fibrous filters through the liquid coating process, and the development of removal efficacy of indoor bioaerosols (tested bioaerosols: *B. subtilis* and *E. coli*) was considered. The antimicrobial performance of treated and un-treated filters was tested, and the outcomes showed a high concentration of chitosan coating had a positive effect on the removal of bioaerosols. An air-cleaning device based on chitosan-coated filters was developed and tested in a real indoor environment. In 3 h of operating, 80.1% bioaerosol was removed which showed the potential of chitosan-coated filter for use in improving indoor air quality.

Because bacteria, fungi, and other contaminants on air filters in ventilation systems or thermal insulation materials on civilian flights may re-enter into the indoor air and endanger the health of passengers, therefore, in a study by Sun et al., residues of pathogens on thermal insulation blankets used for aircraft wall coverings were examined (under mimicry conditions) [66]. In this work, the antibacterial act of positively-charged electret, as well as chitosan modified filters of ventilation systems toward *E. coli* and *B. subtilis* bacteria, was examined based on eco-friendly antibacterial filter materials. The outcomes showed a decrease in *the microorganism's* survival rate. Very effective antibacterial capacity was observed for filters based on both positive charges and chitosan. After 120 min, the survival rate on pristine nylon, nylon/chitosan, as well as chitosan dipped nylon-6 nano-fibrous filters decreased to 8.4%, 7.1%, and 2.8%. Indeed, positive charges and -NH^{3+} groups interacted with the negatively charged *microorganism* and inhibited them.

4.2. Alginate

Alginate, as a polysaccharide resultant from marine algae, is a biodegradable fully ionized polymer containing carboxylate groups that has great features [67] and so far, it has been employed for diverse applications such as preparation vaccine, and personal protective equipment for fighting COVID-19. Through the introduction of appropriate cationic constituents, the antimicrobial feature of alginate is obtained. In a study by Wang et al., the antimicrobial filter was developed

Table 3
The role of role of biopolymers and other natural materials in the fabrication of air filters.

Ref	Results	Microorganism or pollutant	Materials
[63]	(Particulate matter 2.5 > 98.0%, particulate matter10 > 98.4%), high flow rate (1.9 m s^{-1} after 1 h) a low (21 Pa) pressure drop.	Particulate matter	Chitosan/ poly (methylmethacrylate)/ polydimethylsiloxane
[64]	99.3% filtration efficacy for NaCl, and 99.4% for DEHS aerosol (Diisooctyl sebacate)	Diisooctyl sebacate aerosol	N-halamine/ poly(vinyl alcohol)/ chitosan
[65]	In 3 h of operating, 80.1% bioaerosol was removed	*B. subtilis* and *E. coli*	Chitosan/ polypropylene
[66]	After 120 min, the survival rate of microorganisms on pristine nylon, nylon/ chitosan, as well as chitosan dipped nylon-6 nano-fibrous filters decreased to 8.4%, 7.1%, and 2.8%.	*E. coli* and *B. subtilis*	Nylon/chitosan
[68]	99.69% efficiency for particulate matter 2.5 and 99.89% removal efficiency for particulate matter 10	Particulate matters	Cholinium alginate
[69]	94.92 and 96.94% inactivation	Bacteriophage phi 6 and SARS-CoV-2 Delta variant	Calcium alginate films
[70]	99.99% effectiveness toward coronavirus, with low cytotoxicity	Coronavirus	Alginate/copper sulfate
[71]	95% efficiency to capture aerosols	Aerosols	Gelatin/β–cyclodextrin
[72]	Capture effectiveness of modified HEPA filter was up to 2730 pfu/ mm^2 within 10 min.	Influenza virus	Polypropylene/ tannic acid
[73]	95% efficiency of filtration for particulate matter 0.3	Particulate matter	Soy protein isolate/ polymide-6/Ag
[74]	99.99% filtration effectiveness as well as 99.98% antimicrobial performance	*Staphylococcus epidermidisS. epidermidis bioaerosols*	Ethanolic extract of *Sophora flavescens*
[75]	Filters based on tea-tree, rosemary, and garlic extracts showed significant inactivation of *M. luteus* (99.99%, 99.0%, and 99.9% respectively).	*M. luteus* and *E. coli*	Plant extracts (rosemary, tea-tree oil, as well as garlic)
[76]	Good air filtration efficiency of 100% for particular matter 2.5 and 96.4% for particular matter 0.3 and also, the low-pressure drop was observed.	*S. aureus*	Poly(vinyl butyral)/ berberine

using alginate (cholinium alginate) for the removal of particulate matters from the air. In this study, many organic cations containing (cholinium $[Ch]^{+}$) were inserted into alginate through an ion-exchange process with sodium alginate (Na[Alg]) (Fig. 20A) [68]. After that, the alginate-based ionic polymer was loaded on melamine-formaldehyde foam, and finally, the removal performance of the filter for particulate matters (air pollution) was investigated. [Ch][Alg] exhibited very high air purification performance for particulate matters (99.69% efficiency for particulate matter 2.5 and 99.89% removal efficiency for particulate matter 10), the quality factor of 2.9, and an ultralow pressure drop (below 2 Pa). In addition, it showed exceptional antimicrobial action toward *E. coli* due to high positive electrostatic potential, and robust binding anionic bacterial cells to enable sterilization. Based on the results, [Ch][Alg]/melamine formaldehyde-based filter works better than commercial masks (Fig. 20B). This study showed an effective technique for designing important antimicrobial green materials.

Since SARS-CoV-2 Delta and omicron variants, as a great risk to global public health, are emerging, so, Cano-Vicent and co-workers studied the cytotoxicity and anti-viral action of calcium alginate films to inactivate enveloped SARS-CoV-2 [69]. The prepared biomaterial films based on calcium alginate without cytotoxic effects in human keratinocytes showed anti-viral performance against enveloped viruses including bacteriophage phi 6 and SARS-CoV-2 Delta variant with 94.92 and 96.94% inactivation, respectively. The strong anti-viral performance was related to the negative charge density of the alginate network for binding to viral envelopes inactivating membrane receptors. As depicted in Fig. 21, in contact with a viral aqueous solution, hydrophilic films of calcium alginate swell. So, viral particles interact with the negative charge of the surface or porous structure.

To prevent coronavirus transmission, the use of masks is an essential strategy. However, masks become polluted rapidly after use. In a study, Bataglioli et al. developed a textile coating for coronavirus inactivation based on alginate/copper sulfate on disposable PP masks. Many advantages of this study were employing low-cost materials, processed using modest methods to enable an easy scale-up of an efficient anti-viral coating. The prepared masks showed 99.99% effectiveness toward coronavirus, with low cytotoxicity to L929 cells [70].

4.3. Gelatin

Gelatin, as a low-cost protein biopolymer that is attained from collagen hydrolysis, showed antibacterial effectiveness (nano-fibers). Due to the surface functionality, it can absorb pollutants. β–Cyclodextrin is a cyclic oligosaccharide that has been applied for air filtration. So, Kadam et al. reported the preparation of gelatin/β–cyclodextrin composite nano-fibers (diameter ranging 130–247 nm.) using electrospinning for air filtration. The fabricated nano-fibers with 0.029/Pa quality factor and 95% efficiency captured aerosols (0.3–5 μm). Also, the adsorption of VOC on gelatin/β–cyclodextrin nano-fibers was many times greater than the commercial face masks. Furthermore, these nano-fibers showed potential for filtering nano-sized viruses [71].

4.4. Tannic acid

In another interesting study, for capturing of influenza virus and preparing of anti-viral filter, high-efficiency particulate air (HEPA) filter was developed by employing a plant-derived polyphenol. For this aim, by dipping/washing process, polypropylene HEPA filter fabric was covered with tannic acid as a hopeful molecule with anti-viral performance and as a cost-efficient adhesive for several constituents. Preparation of modified air filter for rapid and efficient virus capture and estimation of capture proficiency of HEPA filter and modified HEPA filter can be observed in Fig. 22. Pristine HEPA filter eliminated 8.9–28.5% plaques, whereas modified HEPA filter eliminated all of them [72]. By scanning electron microscopy, virus capture was seen, and tests displayed no cytotoxicity for it. Capture effectiveness of modified HEPA filter was up to 2730 pfu/mm^2 within 10 min. The outcomes confirmed the potential of anti-influenza of filters for preventing the spread of pathogenic viruses.

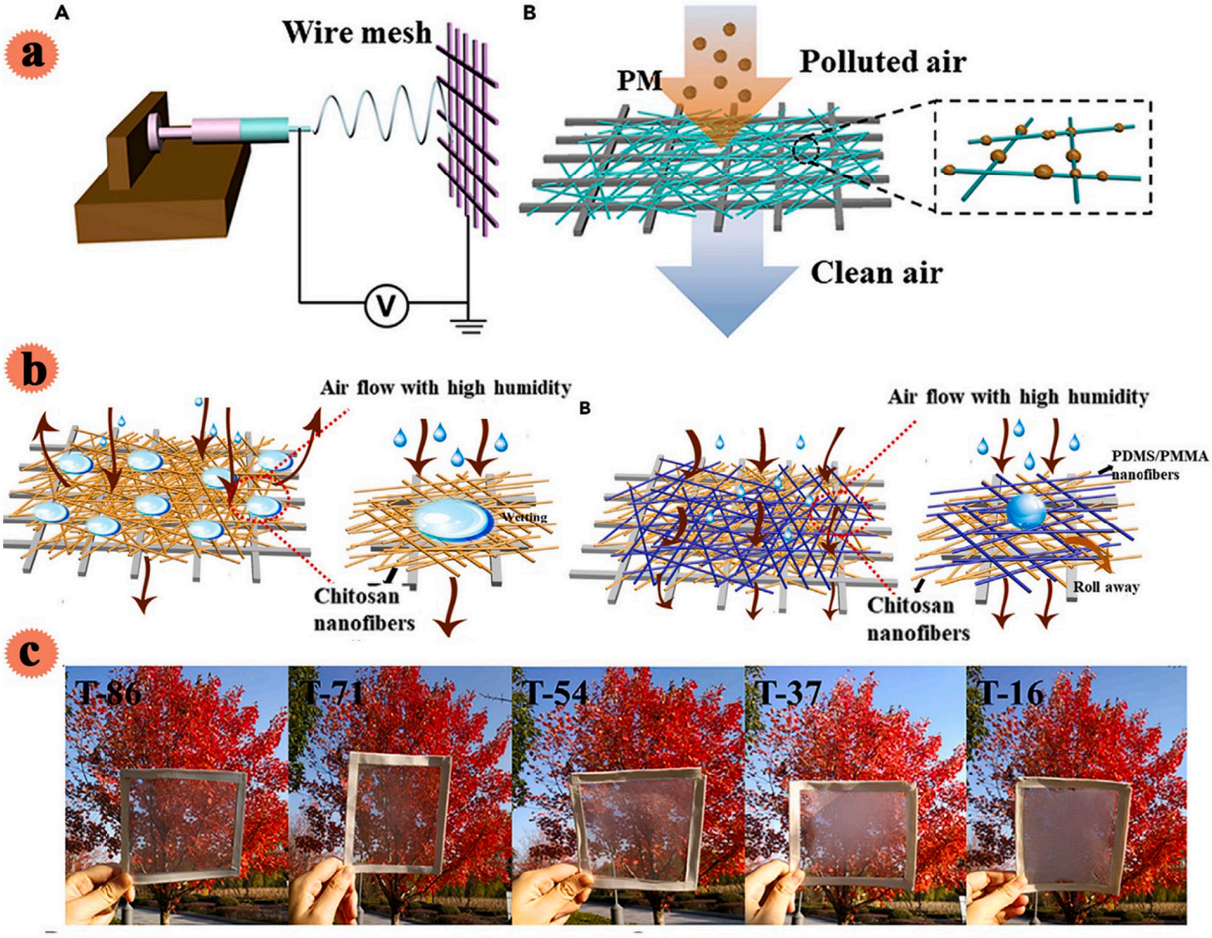

Fig. 18. a: (A) Schematics of fabricating air filters by electrospinning. (B) Schematic illustration of the filtration process of fibrous membranes, b: Schematic illustration of air flow pass through pure chitosan nanofiber filters and PDMS/PMMA-chitosan nanofiber filters under humidity conditions. c: Photographs of PDMS/PMMA-chitosan transparent air filters at different transparencies (Reprinted with permission from [63], Copyright 2019 Elsevier).

4.5. Soy-protein

Soy protein, as a low-cost and abundant plant protein with multi-function and bio-degradability features, is a new bio-based air filtering material with good active sites to trap pollutants and fine particles. Jiang et al. reported effective antimicrobial air filtration by electrospinning the soy protein isolate/polymide-6/Ag salt system. The antimicrobial performance of the filter was checked toward subtilis. It showed 95% efficiency of filtration for particulate matter 0.3. The fabricated membrane revealed a good potential candidate to design a high-performance air filter [73].

4.6. Herbal extract

In an investigation by Choi et al., an antimicrobial air filter was developed by incorporation of herbal extract into nano-fiber fabricated via electrospinning technique to improve indoor air quality [74]. Ethanolic extract of *Sophora flavescens* with excessive antibacterial performance was selected as an antimicrobial herbal substantial. For the electrospinning process, this extract was mixed with a solution of the polymer. The prepared air filters showed 99.99% filtration effectiveness as well as 99.98% antimicrobial performance toward *S. epidermidis* bioaerosols. The prepared air filter based on hybrid nano-fiber of herbal extract/polymer showed the potential for controlling indoor air quality. In another work for the replacement of antimicrobial chemicals in air filters and preparation of self-cleaning air filters, Byun et al. used plant extracts (rosemary, tea-tree oil, as well as garlic) and developed an antimicrobial air filter coating [75]. The antimicrobial performance of plant extracts toward *M. luteus* and *E. coli* was investigated. The surface of poly(ethylene terephthalate) filter was covered with these green extracts by a spray-coating method using silicate polymeric coating. A 9.1% increase in the pressure drop was seen after covering. The fabricated filters by tea-tree oil, immediately inactivated *M. luteus* cell (40–55%), while filters based on the garlic and rosemary did not perform. After 48 h of exposure, filters based on tea-tree, rosemary, and garlic extracts showed significant inactivation of *M. luteus* (99.99%, 99.0%, and 99.9% respectively).

Qin et al. by employing an extract of berberis root plants (berberine), prepared an antibacterial air filter for mask and air filtration [76]. In this study, via electrospinning, composite fibers of poly(vinyl butyral)/berberine hydrochloride were prepared and covered on spun-bonded non-wovens. Good air filtration efficiency of 100% for particular

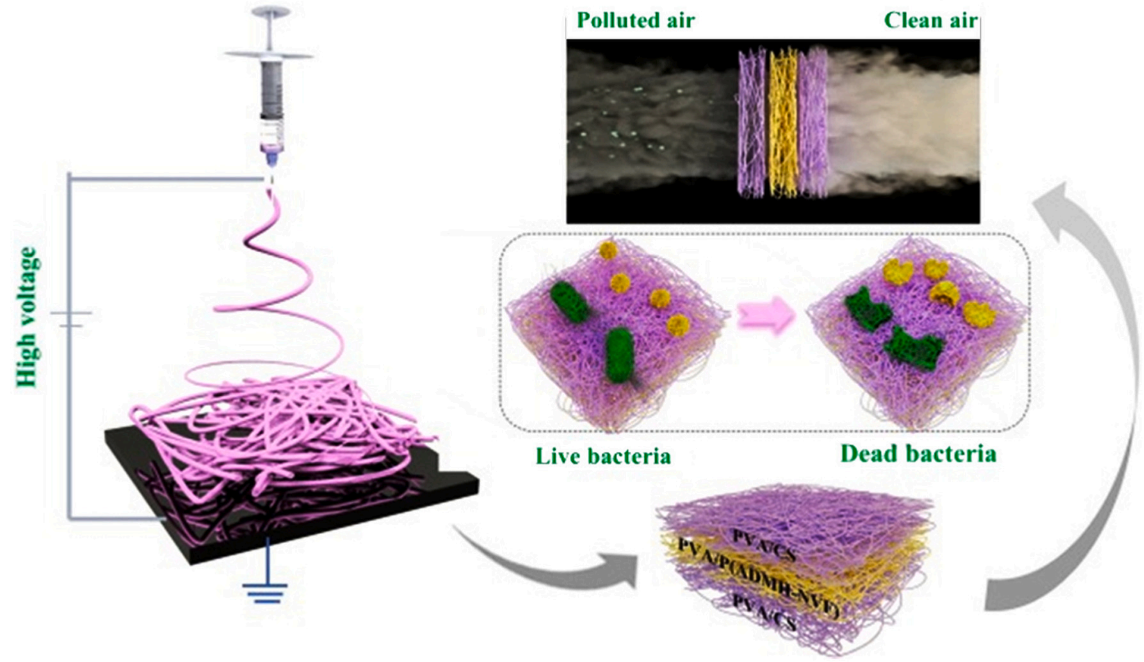

Fig. 19. Schematic illustration of fabrication of the multilayer membranes and application on the antibacterial air filtration (Reprinted with permission from [64], Copyright 2020 Elsevier).

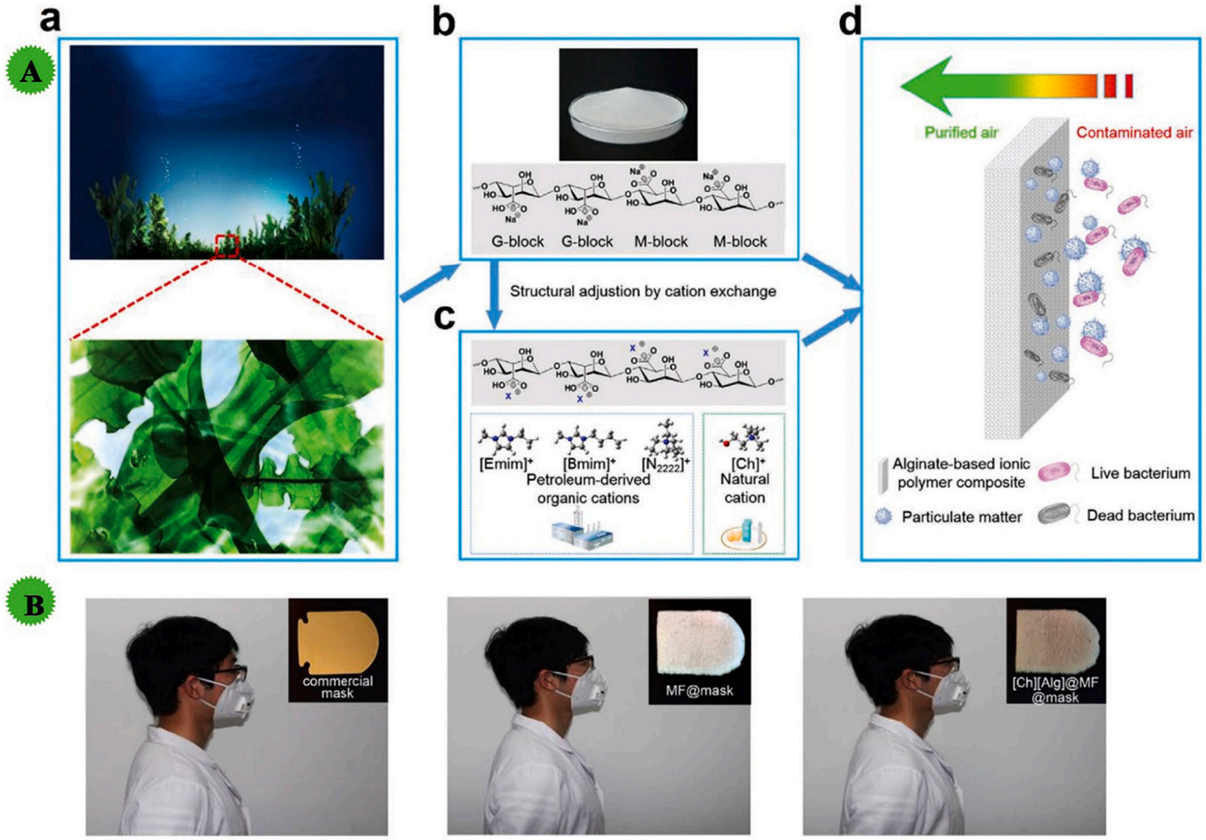

Fig. 20. A: The schematic of alginate-based ionic polymer composites for air purification. a) Top: digital photograph. Bottom: local magnified image of *Laminaria hyperborea*. b) Real product image and structure of sodium alginate: heterogeneous blocks of α-L-guluronate (G-block) and β-D-mannuronate (M-block). c) Structures of conventional organic cations and the natural cation used in this work. d) Illustration of PM removal and sterilization of alginate-based ionic polymer composites. B: Schematic images of commercial mask, MF@mask, and [Ch] [Alg]@MF@mask worn by a man (Reprinted with permission from [68], Copyright 2020 Wiley).

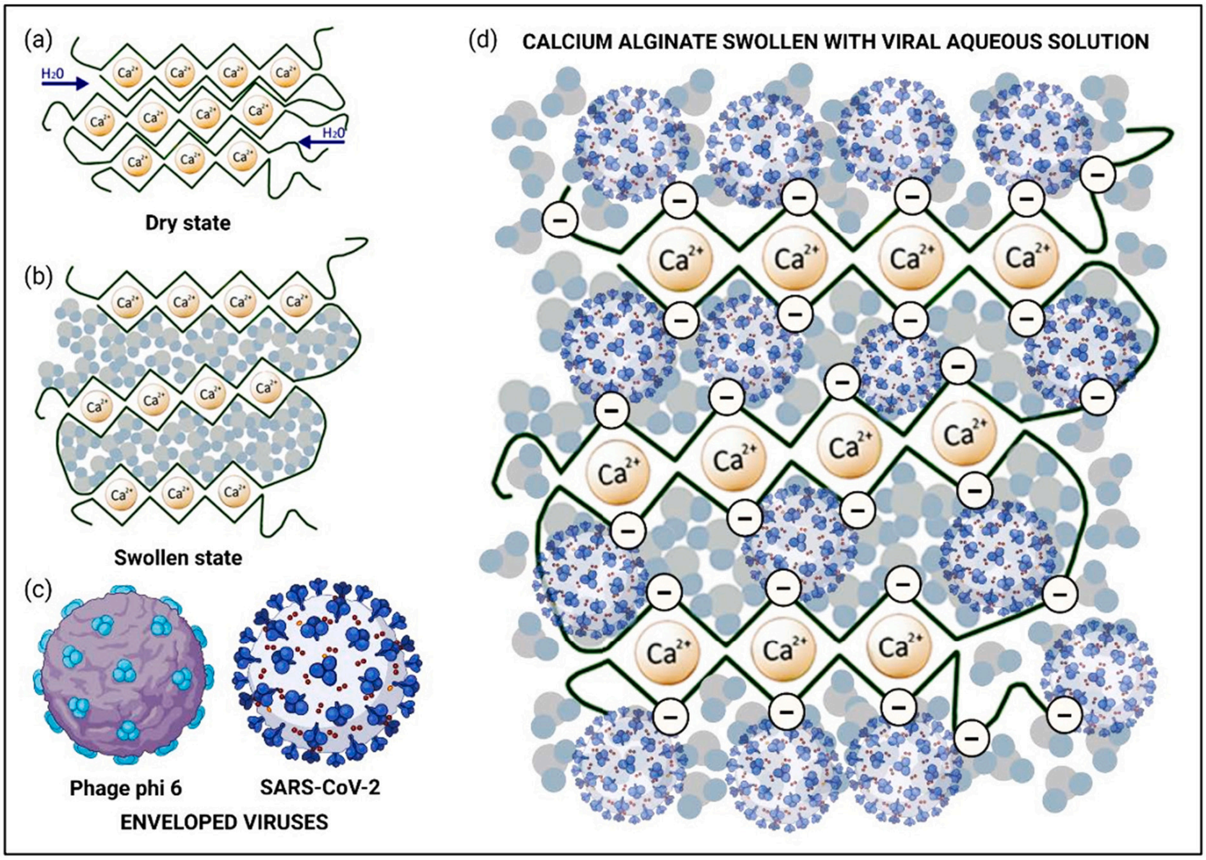

Fig. 21. Inactivation mechanism of SARS-CoV-2 Delta variant and bacteriophage phi 6, in the synthesized negatively charged calcium alginate film: (a) calcium alginate structure in dry state according to the egg-box model; (b) calcium alginate in swollen state after being in contact with a viral aqueous solution; (c) enveloped RNA viruses: bacteriophage phi 6 and SARS-CoV-2 viral morphologies; (d) Negatively-charged calcium alginate interfering with SARS-CoV-2 Delta variant in viral aqueous solution (Reprinted from [69], Copyright 2021 Preprints, Open access).

matter 2.5 and 96.4% for particular matter 0.3 and also, the low-pressure drop was observed. Also, good antibacterial performance (toward *S. aureus*) and hydrophobicity were achieved. In using 5% of berberine, and 0.01 mm thickness, the best outcomes were seen.

5. Conclusion and perspectives

While continuing to promote vaccination among populations in developing countries and underserved areas is important, with the emergence of the more infectious Delta and Omicron variants, preventive methods such as efficient air-conditioners and antimicrobial face masks with low cost and easy access are still effective. Facial masking was adapted all over the world to mitigate the spread of SARS-CoV-2. Besides, air filters have the ability to filter out viruses as well as other infectious particles. According to the obtained findings till now, it is certain that in a closed space with poor ventilation, the hazard of epidemics is high. A wide range of materials plays an important role in the production of anti-viral and antimicrobial air filters. For example, metals/metal oxides nanoparticles or anti-viral ions with anti-viral and antimicrobial properties, including Ag, ZnO, TiO_2, CuO, and Cu are employed in this regard. Also, carbon nanomaterials such as carbon nanotubes or graphene, or derivatives have played a role in the preparation of efficient air filters. In addition, natural materials including biopolymers, herbal extracts with anti-viral properties can be used in the preparation of effective air filters. In this review, we summarized the utilization of diverse materials in the preparation of efficient air filters to apply in the preparation of medical masks and ventilation systems.

Despite numerous advances, existing air filters still suffer from impermeability to air. More techniques should be considered and more emphasis should be placed on pressure drops so that it is not dangerous for people with respiratory problems. Reusable filters should also be provided, as well as cost and waste reduction considerations. Also, further, investigate the mechanical properties of air filters and their flexibility. Covalent organic frameworks and metal-organic frameworks can be used in the preparation of efficient air filters to trap contaminants containing viruses due to their bio-compatibility, porous structures, and high surface-to-volume ratio. More attention can be paid to the 3D printing technique in this regard.

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.

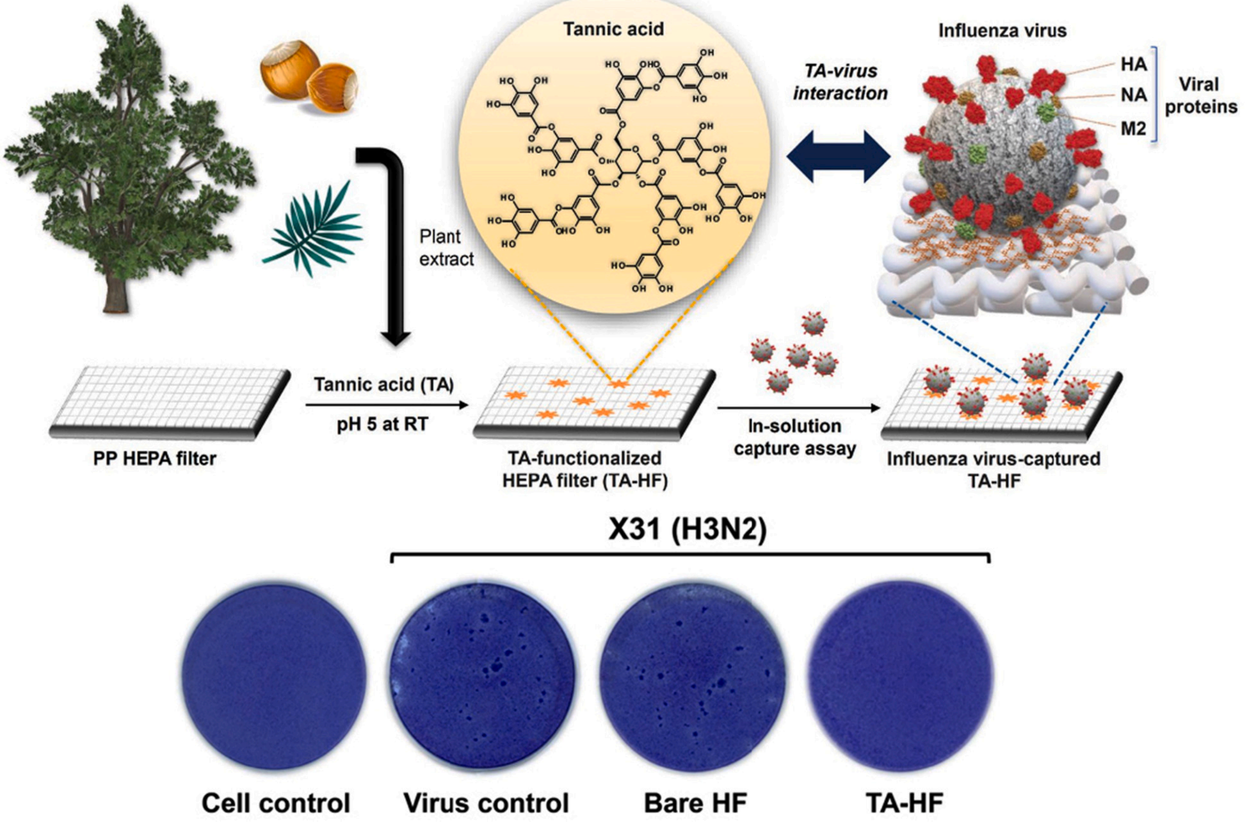

Fig. 22. Preparation of TA-HF for influenza virus capture. Schematic illustration of TA-HF preparation and influenza virus capture based on interaction of TA with viral proteins (*HA* hemagglutinin, *NA* neuraminidase, *M2* matrix-2). *TA* tannic acid, *HF* high-efficiency particulate air filter. And Evaluation of the virus capture efficiency of the bare HF and TA-HF by plaque reduction assay. MDCK cells were incubated with X31, which had been incubated with TA-HF, bare HF, or left untreated (virus control) (Reprinted with permission from [72], Copyright 2021 Nature).

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