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# Advances in Facemasks during the COVID-19 Pandemic Era

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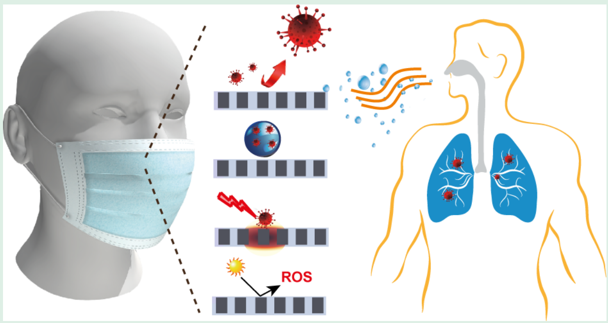

**ABSTRACT:** The outbreak of coronavirus disease (COVID-19) has transformed the daily lifestyles of people worldwide. COVID-19 was characterized as a pandemic owing to its global spread, and technologies based on engineered materials that help to reduce the spread of infections have been reported. Nanotechnology present in materials with enhanced physicochemical properties and versatile chemical functionalization offer numerous ways to combat the disease. Facemasks are a reliable preventive measure, although they are not 100% effective against viral infections. Nonwoven materials, which are the key components of masks, act as barriers to the virus through filtration. However, there is a high chance of cross-infection because the used mask lacks virucidal properties and can become an additional source of infection. The combination of antiviral and filtration properties enhances the durability and reliability of masks, thereby reducing the likelihood of cross-infection. In this review, we focus on masks, from the manufacturing stage to practical applications, and their abilities to combat COVID-19. Herein, we discuss the impacts of masks on the environment, while considering safe industrial production in the future. Furthermore, we discuss available options for future research directions that do not negatively impact the environment.

**KEYWORDS:** *COVID-19, SARS-CoV-2, pandemic, virus, facemasks*

## 1. INTRODUCTION

The ongoing coronavirus (COVID-19) pandemic has resulted in different stages of respiratory infection.[1] COVID-19 is spread through virus-containing respiratory droplets, which are easily suspended in air and, hence, can be regarded as being airborne. The major modes of infection either involve respiratory droplets with aerodynamic diameters of less than 5 $\mu$m (fine particle aerosols) present in the air or those larger than 5 $\mu$m (coarse particle aerosols), which fall rapidly from an infected person (Figure 1).[2] Coarse particle aerosols require close contact to cause infection, whereas fine particle aerosols are more readily transmitted over longer distances.[3] Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection has become a leading cause of morbidity and mortality, resulting in severe economic burden.[4] The severity of COVID-19 ranges from asymptomatic to life-threatening, with a fatality ratio greater than 10% for immunocompromised and elderly individuals. Therefore, there is immediate need for health strategies to limit this disease.[5,6] Various mitigation strategies, such as social distancing, travel restrictions, and prohibiting gatherings, are being implemented to prevent viral transmission.[7] However, these social systems and prohibitions have had limited success.[8] The wearing of masks has been highly recommended to prevent droplet transmission. Masks act as physical barriers that prevent the entry of mucosalivary droplets into the nose and mouth.[9] The use of masks has become a major strategy in combination with other interventions, such as hand washing and social distancing, to reduce the spread of infections resulting from unintentional close contact with infected individuals. However, community trials have demonstrated mixed results.[8,10] Due to the uncertainty of the pandemic, masks have dominated the global market.[11] From homemade cloth masks to medical-grade varieties, masks have gained significant importance in everyday life.[12]

## 2. MECHANISTIC INFORMATION ON VIRUS TRANSMISSION

SARS-CoV-2—the virus that causes COVID-19—is a lipid-based enveloped virus (diameter ~ 0.1 $\mu$m) with spike-like projections that form a crown shape, which gives the coronavirus its name. This virus contains RNA as the genetic material.[13,14] Although the transmission of SARS-CoV-2 is still under investigation, this respiratory viral pathogen can be

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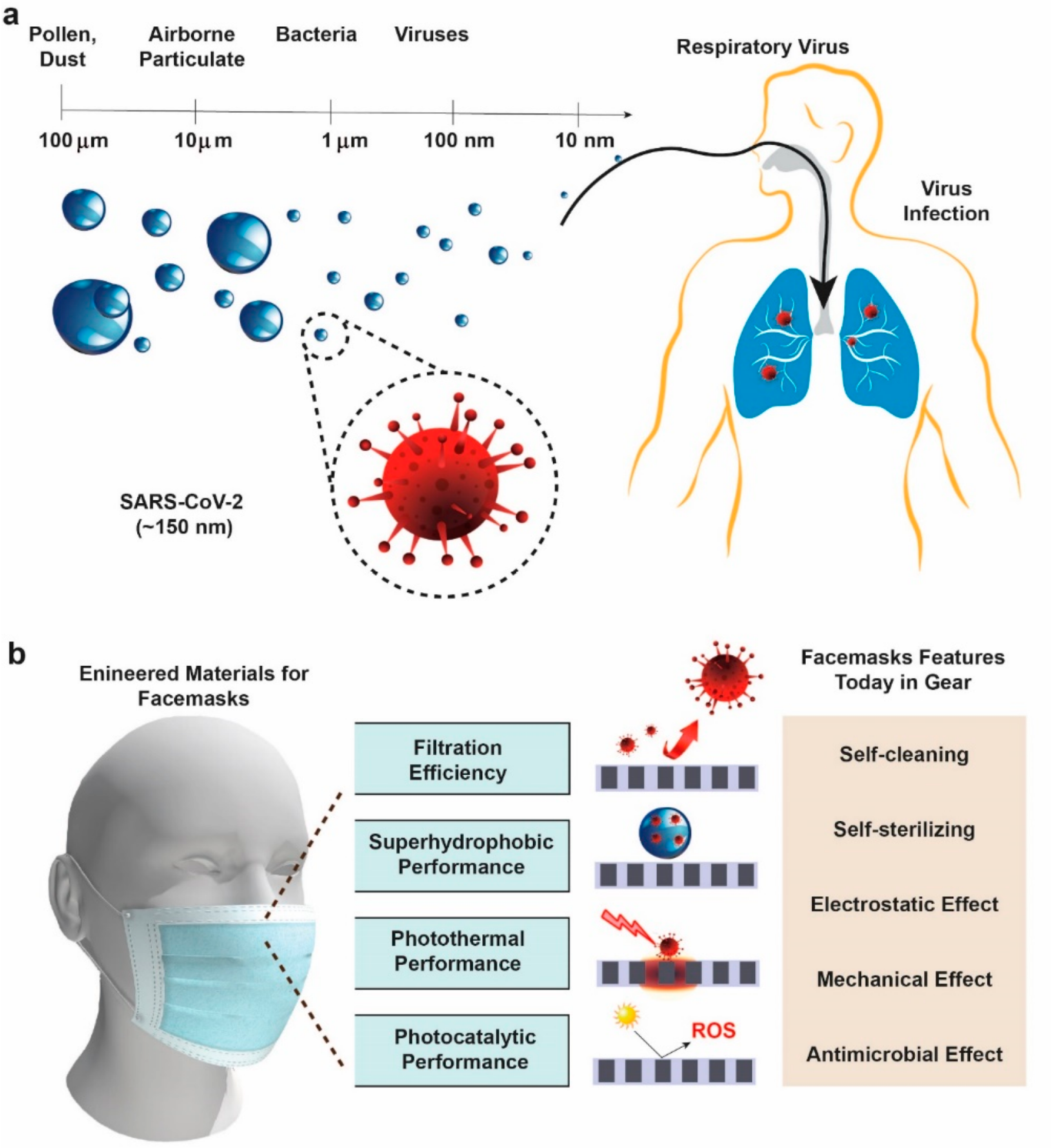

**Figure 1.** Schematic of the transmission of SARS-CoV-2 and the advancement in nanomaterials for facemasks. (a) The SARS-CoV-2 potential mode of transmission is viral aerosols from respiratory droplets of the infected host, which can travel distances longer than six feet in the air. (b) Advanced materials integrated into facemasks can prevent the entry of SARS-CoV-2. Various mechanisms are used to provide the facemask with self-sterilizing and self-cleaning capabilities.

spread through patient-derived bio-aerosols.[15] The bio-aerosols remain viable for 72 h on plastic and stainless steel surfaces containing a 50% tissue-culture infectious dose [$\mathrm{TCID}_{50}$], with a reduction in infectious titer from $10^{3.5}$ to $10^{2.7}$ $\mathrm{TCID}_{50}$ per liter of air.[16] This virus can be spread through three major routes: contact, droplet, and aerosol.[4]

**2.1. Contact Transmission.** Contact transmission can be either direct or indirect.[17] Direct transmission occurs when an infected person comes into direct contact with a healthy individual through hugging or by shaking hands and transmits the virus. No contaminated intermediate is involved in this mode of transmission. In contrast, transmission is regarded as being indirect when a healthy individual uses an object that was previously used by an infected individual or touches any inanimate surface (e.g., a thermometer) containing viral particles.[18]

**2.2. Droplet Transmission.** The virus-containing droplets generated during sneezing, coughing, and talking fall within a 1 m distance due to the coarse particle size. The droplets settle on inanimate surfaces or become attached to the mucosa (nasal passage, eyes, mouth, and respiratory tract) in close contact, which causes infections through droplet transmission.[19]

**2.3. Aerosol Transmission.** Fine droplets are suspended in air for longer periods and travel with the speed of the air. These particles are inhaled with the air and cause infections in healthy individuals. SARS-CoV-2 can be viable for 3 h and floats for several hours.[16]

## 3. TYPES OF FACEMASK THAT COMBAT VIRAL TRANSMISSION

Masks have become vital components of our lives because they can prevent the transmission of viral particles. Mask wearing

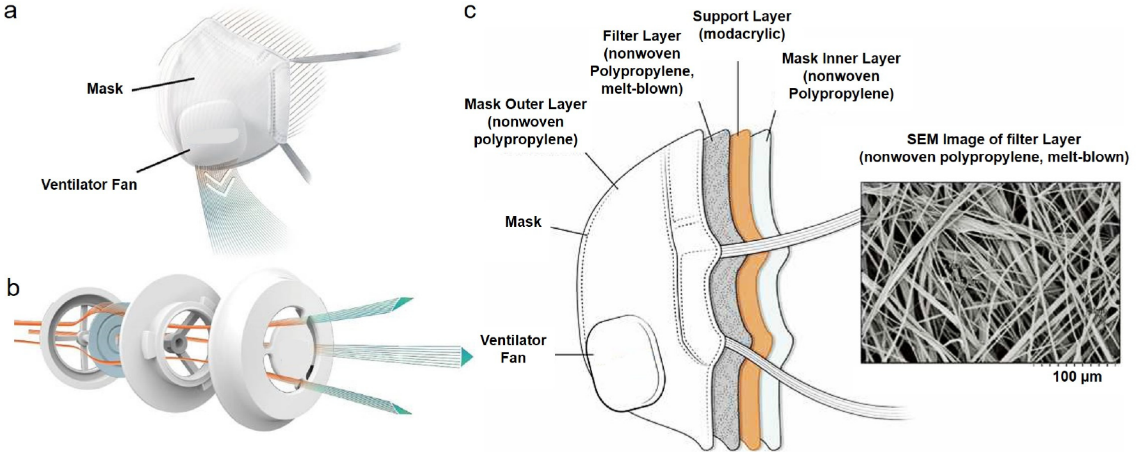

**Figure 2.** Schematic representation of the N95 test mask. (a) Airflow through the test mask during exhalation to enhance wearer comfort and the permitted airflows. (b) Detailed structure of the smart valve showing the permitted air flow from the inside to the outside of the mask. (c) Schematic of the test mask showing the SEM images of the fibers in different layers. Panels a−c reproduced with permission from ref 26. Copyright 2018 AME Publishing Co.

reduces the risk of infection whenever there is contact with an infected person. Normal actions, such as talking, emit an average of 1000 droplets per second, as detected by laser light scattering, which evidence the existence of virus superspreaders.[20,21] Particle emission rates are directly proportional to the speed and loudness of spoken sounds.[21] Covering or masking the speaker's mouth can reduce droplet emissions to low levels, as observed by laser light scattering.[22] Hence, masks act as barriers that prevent droplets from symptomatic and asymptomatic carriers.

This study reveals that masks play two important roles.[11] First, they prevent gas cloud formation during sneezing and coughing, which minimizes rapid turbulent jets of aerosol toward individuals or the environment.[23] Second, the layer present in the mask filters the aerosol and prevents it from entering the nasopharyngeal region.[12] However, repeated breathing makes the mask a virus collector due to exposure to contaminated droplets. The warm and humid conditions inside the mask during respiration can accelerate the penetration of the virus and its spread on the inner side. Hence, the efficiency of the mask in preventing aerosols from entering the respiratory system depends on the type of mask, i.e., the material used to prevent the entry of particles, the fit of the mask and the percentage of air leakage, and the mask-wearing technique.[24] Masks are generally divided into two categories: i.e., (1) certified and (2) homemade.

### 3.1. Certified Masks.

Certified masks are those that fulfill the criteria for government standard certification. These standards are established by the U.S. Centers for Disease Control and Prevention (CDC), the U.S. National Institute for Occupational Safety and Health (NOISH), and the U.S. Food and Drug Administration (FDA).[11] Respirators and medical masks fall under the certified mask category.

#### *3.1.1. Respirators.*

Respirators have been certified by the CDC and fulfill all of the criteria for public use (e.g., filtration efficiency and air permeability).[11] They are non-oil-resistant and are also termed electret masks due to the use of electret filters, which are a type of filter facepiece respirator that act against monodispersed and polydispersed aerosols larger than 20 nm in size. Breathing is improved using a ventilator fan at the outer layer.[24] Respirators are labeled according to filtration properties. European labeled FFP2 and FFP3 masks can filter out 94% and 99% of the aerosol particles, respectively. N95 (United States), KN95 (China), P2 (Australia/New Zealand), Korea first Class (Korea), and DS (Japan) are respirator equivalents to FFP2. N95 respirators comprise four layers, which include inner, support, filter, and mask-filter layers, respectively.[25] The outer layer comprises hydrophobic nonwoven polypropylene (PP), which resists external moisture. The filter layer consists of two layers of melt-blown nonwoven PP that absorb oil- and non-oil-based particles. This filter layer operates on four principles: inertial impaction, interception, diffusion, and electrostatic attraction. The support layer consists of modacrylic, which provides extra thickness and rigidity, thus providing comfort (Figure 2). The innermost layer also comprises hydrophobic nonwoven PP, which resists moisture inside the mask and stabilizes filtration efficiency.[26] These are tightly fitted and are usually worn by healthcare personnel to avoid the risk of pathogenic transmission. Due to their high costs, these masks are not universally affordable.

#### *3.1.2. Medical Masks.*

Medical masks are loosely fitted and disposable, and are regarded as medical devices by the Food and Drug Administration.[11] These masks are used to prevent aerosols in the clinical environment. Such a mask contains a three-layer structure. The inner layer is hydrophilic in nature and absorbs moisture and aerosols from the user. The middle layer is a filter that filters air particles and prevents particles of specific dimensions from entering both sides of the facemask. The outer layer is hydrophobic; hence, it repels aerosols and water droplets from the outer environment.[27] This type of mask is not closely fitted to the face; therefore it is effective against large coarse droplets rather than small ones.[28] However, various studies have shown that medical masks are able to prevent coronaviruses and the influenza virus.[2]

### 3.2. Homemade Masks.

Although there is no guarantee that a simple homemade mask can prevent viral load, the WHO has advised the use of nonmedical masks prepared with at least three layers of either woven or nonwoven fabric, depending on the type of fabric.[29] The CDC has also recommended wearing cloth masks or scarves to reduce respiratory emissions, as laser light scattering has shown that they reduce the amount of particles emitted by covering the speaker's mouth. These masks can prevent respiratory droplets larger than 20−30 $\mu$m in size, and the use of multiple layers efficiently blocks respiratory droplets less than 1−10 μm in size. Usually, homemade masks are made from simple cotton cloth or other common fabrics, with no quality control. Different types of cloth include woven (also called warp and weft, i.e., cross-thread), felted (disorganized fibers in compressed form), and knitted (fibers with interlocking loops), with no fixed standard for material choice, design, number of layers, filtration capacity, and breathability rate.[30] The filtration efficiencies of common fabrics made of polyester, cotton, silk, and nylon were found to be 5−25%.[31] Filtration efficiency depends on the thread count and number of cloth layers, for which 300 threads per inch (TPI) or more is associated with a filtration efficiency of more than 80%.[30] These masks are good alternatives, as medical masks are scarce in a pandemic.[32] Reusable cloth masks provide the best solution for the current pollution burden created by disposable masks. Several studies have shown successful cloth masks fabricated with four-layer 100-TPI muslin cloth, two tea-towel layers, two cotton T-shirt layers, two linen tea-towel layers, two 600-TPI cotton layers, and 600-TPI cotton with 90-TPI flannel.[32−35] However, N95 respirators and surgical facemasks provide the best protection in a high-risk environment.[36]

The above discussion highlights the need to properly set up reusable cloth masks. These masks should be labeled with the composition of the material, thread count, weave, and the number of layers prior to marketing.[30] Table 1 lists materials used to prepare cloth masks.

**Table 1. Materials Used to Make Cloth Masks**

| material | fiber composition |
|---|---|
| T-shirt[35] | 100% cotton |
| fleece sweater[151] | 100% cotton |
| pillowcase A[151] | air-jet down-proof fabric |
| pillowcase B[151] | jet satin |
| pillowcase C[151] | jet satin |
| down jacket[151] | 100% polyurethane |
| jeans[151] | cotton and polyurethane |
| medical gauze[117] | absorbent cotton |
| scarf[152] | polyester |
| tea towel[35] | linen |
| handkerchief[117] | cotton |
| napkin[31] | silk |
| exercise pants[31] | nylon |
| paper towel[31] | cellulose |
| tissue paper[31] | cellulose |
| toddler wrap[31] | polyester |
| towel[31] | polyester |

## 4. IMPORTANT PARAMETERS FOR MASK EFFICACY

Mask wearing reduces the chance of viral particles and other contaminants entering the respiratory system. The viral load, which is filtered, totally depends on the type of mask used. Various studies have demonstrated that, compared to normal homemade masks, certified masks exhibit high efficacies against influenza viral loads.[11,37] Medical masks effectively block different types of influenza virus, depending on their size, whereas the rhinovirus was not blocked.[2] Medical masks were able to readily prevent influenza viral particles with particle sizes greater than 5 μm (coarse), whereas smaller particles were difficult to prevent.[28] Most studies suggest that N95 and medical masks are similarly effective against the influenza virus; there was only a slight difference in the risk level at the 95% confidence level and a risk ratio of 0.84, which indicates risk of less than unity.[38,39] Owing to the pandemic, covering the nose and mouth, whether with homemade masks, scarves, or commercial masks, has become mandatory. However, to prevent influenza-like illnesses, certified masks are superior alternatives to cloth masks in environments where there is a heightened risk of infection.[39,40] Approximately 97% of particles penetrate cloth masks, whereas 44% and <0.01−0.1% penetrate medical masks and respirators, respectively.[40] Respirators are 50- and 25-fold more reliable than homemade and medical masks, respectively.[12] Cloth masks can be reused many times, which increases the risk of infection due to the effectiveness of cleaning and moisture-retention properties.[40] However, with proper material selection and good sanitization practices, cloth masks are suitable alternatives to certified masks due to the scarcity of masks during the pandemic. Table 2 summarizes the filtration properties of common facemask materials to demonstrate the efficiency.

**4.1. Factors Affecting the Efficacy of Masks.** Facemasks are used to prevent the entry of unwanted airborne particles into the respiratory system. Since masks are used as personal protective equipment, they should satisfy the performance criteria specified by the American Society of Testing and Materials (ASTM) F2100 standard.[9] In general, masks should possess the following five characteristics: (1) particulate filtration efficiency, (2) bacterial filtration efficiency, (3) fluid resistance, (4) differential pressure, and (5) flammability. These characteristics are dependent on the material used and the mask design.

**4.2. Materials Used in Masks.** Different polymer fibers, such as polyester, polyethylene, PP, polyamide, polycarbonate, and polyphenylene oxide, are used to manufacture masks. These materials are slippery enough to exhibit hydrophobic and nonabsorbent properties (Figure 3).[24] In particular, PP is in high demand due to its nonabsorbent properties and the ability to repel humidity.[41] In addition, it is cost-effective, reusable, and 3D printable and exhibits good mechanical performance (e.g., tensile strength, rheological properties, and dynamic mechanical properties).[42] Other fibers, such as polyester rayon, glass, and cellulose are also utilized; however, these fibers are less efficient than PP.[43] Hence, PP has been used to seal the edges of standard masks to prevent leakage or particle penetration (sub-micrometer aerosols) from gaps formed between the face and the mask.[24]

Combining these polymers with nanofiber filters can increase air flow efficiency.[44] The nanofibers used on nanoporous polyethylene increase the capture efficiency of particulate matter (PM) to 99.6% (Figure 4a).[45] Polyacrylonitrile fibers in combination with silver nanoparticles (NPs) exhibit reusable properties and demonstrate advanced performance against the transmission of bacteria from the environment to the user, and vice versa.[46] Nonwoven PP substrates containing electret poly(ether sulfone)/barium titanate nanofibrous membranes facilitate the optimization of the injection charge energy with high porosity. This enables access to good air and limited water vapor permeability, and a filtration efficiency of 99.99%, with thermal comfort.[47] The melt-blown and nanofiber filters used in N95 masks possess high filtration efficiencies.[48] Commercially available masks are produced from these materials. Simple homemade masks use cotton, silk, linen, tissue paper, and household materials, such as towels and pillowcases; however, these materials lack structural integrity

Table 2. Comparison of the Filtration Efficacy and Pressure Drop of a Variety of Materials[24,31,32]

| mask type | | material used[a] | structure | filtration efficiency (%) | $\Delta P$ (Pa)[b] | reusable |
|---|---|---|---|---|---|---|
| certified mask | medical mask | polypropylene (no gap) | nonwoven | 76 ± 22 | 2.5 | no |
| | | polypropylene (gap) | nonwoven | 50 ± 7 | 2.5 | no |
| | respirator | polypropylene (no gap) | nonwoven | 85 ± 15 | 2.2 | no |
| | | polypropylene (gap) | nonwoven | 34 ± 15 | 2.2 | no |
| homemade mask | | cotton single layer | woven | 79 ± 23 | 2.5 | yes |
| | | cotton double layer | woven | 82 ± 19 | 2.5 | yes |
| | | cotton quilt | woven | 96 ± 2 | 2.7 | yes |
| | | quilter's cotton single layer | woven | 9 ± 13 | 2.2 | yes |
| | | quilter's cotton double layer | woven | 38 ± 11 | 2.5 | yes |
| | | cotton + silk (no gap) | woven | 94 ± 2 | 3.0 | yes |
| | | cotton + silk (gap) | woven | 37 ± 7 | 3.0 | yes |
| | | cotton + flannel | woven | 95 ± 2 | 3.0 | yes |
| | | silk single layer | woven | 54 ± 8 | 2.5 | yes |
| | | silk double layer | woven | 65 ± 10 | 2.7 | yes |
| | | silk quadrilayer | woven | 86 ± 5 | 2.7 | yes |
| | | nylon | woven | 23.33 ± 1.18 | 244.0 ± 5.5 | yes |
| | | chiffon single layer | woven | 67 ± 16 | 2.7 | yes |
| | | chiffon double layer | woven | 83 ± 9 | 3.0 | yes |
| | | flannel | woven | 57 ± 8 | 2.2 | yes |

[a] All materials except Nylon were tested at a flow rate of 1.2 $ft^3/min$ (CFM), and the average particle size range was <300 nm ± error. [b] $\Delta P$ = pressure drop.

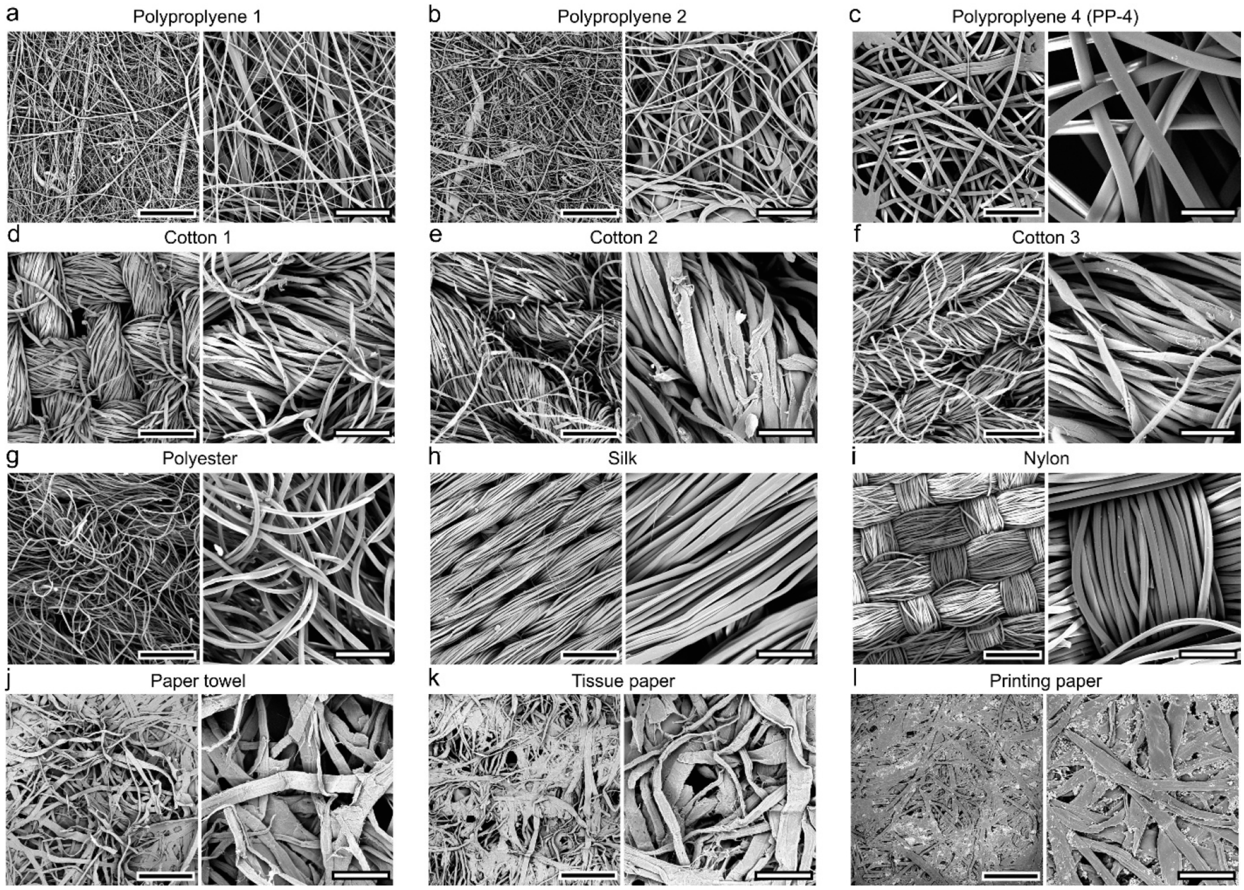

**Figure 3.** High- and low-resolution SEM images of the physical morphology of various household materials showing the microscopic structure. The images are provided in pairs of different resolutions (left scale bar, 300 μm; right scale bar, 75 μm).SEM images of polypropylene samples (a, b) and common Spunbond fabric (c). (d–f) SEM images of cotton samples. (g–i) SEM images of polyester, silk, and nylon, respectively. (j–l) SEM image of cellulose-based products. Panels a–i reproduced with permission from ref 31. Copyright 2020 American Chemical Society.

and particle filtration efficiency. Hence, extensive modification is required to ensure that these masks satisfy the demands of the pandemic, which include reusability and self-cleaning features to reduce unnecessary load on the environment.

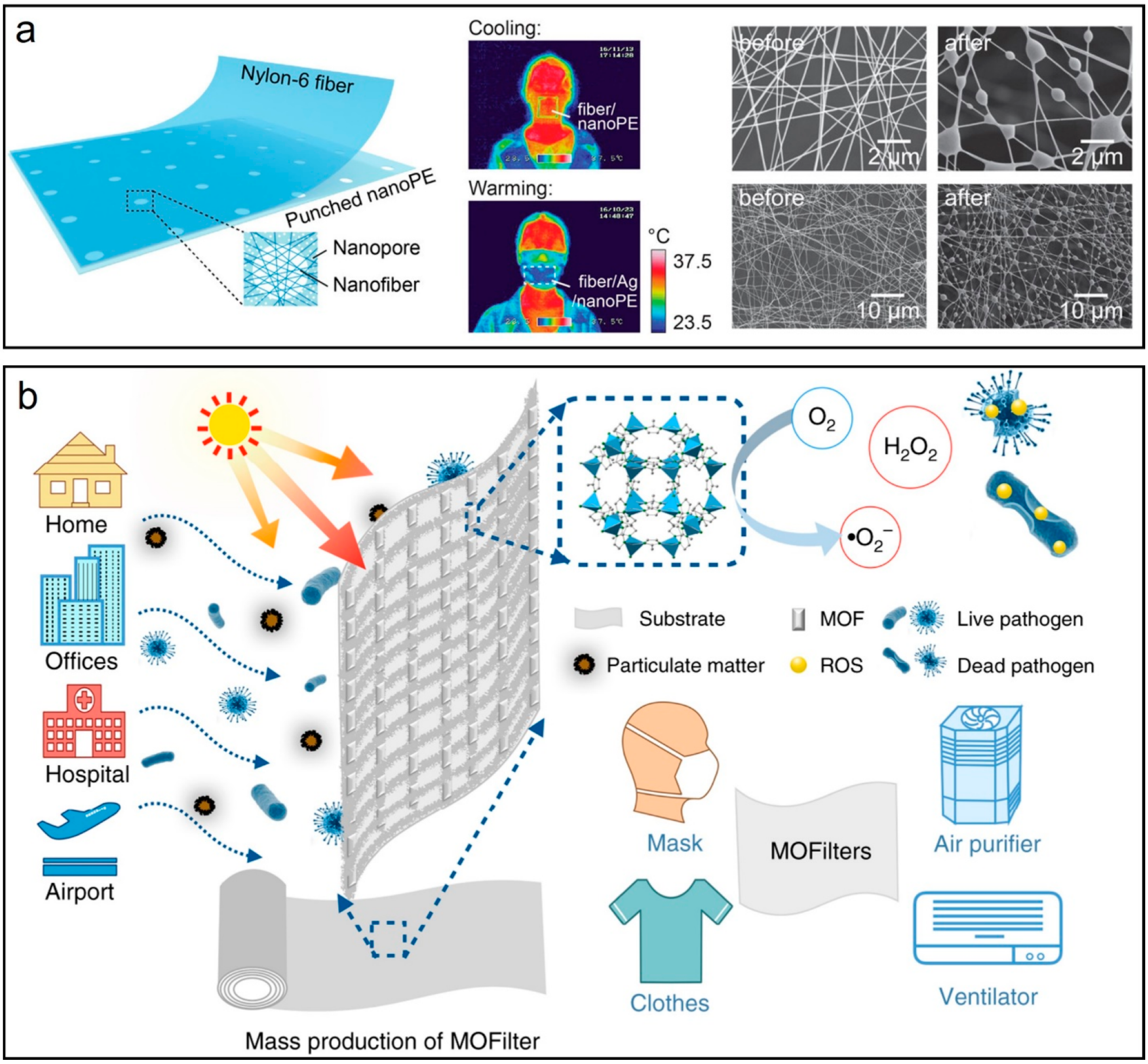

**Figure 4.** (a) Scheme for proposed facemasks with electrospun nylon-6 nanofibers on needle-punched nanoporous-polyethylene substrate (left). Thermal imaging of the fiber composite layers of facemasks worn on the human face under different conditions (middle). SEM images of the fibers before and after filtering the particulate (right). Reproduced with permission from ref 45. Copyright 2017 American Chemical Society. (b) Schematic representation of the MOF-based filter (MOFilter) for integrated air cleaning and facemask applications. Reproduced with permission from ref 91, Copyright 2017 Springer Nature.

**4.3. Enhancing the Air-Filter Performance.** PM capture is a property that monitors the ability of the mask to filter droplets. Polymer fibers, which capture PM based on their size, are normally used in masks. Only larger particles are captured in these filters; hence, the fine pore sizes of nanofiber membranes are required to prevent tiny aerosol particles with air-filtering capacity. Recent development in membrane filters have focused on their light weights with small diameters and high surface areas, which enhances air resistance. New innovations in polymer nanofiber membranes, electret membranes, and porous metal−organic framework (MOF) filters help to enhance air-filter performance.[9]

## 5. INVOLVEMENT OF NANOTECHNOLOGY TO IMPROVE THE QUALITY OF FACEMASKS

Masks need to be enhanced to increase the levels of protection that they provide, which can be achieved by changing the design of the mask, with proper enhancement in the filter capacity of the material used in the mask. Modifying the design by implementing various advancements, such as self-cleaning properties, antimicrobial properties, comfort, and cost effectiveness, will satisfy the unmet needs of current mask technologies.

**5.1. Nanofibrous Membranes.** Electrospinning is used to achieve the nanoscale diameters of nanofibers, with large specific surface areas and interconnected porous networks.[49,50] This method can fabricate polyacrylonitrile nanofibers (diameter ∼ 200 nm) used for air purification that can capture PM less than 2.5 mm in size ($PM_{2.5}$).[50,51] The nanofibers generated using this method possess enhanced filtration (>95%), optical transparency (up to 90%), low weight, and strong PM adhesion.[50] To increase the properties of these nanofibers, their surface chemistry and mechanical properties are modified. Technological advances in electrospinning, particularly cutting-edge electrospinning/netting technologies, enable the fabrication of interconnected nanonets with ultrafine diameters of less than 20 nm and pore less than 200 nm in size.[52] The aforementioned technology demonstrated promising potential regarding fine particulate filtration, with an efficiency of 99.985% for $PM_{0.26}$ removal.[53,54]

**5.2. Electret Membranes.** Rather than passively capturing air particles, charge-mediated filtration facilitates efficient air filtration because electrostatic action is used to attract and repel particles from longer distances, without depending on the pore size of the filter. In general, an electret membrane is fabricated using three charging techniques: in situ charging, corona charging, and tribocharging.[54]

During in situ charging, nanofibers are integrated with charge storage enhancers, such as NPs. NPs, including magnesium stearate, titanium dioxide, poly(tetrafluoroethylene) (PTFE), boehmite, silicon nitride, and silicon dioxide, are added to the electrospinning solution before nanofiber fabrication.[55−58] When magnesium stearate is used, 98.94% of $PM_{2.5}$ was filtered at a surface potential of 4.78 kV. Similarly, $SiO_2$ NPs demonstrate this effect at 12.4 kV.[55,58] Further, corona charging enhanced the $PM_{2.5}$ filtration efficiency (up to 99.22%) using magnesium stearate at a charging voltage of 100 kV for 30 s. This integrated the charged particles through melt blowing under an external electric field.[59] Both of these cannot function well once they come in contact with moisture or oil droplets. Hence, they are not applicable in hazy environments because they impact the surface charge of the filter.[60]

Tribocharging nanofibers using a triboelectric nanogenerator (TENG), which continuously supplies charge to stably filter air, overcomes this limitation.[61,62] The advantage of this technology is that it utilizes vibrational energy from air, water, and human behavior (movement), which is promising for the continuous operation of electronics.[63] TENGs that utilize a rotator (R-TENGs) provide continuous charge to the nanofiber and filter particles that are less than 100 nm in size.[61] Using the same principle, a self-powered electrostatic adsorption facemask (SEA-FM) was designed, which uses respiration to supply energy, and can filter 99.2 wt % coarse and fine particulates and 86.9 wt % ultrafine particulates.[62] This advanced system yielded a reusable and washable triboelectric air filter that can be charged through friction between nylon and PTFE fabrics. The system exhibited high-efficiency filtration properties of 84.7% for $PM_{0.5}$ and 96% for $PM_{2.5}$.[64] This mechanism overcomes the limitations of in situ and corona charging, thereby demonstrating its effectiveness in humid environments and providing an opportunity to advance facemask fabrication.

**5.3. MOF-Based Filters.** MOF-based filters contain crystalline powdered materials composed of transition-metal cations and multidentate organic linkers and are highly porous and thermally stable.[65] Such a filter exhibits high filtration efficiency due to the presence of binding sites and functional groups present on the MOF that electrostatically interact with pollutants. The use of a MOF on a polymer improved the surface area, resulting in high efficiencies of up to 88.335% and 89.67% for the removal of $PM_{2.5}$ and $PM_{10}$, respectively.[66] The MOF-based filter synthesized using the roll-to-roll hot pressing method can operate in high (80−300 °C) temperature ranges and demonstrated reusable and washable properties.[67] Polypropylene microfibers with 2D assembled MOFs exhibit filtration efficiencies of 92.5% and 99.5% for $PM_{2.5}$ and $PM_{10}$, respectively, at low pressure drops. Due to its superior thermal properties, MOF-based filters can be used in harsh environments.[68,69]

**5.4. Antimicrobial Properties.** Air contains a variety of particulate matter along with microorganisms, which can directly adhere to the respiratory system and become pathogenic. The microorganisms present in the aerosol can be filtered for certain sizes but cannot be killed. Hence, they can become localized in the filter and their population can grow, which decreases filter quality and impacts air purification. Further, viable organisms present in the filter cause secondary infection after disposal, which is a major cause of the spread of disease.[70−72] Various antimicrobial agents, such as graphene, MOFs, metal oxide, and NPs, can be incorporated in the filter to remove microbial load and efficiently filter air.[8]

*5.4.1. Use of Nanoparticles.* NPs synthesized using silver, zinc, gold, aluminum, and copper demonstrate potential antimicrobial effects. Various antimicrobial properties that arise through mechanisms involving metal ion generation and the photocatalytic effect stress microbes through the formation of reactive oxygen species (ROS) that rupture cell membranes.[73−76] Metal-based NPs, which generate positive ions that bind to ATP and DNA according to charge, are toxic to the cell walls and envelopes of viruses.[77,78] These NPs are also toxic to multidrug-resistant bacteria but are mildly toxic to humans in the same concentrations used on these pathogens.[79−81] Silver NPs bind to thiol groups and exhibit antimicrobial properties.[82] NP synergism on the filter enhances filtration properties by lowering the high pressure drop. PTFE nanofibers combined with Ag/ZnO nanorods are 100% efficient against *Escherichia coli* (*E. coli*), thereby increasing gas penetration.[83] Similarly, Ag@MWCNTs incorporated in $Al_2O_3$ filters demonstrate an antimicrobial effect greater than 98% against indoor microorganisms, with 99.99% formaldehyde degradation.[84] AgNPs on yarn endow it with reusability after 100 washing cycles, while remaining effective against various bacteria, including the *Bacillus*, *Staphylococcus*, *Chlamydia*, *Pseudomonas*, and *Escherichia* genera, as well as fungi. Both Gram-positive and Gram-negative bacteria are susceptible to silver NPs.[85] Copper and copper oxide are used as antiviral and antimicrobial agents because oxidation by Cu(I) produces ROS.[86,87] The use of CuO in masks is effective against different influenza viruses, with a 99.85% filtration efficiency and a 99.99% virus titer reduction. N95 masks incorporating CuO meet the European EN 14683:2005 and NIOSH standards.[88] Similarly, CuI-incorporated masks are 99.99% effective against the influenza A virus.[9] Some CuO-incorporated masks are reusable after their first use.[9] Mixtures of Ag and $TiO_2$ NPs on mask surfaces are highly bactericidal, without affecting human health. A 100% bacterial reduction was observed using this mixture.[89] Similarly, a combination of $Cu_2O$ and $Ag_4O_4$ reduced 96% of an HIV population in 30 min and 86% of an *E. coli* colony in 3 h. Combinations of NPs have been shown to significantly act against microbes within short intervals of time compared to single NPs. Appropriately depositing NPs on a filter enhances filtration properties by employing their biocidal properties.

Certain nanomaterials photocatalytically generate ROS that kill microbes. Titanium oxide ($TiO_2$) and zinc oxide (ZnO) NPs exhibit efficient particulate filtration with bacterial removal through their photocatalytic activities.[90] ZnO NPs coated on polyester fabric masks reduce 98% of bacteria within

1 h of incubation. Similarly, Zn-imidazolate incorporated into a MOF removed 97% of PM with a bactericidal effect in excess of 99.99%. These photocatalytic properties operate well under abundant sunlight (Figure 4b).[91]

*5.4.2. Use of Natural Extracts.* Natural product extracts of olive, mangosteen, grapefruit seed, tea tree, and *Sophora flavescens* (*So. flavescens*) exhibit antimicrobial properties that are due to flavonoids.[70,72,92−95] These extracts can be sprayed on fibrous filter surfaces to inhibit DNA gyrase and cause cell membrane dysfunction in microbes attached to the filter.[71,72] A mixture of poly(vinylpyrrolidone) and *So. flavescens* produced a nanofibrous membrane through electrospinning that exhibited 99.98% antimicrobial activity against *Staphylococcus epidermidis* (*S. epidermidis*) and 99.99% filtration efficiency with low pressure drop.[96] The advantages of using natural extracts are low cost, low toxicity, and reduced environmental harshness.[93,97,98] However, durability is a point of concern because natural products are easily impacted by temperature and natural oxidation.[72,95,99]

*5.4.3. Use of MOFs.* MOFs combined with fibers have demonstrated excellent antimicrobial effects. The presence of uniformly distributed metal active sites, their porous structures, and high surface areas endow MOFs with promising antimicrobial characteristics and high filtration efficiencies.[100,101] The combination of MOFs and cellulose fibers (CFs, ZIF-8@CF) exhibited a 99.99% photocatalytic biocidal affect against *E. coli*, with the removal of 96.8% $PM_{2.5}$ at a low pressure drop.[91] The bactericidal effect is due to the production of ROS because the photoelectrons at $Zn^+$ centers become trapped.[91] MOFs have demonstrated potential action against microbes present in the, which increases the filtering capacity of the filter fibers.

*5.4.4. Use of Chemical Disinfectants.* The safe use of masks involves the utilization of various household and synthetic chemicals to kill surface microbes. A coating of citric acid on the exterior mask surface inactivates the hemagglutinin (HA) of the virus membrane and prevents it from undergoing pathogenesis.[102,103] NaCl (table salt) is an important virucidal agent that attacks virus membranes and increases the filtration efficiency of coated filters.[104] Some cationic ammonium compounds, e.g., 3-(trimethoxysilyl)propyl dimethyl octadecyl ammonium chloride and related products, are used to surface-coat glass and fibers to prevent microbial effects. Hence, this same principle is used in facemasks, even though biocidal activity has not been reported.[105]

*5.4.5. Use of 2D Materials.* Two-dimensional materials such as $MoS_2$, graphene, and graphene products are good antimicrobial agents due to their sharp edges that can act as nanoknives and damage microbial cells. Some of these materials exhibit photocatalytic and photothermal effects, which enhance antimicrobial properties.[106] The use of these materials on mask-filter surfaces enhances microbicidal properties;[107,108] consequently, filtration efficacy needs to be studied.

**5.5. Nanotechnologies for COVID-19 Facemasks.** The ongoing COVID-19 pandemic has increased the potential risk to frontline healthcare professionals, as well as aged and immunocompromised people, due to the lack of a vaccine or appropriate therapy. Hence, PPE provides one of the few solutions to this problem, especially commonly available facemasks, and nanotechnology-based improvements to PPE can help to fight COVID-19[109] because they are comfortable and safe to use while protecting against biological and chemical risks. The use of nanotechnology in personal protective equipment, especially facemasks, can increase hydrophobicity and antimicrobial activity without affecting the air filtration rate and state of the material; these properties help to repel the COVID-19 virus during sneezing and coughing. As a nanomaterial, nanofibers are light, easy to use, and comfortable, and can prevent particles less than 50 nm in size from passing through, which cannot be achieved by surgical facemasks that are unable to prevent particles in the 10−80 nm range from passing through. Consequently, nanofiber-based masks can comfortably be used by frontline health workers for long times without irritation caused by temperature and pressure. Modifying the surface of a facemask with nanoparticles that can inactivate viruses through oxidation is another strategy for combatting COVID-19 as it attaches itself to the surface.[110] Conductive microporous graphene can trap microbes and use electrical charges to destroy them; this is also applicable to SARS-CoV-2.[111] Apart from their photothermal and photodynamic properties, these kinds of nanomaterial generate reactive oxygen species (ROS) as part of their intrinsic antiviral mechanism.[112] Various biodegradable lipid-based nanomaterials are being used, with human health and the environment as priorities.[112] Modifying nanocomposites by combining bio-adhesive shellac and copper nanoparticles imparts self-cleaning properties and photoactivity, which can deactivate the COVID-19 virus.[113]

**5.6. Comfort Design, Self-Sterilization, and Cost Effectiveness.** The current pandemic has made wearing a mask compulsory. Wearing masks for prolonged times is uncomfortable for most people. Hence, improved breathing ability and comfort are required to facilitate the prolonged use of masks.[9] Comfort is characterized by lightness and softness; comfortable masks should be easily attached by ear loops that do not affect the face. The microencapsulation of paraffin wax aids temperature transition; it absorbs the heat generated during respiration and melts, thereby decreasing the temperature inside the mask. The wax then resolidifies as energy is released. Thus, it maintains the cooling system inside the mask and the face area, which makes it user-friendly.[114,115] Some N95 masks contain microfans, which can be particularly useful in tropical climates. The use of changeable filters can provide comfort after prolonged use of the same mask. 3D printed skeletons aid in the design of comfortable, airtight masks with improved breathability. The majority of medical masks are disposable, which is environmentally burdensome; hence, sterilization is a significant step toward making masks reusable, cost-effective, and eco-friendly. Various sterilization approaches, such as Joule heating, UV disinfection, and the use of materials that self-sterilize under sunlight or have specific mechanical properties make conventional homemade and medical masks reusable, thereby reducing the financial burden of continuously purchasing masks.[116]

## 6. FILTRATION EFFICIENCY

Given the abundance of mask shapes, colors, and materials, it is difficult to predict the most protective mask. This pandemic has prompted the rapid development of mask manufacturing industries; further, one of the most important factors of mask selection is its filtration efficacy.[10] SARS-CoV-2 particles are transmitted from person to person by aerosols that are exhaled during breathing, coughing, or talking,[16] with the largest droplets influenced by gravity. Therefore, the majority of droplets precipitate before contacting the target; however, a small fraction (<3 $\mu$m) are primarily governed by diffusion and

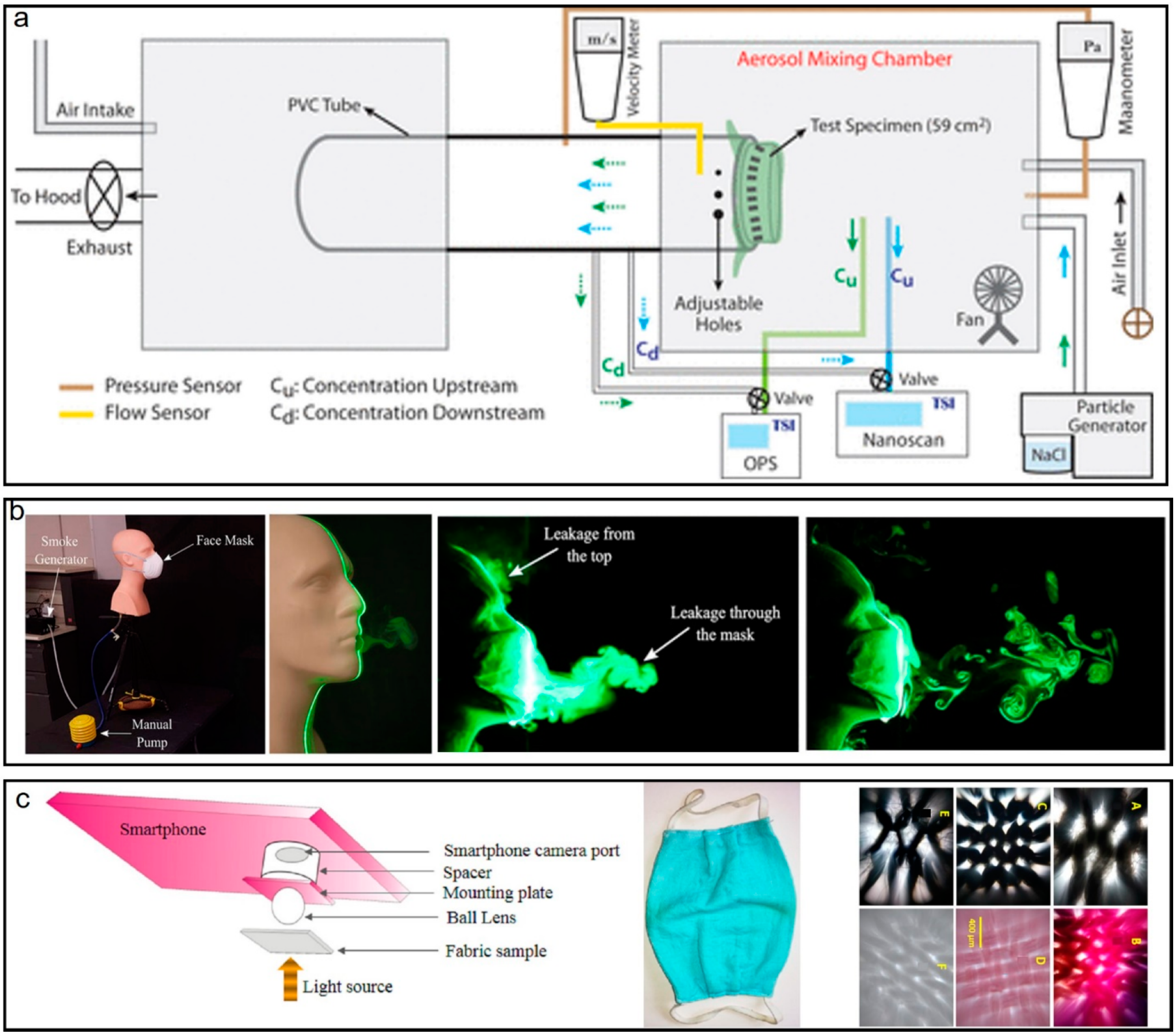

**Figure 5.** (a) Schematic of the experimental setup. A polydisperse NaCl aerosol was introduced into the mixing chamber, where it was mixed and passed through the material being tested (i.e., the test specimen). The test specimen was held in place using a clamp for a better seal. The aerosol was sampled before (upstream, $C_{up}$) and after (downstream, $C_{down}$) it passed through the specimen. The pressure difference was measured using a manometer, and the aerosol flow velocity was measured using a velocity meter. Two circular holes with a diameter of 0.635 cm were used to simulate the effect of gaps on the filtration efficiency. The sampled aerosols were analyzed using particle analyzers (OPS and Nanoscan), and the resultant particle concentrations were used to determine the filter efficiencies. Reproduced from ref 32. Copyright 2020 American Chemical Society. (b) Left two panels, experimental setup for qualitative visualization of simulated coughs and sneezes; right two panels, laser sheet illuminating a puff emerging from the mouth. Facemask constructed using a folded handkerchief. Images taken at 0.5 and 2.27 s. Reproduced with permission from ref 122. Copyright 2020 AIP Publishing. (c) Left, Schematics of the optical setup of the smartphone microscope. Middle, Photograph of a cloth facemask used in this study. Right, Bright field optical images of cloth facemask. Bright patches and dark regions are the pores and the yarns, respectively. Reproduced with permission from ref 123. Copyright 2020 PeerJ.

electrostatic interactions.[9] Therefore, the efficiency of the mask depends on multiple factors, such as material type, the number of layers in the mask, and how the mask fits the person's face. The following methods should be used to evaluate mask performance.

**6.1. Automatic Filter Testing.** The efficiency of a facemask is conventionally estimated by measuring the particle concentration before and after particle filtration. For this purpose, automatic filter testers are typically used.[117] This apparatus usually contains an aerosol generation pump, which generates NaCl or oil solution particles that are spread by the air pump through the filter. The setup also consists of a pressure flowmeter to ensure similarity with physiological conditions. The input and output droplet concentrations are measured by a photometer. This measurement principle has been approved by NOISH.[117]

To quantify efficiency, various metrics are used:

filtration efficiency:

$$\mathrm{FE} = \frac{C_{up} - C_{down}}{C_{up}} \times 100\%$$

where $C_{down}$ and $C_{up}$ are the downstream and upstream filter concentrations, respectively. The formula describes the fraction of particles filtered by the filter.[117]

Table 3. Comparison of the Decontamination Methods for Facemasks

| decontamination type | advantages | disadvantages | ref |
|---|---|---|---|
| UV irradiation | • simple and robust method<br>• can be done in everyday settings<br>• provides good decontamination | • timing and energy of exposure should be appropriate; otherwise mask can be damaged<br>• may not cover the whole area | 125−130 |
| dry heating | • simple and robust method<br>• can be done in everyday settings<br>• can cover the whole mask area<br>• provides good decontamination | • heat can easily damage mask and increase the particle penetration | 126, 127 |
| steam heating | • simple and robust method<br>• can be done in everyday settings<br>• can cover the whole mask area<br>• provides good decontamination | • if temperature is too high, mask fibers may be damaged | 126, 127 |
| hydrogen peroxide vapor | • can cover the whole mask area<br>• high capacity | • requires special equipment | 126,127 |
| organic solvents (ethanol, isopropanol), bleach | • can be done in everyday settings | • increases the particle penetration of the mask | 126, 127 |
| soap | • can be done in everyday settings | • removes the fiber charge; increases the particle penetration | 126, 127 |
| UV + microwave | • provides good decontamination | • increases the particle penetration of mask | 129, 130 |

protection degree:

$$\mathrm{PD} = \left(1 - \frac{\int (C_{\mathrm{wf}}/C_{\mathrm{D}})\,\mathrm{d}t}{\int (C_{\mathrm{nf}}/C_{\mathrm{D}})\,\mathrm{d}t}\right) \times 100\%$$

where $C_{\mathrm{wf}}$ and $C_{\mathrm{nf}}$ are the output concentrations without a mask and CD is the concentration of particles at a certain distance from the source. The integrals in this equation show the level of particle exposure over time.[118]

penetration:

$$P = \frac{C_{\mathrm{down}}}{C_{\mathrm{up}}} \times 100\%$$

This criterion identifies which portion of the particles penetrating the filter.[119]

Various studies were conducted using an automated filter tester (AFT) to determine mask performance. Konda et al. used NaCl aerosol to estimate the filtration efficiency of different fabrics (Figure 5a).[32] In this study, cotton quilt, silk, flannel, chiffon, and various combinations of multilayered fabric masks were compared to N95 and surgical masks. The combination of one layer of cotton, two layers of silk, and one layer of chiffon yielded a result comparable to that of the N95 mask. NaCl aerosol testing using human volunteers was performed by Sickbert-Bennet et al. Various commercial masks were examined and different designs and sizes were compared. The results revealed that mask fitting is important for efficiency; further, surgical masks with ties fit the face almost twice as well as those with ear loops. Also, the wrong size of respirator led to worse performance than a well-chosen one.[120] Lai et al. investigated the leakage effect on the masks. Different mask fits were tested under different air flow conditions, with a fully sealed fit demonstrating a higher degree of protection; however, the mask performed worse over time.[118] Jung et al. tested various mask designs, including ones with different sides and layers. The most effective mask was the KF94 quarantine mask. In contrast, cotton masks exhibited high particle penetration. Pressure drops were measured and found to meet NIOSH, and KFDA standards.[119]

### 6.2. Alternative Methods of Efficiency Testing.

Although the AFT method is a good standard technique for understanding mask efficiency in industrial settings, it does not consider variations in human face shapes and wearing behavior. In addition, it is difficult to incorporate a biological sample, which is crucial when considering the viability of living pathogens in respiratory droplets.

Leung et al. conducted a study on mask wearing among persons of different genders and ages, which demonstrated the effectiveness of masks during the pandemic. Respiratory aerosols were collected from individuals who were breathing and coughing while wearing masks. In this study, the existence of four strains of coronavirus, three strains of influenza A, and rhinovirus in respiratory droplets was assessed. Wearing surgical masks resulted in a decline in the presence of influenza A and coronavirus; however, no difference was observed for rhinovirus.[2] To assess bacterial filtration during sneezing, Rodriguez-Palacios et al. mimicked sneezing activity by applying a high-volume trigger single-v-orifice sprayer. A bacterial suspension was sprayed on agar plates from various distances through different textile materials having more droplet patterns and estimation of bacterial count. On the basis of the results, the most effective fabric was that of the three-layer surgical mask, whereas the least effective fabric was single-layered cotton.[121] To increase awareness of mask type and the effectiveness of mask fitting, Verma et al. developed a method for visualizing the effectiveness of masks. The fog from a vapor generator machine was supplied to a manikin and

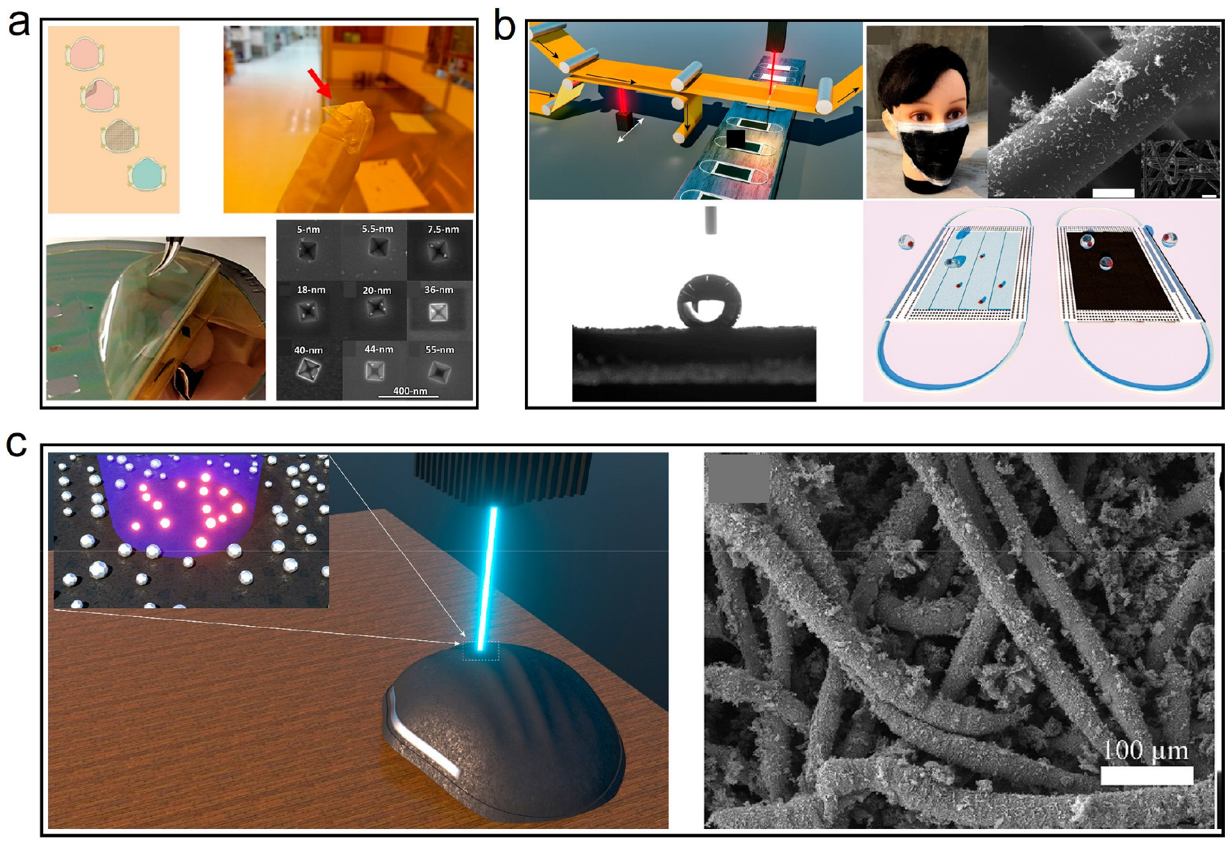

**Figure 6.** (a) Schematic showing the use of the nanoporous membrane fabricated on an 8 in. wafer on a reusable N95 mask after folding it. The membrane can be replaced after every use. Scanning electron microscopy images of the nanoapertures. Reproduced with permission from ref 137. Copyright 2020 American Chemical Society. (b) Demonstration of the dual-mode LIFT for roll-to-roll production of a graphene-coated mask. Right upper, photograph and SEM images of the laser-fabricated graphene mask. Left down, superhydrophobic surface of graphene-coated mask measured by water contact angle. Right down, demonstration of self-cleaning properties of facemask. Reproduced with permission from ref 116. Copyright 2020 American Chemical Society. (c) Left, illustration of the 405 nm laser diode decontamination. The inset illustrates the plasmonic heating of the silver NPs. Right, FESEM image of the sample after 100 cycles of laser decontamination. Reproduced with permission from ref 144. Copyright 2020 American Chemical Society.

visualized by a high-speed camera. The results showed that stitched masks may be as effective as commercial masks, while one-layered bandanas were not (Figure 5b).[122] The most crucial factors for efficacy are the material and design. Neupane et al. developed a mobile phone microscope that enables the pore size of a mask to be visualized. Although filtration was not investigated, the authors postulate that there may be a correlation with particle penetration (Figure 5c).[123]

## 7. DECONTAMINATION

In 2020, the global COVID-19 pandemic resulted in the widespread use of personal protection equipment, such as facemasks, in public places.[124] However, owing to the shortage of PPE and its negative environmental impact, facemasks that were originally designed for single use, should be reused. The main requirements for decontamination methods are that they should not (1) ruin the structural integrity of the mask, (2) impact proper fitting, (3) impact filtration efficiency, and (4) leave residual chemicals (Table 3). Recent studies have proposed various physical and chemical sanitization methods, which are discussed below.[9]

**7.1. Physical Methods of Decontamination.** UV irradiation is one of the methods routinely used to decontaminate medical equipment. Multiple studies have investigated the decontamination of N95 respirators with UV light, which negligibly (<5%) impacted the filtration performance of the masks. The recommended disinfection energy is 3 J/cm$^2$, which is higher than that required for influenza viruses and SARS-CoV-2 to survive. In addition, sterilization using UV radiation is not recommended if the mask is wet, the mask has already undergone three UV exposure procedures, the lifespan of the mask is complete, or the mask has been contaminated by the user's biofluids.[125] Another method of decontamination involves heating, which includes, but is not limited to, the use of microwaves, rice cookers, and autoclaves.[105] Viscusi et al. used the microwave decontamination approach, which melted the SN95-E and P-100 respirator models after 2 min exposure in a 1100 W oven.[126]

The steaming and dry heating of the N95 mask in an autoclave were investigated by Lin et al. The mask was placed in an autoclave for 15 min at 121 °C, which led to the death of almost 100% of *Bacillus subtilis* spores. Also, in this study, a rice cooker was used as a dry-heating decontamination method for 3 min at temperatures ranging from 149 to 164 °C. Unlike the study mentioned earlier, the performance of the respirator was not impacted.[127]

**7.2. Chemical Methods of Decontamination.** Hydrogen peroxide vapor or a liquid organic solvent is used in chemical decontamination methods. Hydrogen peroxide vapor is extensively used to sterilize facilities and hospital equipment;

this procedure is performed using a hydrogen peroxide vaporizer. The main advantage of this method compared to UV irradiation is that the former does not have "blind spots" and homogeneously sanitizes the entire area.[9] Also, compared to other chemical methods, hydrogen peroxide is readily decomposed; therefore, it does not leave harmful residuals on the mask.[9] Kumar et al. demonstrated that treating the N95 respirator with 35% hydrogen peroxide vapor for 1 h did not leave any viable SARS-CoV-2.[128] Other chemical methods include the use of organic solvents, such as ethanol and isopropanol, and bleach and soap. Lin et al. compared disinfection using 70% ethanol, 100% isopropanol, and 0.5% bleach. N95, gauze, and Spunlace masks were dipped into these solutions for 10 min. In all cases, particle penetration increased.[129] Shaffer et al. used 1 g/L soap solution and immersed N95 and P100 respirators for 2 and 20 min, respectively. In all cases, particle penetration for both respirators increased due to the loss of fiber charge.[126]

**7.3. Hybrid Methods.** Rather than using a single decontamination method, hybrid methods involve the combination of several physical methods. He et al. demonstrated the integrated disinfection of surgical masks, FFP1, FFP2, and FFP3, using both UV radiation and microwave heating. Compared to the use of single methods, such as UV, microwave, ethanol, and steam treatments, the combined method exhibited the highest bacterial mortality rate; however, the combined method was also the worst in terms of recovery.[129] Another study that combined UV and moist heating was conducted by Banerjee et al. In this study, the parameters for the most cost-effective and efficient removal of pathogens without damaging the mask were determined.[130]

Despite the variety of methods, there is still room for improvement. Chemical and hybrid approaches are more likely to cause fiber damage that can reduce the lifespan of the mask; therefore, physical approaches are preferred.

## 8. RECENT ADVANCES IN FACEMASK MATERIALS

The COVID-19 pandemic has revealed the urgent need for innovative materials as effective antiviral fabrics.[131] Although existing materials used for facemasks provide good levels of protection, intensive research efforts have been devoted to improving their performance and comfort. Material development has focused on improving the filtering efficiency and engineering additional antimicrobial functionalities for large-scale approaches.[132] On the basis of the abundance of approaches for chemical functionalization, materials engineering provides multiple approaches to withstanding this crisis. To prevent the spread of COVID-19, healthcare workers and the general public are encouraged to wear masks that can self-sterilize, thus enabling reuse or recyclability.[6] To combat this pandemic, a multidisciplinary perspective encompassing diverse fields, such as virology, biology, medicine, engineering, chemistry, materials science, and computational science, is required. In the past decade, knowledge regarding antimicrobial surfaces has increased, which could be used against different classes of virus, including new variants.[133−135] These surface modifications are resistant to viral adhesion and can kill viruses. Recently, facemasks have been subjected to intensive research to improve filtration efficiency, user comfort, and performance by properly designing the material composition.[136] In this section, we introduce recent advances in the efficient filtration and removal of viruses by facemasks.

**8.1. Facemask Modification by Advanced Filters.** Owing to the COVID-19 pandemic, the CDC has recommended the use of N95 filters, which have a minimum filtration efficiency of 95% for particles that are 0.3 $\mu$m in size. However, SARS-CoV-2 is actually ~150 nm in size. Therefore, to increase viral filtration efficiency, facemasks must capture fine PM. Existing commercial facemasks mainly comprise randomized polymer fibers with diameters ranging from a few micrometers to tens of micrometers. Owing to the porous structure of the thick layer of polymer fibers, tiny particles may be trapped. These densely packed fibers influence the performance of facemasks by enabling the virus to be captured more efficiently, whether mechanically, electrostatically, or chemically. For example, the use of flexible nanoporous membranes in N95 masks has been demonstrated to facilitate their reuse (Figure 6a).[137,138] These polymeric membranes, with pores down to 5 nm in size, less than 0.12 g in weight, and theoretical airflow rates above 85 L/min exhibit excellent breathability. Therefore, a proposed solution involves the development of nanoporous membranes that can be attached to an N95 mask to provide additional protection against SARS-CoV-2.

**8.2. Facemask Modification by Superhydrophobic Substances.** Superhydrophobic surfaces possess self-cleaning features that have been significantly utilized in medical sciences.[138−141] The surfaces of facemasks containing polymer fibers are smooth at the nanoscale level but lack superhydrophobic properties. Recently, the surface of a facemask was modified with graphene using a dual-mode laser. This graphene-modified surface demonstrated remarkable self-cleaning properties due to its superhydrophobic nature (Figure 6b). The wettability of the mask surface was investigated by measuring the static contact angle, which increased from 110° to 141°. This superhydrophobic mask can repel incoming aqueous droplets. The nonwetting enhancement of the facemask was due to the laser-induced transfer of nanostructured flakes to smooth fibers with diameters of ~20 $\mu$m.[116]

**8.3. Facemask Modification Using Photothermal Materials.** SARS-CoV-2 can be deactivated at 56 °C within 15 min.[142,143] Consequently, mask surfaces have been modified using nanomaterials to enable self-sterilization. Plasmonic heating has recently been used to deactivate the virus. During plasmonic heating, photonic energy is converted into heat through the vibration of photon-excited electrons into phonons. Silver NPs were directly deposited on the surface of an N95 mask by pulsed laser-induced transfer. This NP-modified surface exhibited broad optical absorption with an absorption band at 405 nm, indicative of plasmonic-enhanced absorption through silver NP modification. Plasmonic photothermal decontamination was studied using solar energy (600 W/m$^2$), which resulted in a 60 °C increase in temperature; such a high temperature sufficiently inactivated SARS-CoV-2 (Figure 6c).[144] Due to their photothermal properties, graphene-coated masks have also been used to sterilize viruses that can potentially remain on the facemask surface. Graphene-coated masks demonstrated excellent absorption (>95%) across the entire solar spectrum (300−2500 nm). The surface temperatures of graphene-coated masks were elevated (>70 °C) within 40 s of solar illumination. The graphene coating endowed the mask with promising self-sterilization features.[145]

**8.4. Facemask Modification Using Photocatalytic Materials.** Photocatalysis is a unique antiviral strategy for inactivating SARS-CoV-2. After irradiation with light, photocatalytic materials generate ROS in the presence of oxygen, which ultimately attack the virus, damaging its proteins, nucleic acids, and lipid membrane. $TiO_2$-based photocatalytic materials exhibit markedly low hole−electron recombination rates, as well as fast interfacial charge carrier transfer rates, which are favorable for enhancing photocatalytic activity.[146,147] Recently, a $TiO_2$ nanowire-based filter was successfully developed for facemask applications. The enhanced photocatalytic properties of this mask contributed to producing ROS upon UV illumination. The size of the facemask filter can be tuned during the fabrication of $TiO_2$ nanowires on the filter paper, which enables the efficient trapping of pathogens of different sizes. This filter was easily sterilizable and reusable, and exhibited antiviral properties, thereby providing a potent preventative tool against the rapid transmission of SARS-CoV-2 during the pandemic.[148]

## 9. FUTURE PERSPECTIVES AND CONCLUSION

Since the World Health Organization (WHO) recommended wearing facemasks in public areas, the global demand for facemasks has escalated, thus impacting the world. This COVID-19 pandemic era has prompted new social norms, including the wearing of facemasks. Further, there has been rapid industrial and scientific advancements regarding the use of facemasks to reduce COVID-19 transmission. An economic analysis has suggested that public mask wearing could save thousands of U.S. dollars per person per mask. Governments and health authorities have provided clear guidelines for the production, use, and sanitization of facemasks. In addition, numerous countries have distributed surgical masks (South Korea, Japan, and Taiwan) to ensure access to masks with proper distribution and rationing mechanisms, thus limiting discrimination.

**9.1. Environmental Impact of Facemasks.** Existing textile industries are reported to be the second largest source of environment pollution after the oil industry. Since the COVID-19 outbreak, the general public has begun wearing facemasks, which has generated demand for raw materials, thus causing negative environmental impacts.[149] A study from University College London (UCL) suggested that 66,000 tons of contaminated plastic waste would be produced if each person in the United Kingdom began to wear a facemask each day for a year. On the basis of this prediction, 178,200 tons of greenhouse gases would be released into the environment per year. Further, the subsequent amount of energy required for manufacture, transportation, and incineration would also be expected to further increase the carbon footprint of facemasks.[150] When considered on a global scale, such a substantial amount of medical waste will severely impact the ecosystem and human health. In contrast, a recent survey demonstrated that over 21% of doctors working in high-risk areas during the pandemic reported shortages of facemasks. Given this dilemma, we must address both challenges, which requires cooperation between policy makers, industry personnel, researchers, and the general public.[151] This sudden demand for masks will exacerbate existing global environmental issues. Therefore, research needs be undertaken in the textile industry to design smart, environmentally sustainable, protective materials that are washable and reusable and that can potentially reduce the amount of medical waste contributing to environmental pollution.[152]

**9.2. Global Market for Facemasks.** The global protective facemask market is expected to undergo impressive growth due to increasing safety concerns among people. In 2018, nonwoven fabrics accounted for 64.3% of the global medical textiles market. Prior to the COVID-19 pandemic, the global personal protective equipment market was expected to grow to U.S. dollar 79.66 billion at a compound annual growth rate of ~6.6% from 2018. Since the outbreak of COVID-19, the global demand for nonwoven fabrics was projected to grow at an average rate of 5.0% per annum, but supplies are running low. Owing to the crisis, the price of raw materials, such as PP fiber, has increased in Asia, and some countries have imposed export bans on raw materials for making facemasks.[14]

**9.3. Social and Health Impact.** Following the outbreak of COVID-19, people have faced unprecedented challenges. Wearing facemasks for the entire day could result in heat stress, discomfort to the skin, and potential emotional and social losses during communication.[153] Our new social norms require the same thought as to where our actions are interconnected, which extend beyond boundaries and cultural heterogeneity.[154] The real challenge moving forward will be how to better understand the areas in which the health of humans, animals, plants, and the environment interface, which is the fundamental concept underlying the One Health approach. The current challenge should be embraced as an opportunity to remind our globalized world that there are critical scientific solutions to address this situation, owing to multidisciplinary knowledge and diversity.[155]

**9.4. Sustainable Solution for Facemasks.** The unprecedented challenges in the textile industry have provided a new opportunity to combat current difficulties. Plastic-based disposable items used by the general public contribute to plastic pollution in oceans. New technologies that replace these plastics or sterilize this infectious waste should be investigated urgently. Reusing facemasks provides a straightforward method for reducing plastic-based pollution.[149] The manufacture of facemasks should involve the use of biodegradable polymers or natural materials, such as cellulose or cotton, which can replace the current plastic-based facemasks. The use of changeable filter layers that can be replaced inside the facemask is also a viable option. In addition, advanced features could be incorporated into the design of facemasks to enable self-sanitizing and self-cleaning.

**9.5. Advancements in Cloth Masks.** The emergence of COVID-19 has resulted in the global wearing of masks as a preventive measure. Mask demand is so high that a disposable facemask crisis has resulted; this demand and supply chain has given rise to a new critical environmental challenge by adding 250,000 tons of plastic pollution per day.[113] The preparation of polypropylene, which is used to make disposable masks, emits toxic dioxin to the environment, which is a cause of air pollution.[156] Reusable, sustainable, and environmentally friendly masks provide a solution to this problem. Cloth masks are alternatives to polypropylene masks;[149,156] however, they are not as effective as respirators and medical masks, but they can be improved to overcome the current pandemic and environmental problems. The quality of a cloth mask can be improved through modification; for example by altering the material type and its parameters (thickness, weight, and water resistance) and its construction (number of layers, TPI) such that nanometer-sized particles can be filtered.[157] The efficacies of these materials are based on fit and filtration. A loosely fitting mask is a high-risk factor for infection, as tiny particulates easily pass through gaps. There needs to be a balance between proper fit and filtration efficiency, and improving one of these aspects cannot increase effectiveness alone.[158] Critical analyses of alternative sources will effectively enhance waste management while limiting COVID-19 transferal.[149]

This COVID-19 pandemic has prompted global research into developing viable, better-protecting, and comfortable facemask solutions through materials innovation and technology advancement. This review summarizes facemasks developed from the perspective of public health and discusses present research efforts into engineering facemasks with advanced properties, such as antimicrobial activity, superhydrophobicity, transparency, self-cleaning, and detection capabilities.

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### Notes

The authors declare no competing financial interest.

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## ■ REFERENCES

(1) Tellier, R. Review of aerosol transmission of influenza A virus. *Emerging Infect. Dis.* **2006**, *12* (11), 1657−1662.

(2) Leung, N. H. L.; Chu, D. K. W.; Shiu, E. Y. C.; Chan, K.-H.; McDevitt, J. J.; Hau, B. J. P.; Yen, H.-L.; Li, Y.; Ip, D. K. M.; Peiris, J. S. M.; Seto, W.-H.; Leung, G. M.; Milton, D. K.; Cowling, B. J. Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nat. Med.* **2020**, *26* (5), 676−680.

(3) Brankston, G.; Gitterman, L.; Hirji, Z.; Lemieux, C.; Gardam, M. Transmission of influenza A in human beings. *Lancet Infect. Dis.* **2007**, *7* (4), 257−265.

(4) Kutter, J. S.; Spronken, M. I.; Fraaij, P. L.; Fouchier, R. A. M.; Herfst, S. Transmission routes of respiratory viruses among humans. *Curr. Opin. Virol.* **2018**, *28*, 142−151.

(5) Bai, Y.; Yao, L.; Wei, T.; Tian, F.; Jin, D.-Y.; Chen, L.; Wang, M. Presumed Asymptomatic Carrier Transmission of COVID-19. *JAMA* **2020**, *323* (14), 1406−1407.

(6) Worby, C. J.; Chang, H.-H. Face mask use in the general population and optimal resource allocation during the COVID-19 pandemic. *Nat. Commun.* **2020**, *11* (1), 4049.

(7) Anderson, R. M.; Heesterbeek, H.; Klinkenberg, D.; Hollingsworth, T. D. How will country-based mitigation measures influence the course of the COVID-19 epidemic? *Lancet* **2020**, *395* (10228), 931−934.

(8) Leung, C. C.; Lam, T. H.; Cheng, K. K. Mass masking in the COVID-19 epidemic: people need guidance. *Lancet* **2020**, *395* (10228), 945.

(9) Chua, M. H.; Cheng, W.; Goh, S. S.; Kong, J.; Li, B.; Lim, J. Y. C.; Mao, L.; Wang, S.; Xue, K.; Yang, L.; Ye, E.; Zhang, K.; Cheong, W. C. D.; Tan, B. H.; Li, Z.; Tan, B. H.; Loh, X. J. Face Masks in the New COVID-19 Normal: Materials, Testing, and Perspectives. *Research* **2020**, *2020*, 7286735.

(10) Eikenberry, S. E.; Mancuso, M.; Iboi, E.; Phan, T.; Eikenberry, K.; Kuang, Y.; Kostelich, E.; Gumel, A. B. To mask or not to mask: Modeling the potential for face mask use by the general public to curtail the COVID-19 pandemic. *Infectious Disease Modelling* **2020**, *5*, 293−308.

(11) Li, T.; Liu, Y.; Li, M.; Qian, X.; Dai, S. Y. Mask or no mask for COVID-19: A public health and market study. *PLoS One* **2020**, *15* (8), No. e0237691.

(12) van der Sande, M.; Teunis, P.; Sabel, R. Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population. *PLoS One* **2008**, *3* (7), No. e2618.

(13) Bar-On, Y. M.; Flamholz, A.; Phillips, R.; Milo, R. SARS-CoV-2 (COVID-19) by the numbers. *eLife* **2020**, *9*, No. e57309.

(14) Karim, N.; Afroj, S.; Lloyd, K.; Oaten, L. C.; Andreeva, D. V.; Carr, C.; Farmery, A. D.; Kim, I.-D.; Novoselov, K. S. Sustainable Personal Protective Clothing for Healthcare Applications: A Review. *ACS Nano* **2020**, *14*, 12313−12340.

(15) Santarpia, J. L.; Rivera, D. N.; Herrera, V.; Morwitzer, M. J.; Creager, H.; Santarpia, G. W.; Crown, K. K.; Brett-Major, D.; Schnaubelt, E.; Broadhurst, M. J.; Lawler, J. V.; Reid, S. P.; Lowe, J. J. Aerosol and Surface Contamination of SARS-CoV-2 Observed in Quarantine and Isolation Care. *Sci. Rep.* **2020**, *10*, 12732.

(16) van Doremalen, N.; Bushmaker, T.; Morris, D. H.; Holbrook, M. G.; Gamble, A.; Williamson, B. N.; Tamin, A.; Harcourt, J. L.; Thornburg, N. J.; Gerber, S. I.; Lloyd-Smith, J. O.; de Wit, E.; Munster, V. J. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382* (16), 1564−1567.

(17) Ching, P.; Harriman, K.; Li, Y. *Infection prevention and control of epidemic-and pandemic-prone acute respiratory diseases in health care: WHO interim guidelines*; World Health Organization (WHO): Geneva, Switzerland, 2007; pp 1−90.

(18) Siegel, J. D.; Rhinehart, E.; Jackson, M.; Chiarello, L.; Health Care Infection Control Practices Advisory Committee.. 2007 Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Health Care Settings. *Am. J. Infect. Control* **2007**, *35* (10), S65−S164.

(19) Hall, C. B.; Douglas, R. G.; Schnabel, K. C.; Geiman, J. M. Infectivity of respiratory syncytial virus by various routes of inoculation. *Infect. Immun.* **1981**, *33* (3), 779−783.

(20) Anfinrud, P.; Stadnytskyi, V.; Bax, C. E.; Bax, A. Visualizing Speech-Generated Oral Fluid Droplets with Laser Light Scattering. *N. Engl. J. Med.* **2020**, *382* (21), 2061−2063.

(21) Asadi, S.; Wexler, A. S.; Cappa, C. D.; Barreda, S.; Bouvier, N. M.; Ristenpart, W. D. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* **2019**, *9* (1), 2348.

(22) Stadnytskyi, V.; Bax, C. E.; Bax, A.; Anfinrud, P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. *Proc. Natl. Acad. Sci. U. S. A.* **2020**, *117* (22), 11875−11877.

(23) Bourouiba, L. Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. *JAMA* **2020**, *323* (18), 1837−1838.

(24) Tcharkhtchi, A.; Abbasnezhad, N.; Zarbini Seydani, M.; Zirak, N.; Farzaneh, S.; Shirinbayan, M. An overview of filtration efficiency through the masks: Mechanisms of the aerosols penetration. *Bioactive Materials* **2021**, *6* (1), 106−122.

(25) Ippolito, M.; Vitale, F.; Accurso, G.; Iozzo, P.; Gregoretti, C.; Giarratano, A.; Cortegiani, A. Medical masks and Respirators for the Protection of Healthcare Workers from SARS-CoV-2 and other viruses. *Pulmonology* **2020**, *26* (4), 204−212.

(26) Zhou, S. S.; Lukula, S.; Chiossone, C.; Nims, R. W.; Suchmann, D. B.; Ijaz, M. K. Assessment of a respiratory face mask for capturing air pollutants and pathogens including human influenza and rhinoviruses. *J. Thorac. Dis.* **2018**, *10* (3), 2059−2069.

(27) Yao, B.-g.; Wang, Y.-x.; Ye, X.-y.; Zhang, F.; Peng, Y.-l. Impact of structural features on dynamic breathing resistance of healthcare face mask. *Sci. Total Environ.* **2019**, *689*, 743−753.

(28) Milton, D. K.; Fabian, M. P.; Cowling, B. J.; Grantham, M. L.; McDevitt, J. J. Influenza Virus Aerosols in Human Exhaled Breath: Particle Size, Culturability, and Effect of Surgical Masks. *PLoS Pathog.* **2013**, *9* (3), No. e1003205.

(29) Anfinrud, P.; Bax, C. E.; Stadnytskyi, V.; Bax, A., Could SARS-CoV-2 be transmitted via speech droplets? *medRxiv (Infectious Diseases (except HIV/AIDS))*, Apr. 6, 2020, 2020.04.02.20051177. https://doi.org/10.1101/2020.04.02.20051177 (accessed 2021-01-13).

(30) Clase, C. M.; Fu, E. L.; Ashur, A.; Beale, R. C. L.; Clase, I. A.; Dolovich, M. B.; Jardine, M. J.; Joseph, M.; Kansiime, G.; Mann, J. F. E.; Pecoits-Filho, R.; Winkelmayer, W. C.; Carrero, J. J. Forgotten Technology in the COVID-19 Pandemic: Filtration Properties of Cloth and Cloth Masks-A Narrative Review. *Mayo Clin. Proc.* **2020**, *95* (10), 2204−2224.

(31) Zhao, M.; Liao, L.; Xiao, W.; Yu, X.; Wang, H.; Wang, Q.; Lin, Y. L.; Kilinc-Balci, F. S.; Price, A.; Chu, L.; Chu, M. C.; Chu, S.; Cui, Y. Household Materials Selection for Homemade Cloth Face Coverings and Their Filtration Efficiency Enhancement with Triboelectric Charging. *Nano Lett.* **2020**, *20* (7), 5544−5552.

(32) Konda, A.; Prakash, A.; Moss, G. A.; Schmoldt, M.; Grant, G. D.; Guha, S. Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks. *ACS Nano* **2020**, *14* (5), 6339−6347.

(33) Quesnel, L. B. The efficiency of surgical masks of varying design and composition. *Br. J. Surg.* **1975**, *62* (12), 936−40.

(34) Greene, V. W.; Vesley, D. Method for evaluating effectiveness of surgical masks. *J. Bacteriol.* **1962**, *83* (3), 663−667.

(35) Davies, A.; Thompson, K.-A.; Giri, K.; Kafatos, G.; Walker, J.; Bennett, A. Testing the efficacy of homemade masks: would they protect in an influenza pandemic? *Disaster Med. Public Health Prep* **2013**, *7* (4), 413−418.

(36) Long, Y.; Hu, T.; Liu, L.; Chen, R.; Guo, Q.; Yang, L.; Cheng, Y.; Huang, J.; Du, L. Effectiveness of N95 respirators versus surgical masks against influenza: A systematic review and meta-analysis. *J. Evid Based Med.* **2020**, *13* (2), 93−101.

(37) Makison Booth, C.; Clayton, M.; Crook, B.; Gawn, J. M. Effectiveness of surgical masks against influenza bioaerosols. *Journal of Hospital Infection* **2013**, *84* (1), 22−26.

(38) Offeddu, V.; Yung, C. F.; Low, M. S. F.; Tam, C. C. Effectiveness of Masks and Respirators Against Respiratory Infections in Healthcare Workers: A Systematic Review and Meta-Analysis. *Clin. Infect. Dis.* **2017**, *65* (11), 1934−1942.

(39) Radonovich, L. J., Jr; Simberkoff, M. S.; Bessesen, M. T.; Brown, A. C.; Cummings, D. A. T.; Gaydos, C. A.; Los, J. G.; Krosche, A. E.; Gibert, C. L.; Gorse, G. J.; Nyquist, A.-C.; Reich, N. G.; Rodriguez-Barradas, M. C.; Price, C. S.; Perl, T. M. N95 Respirators vs Medical Masks for Preventing Influenza Among Health Care Personnel: A Randomized Clinical Trial. *JAMA* **2019**, *322* (9), 824−833.

(40) MacIntyre, C. R.; Seale, H.; Dung, T. C.; Hien, N. T.; Nga, P. T.; Chughtai, A. A.; Rahman, B.; Dwyer, D. E.; Wang, Q. A cluster randomised trial of cloth masks compared with medical masks in healthcare workers. *BMJ. Open* **2015**, *5* (4), No. e006577.

(41) Akalin, M.; Usta, I.; Kocak, D.; Ozen, M. S. Investigation of the Filtration Properties of Medical Masks. In *Medical and Healthcare Textiles*; Anand, S. C., Kennedy, J. F., Miraftab, M., Rajendran, S., Eds.; Woodhead, 2010; pp 93−97, DOI: 10.1533/9780857090348.93.

(42) Banerjee, S. S.; Burbine, S.; Kodihalli Shivaprakash, N.; Mead, J. 3D-Printable PP/SEBS Thermoplastic Elastomeric Blends: Preparation and Properties. *Polymers* **2019**, *11* (2), 347.

(43) Madsen, P. O.; Madsen, R. E. A study of disposable surgical masks. *Am. J. Surg.* **1967**, *114* (3), 431−435.

(44) Skaria, S. D.; Smaldone, G. C. Respiratory Source Control Using Surgical Masks with Nanofiber Media. *Ann. Occup. Hyg.* **2014**, *58* (6), 771−781.

(45) Yang, A.; Cai, L.; Zhang, R.; Wang, J.; Hsu, P.-C.; Wang, H.; Zhou, G.; Xu, J.; Cui, Y. Thermal Management in Nanofiber-Based Face Mask. *Nano Lett.* **2017**, *17* (6), 3506−3510.

(46) Kharaghani, D.; Khan, M. Q.; Shahzad, A.; Inoue, Y.; Yamamoto, T.; Rozet, S.; Tamada, Y.; Kim, I. S. Preparation and In-Vitro Assessment of Hierarchal Organized Antibacterial Breath Mask Based on Polyacrylonitrile/Silver (PAN/AgNPs). *Nanomaterials* **2018**, *8* (7), 461.

(47) Wang, N.; Cai, M.; Yang, X.; Yang, Y. Electret nanofibrous membrane with enhanced filtration performance and wearing comfortability for face mask. *J. Colloid Interface Sci.* **2018**, *530*, 695−703.

(48) Ullah, S.; Ullah, A.; Lee, J.; Jeong, Y.; Hashmi, M.; Zhu, C.; Joo, K. I.; Cha, H. J.; Kim, I. S. Reusability Comparison of Melt-Blown vs Nanofiber Face Mask Filters for Use in the Coronavirus Pandemic. *ACS Applied Nano Materials* **2020**, *3* (7), 7231−7241.

(49) Ahmed, F. E.; Lalia, B. S.; Hashaikeh, R. A review on electrospinning for membrane fabrication: Challenges and applications. *Desalination* **2015**, *356*, 15−30.

(50) Liu, C.; Hsu, P.-C.; Lee, H.-W.; Ye, M.; Zheng, G.; Liu, N.; Li, W.; Cui, Y. Transparent air filter for high-efficiency PM2.5 capture. *Nat. Commun.* **2015**, *6* (1), 6205.

(51) El Morabet, R. Effects of Outdoor Air Pollution on Human Health. *Reference Module in Earth Systems and Environmental Sciences, Encyclopedia of Environmental Health*, 2nd ed.; Elsevier: 2019; pp 278−289, DOI: 10.1016/B978-0-12-409548-9.11509-X.

(52) Wang, X.; Ding, B.; Sun, G.; Wang, M.; Yu, J. Electro-spinning/netting: A strategy for the fabrication of three-dimensional polymer nano-fiber/nets. *Prog. Mater. Sci.* **2013**, *58* (8), 1173−1243.

(53) Wang, N.; Yang, Y.; Al-Deyab, S. S.; El-Newehy, M.; Yu, J.; Ding, B. Ultra-light 3D nanofibre-nets binary structured nylon 6−polyacrylonitrile membranes for efficient filtration of fine particulate matter. *J. Mater. Chem. A* **2015**, *3* (47), 23946−23954.

(54) Tsai, P. P.; Schreuder-Gibson, H.; Gibson, P. Different electrostatic methods for making electret filters. *J. Electrost.* **2002**, *54* (3), 333−341.

(55) Liu, J.; Zhang, H.; Gong, H.; Zhang, X.; Wang, Y.; Jin, X. Polyethylene/Polypropylene Bicomponent Spunbond Air Filtration Materials Containing Magnesium Stearate for Efficient Fine Particle Capture. *ACS Appl. Mater. Interfaces* **2019**, *11* (43), 40592−40601.

(56) Wang, S.; Zhao, X.; Yin, X.; Yu, J.; Ding, B. Electret Polyvinylidene Fluoride Nanofibers Hybridized by Polytetrafluoroethylene Nanoparticles for High-Efficiency Air Filtration. *ACS Appl. Mater. Interfaces* **2016**, *8* (36), 23985−23994.

(57) Liu, F.; Li, M.; Shao, W.; Yue, W.; Hu, B.; Weng, K.; Chen, Y.; Liao, X.; He, J. Preparation of a polyurethane electret nanofiber membrane and its air-filtration performance. *J. Colloid Interface Sci.* **2019**, *557*, 318−327.

(58) Ding, X.; Li, Y.; Si, Y.; Yin, X.; Yu, J.; Ding, B. Electrospun polyvinylidene fluoride/SiO2 nanofibrous membranes with enhanced electret property for efficient air filtration. *Composites Communications* **2019**, *13*, 57−62.

(59) Zhang, H.; Liu, J.; Zhang, X.; Huang, C.; Jin, X. Design of electret polypropylene melt blown air filtration material containing nucleating agent for effective PM2.5 capture. *RSC Adv.* **2018**, *8* (15), 7932−7941.

(60) Jiang, P.; Zhao, X.; Li, Y.; Liao, Y.; Hua, T.; Yin, X.; Yu, J.; Ding, B. Moisture and oily molecules stable nanofibrous electret membranes for effectively capturing PM2.5. *Composites Communications* **2017**, *6*, 34−40.

(61) Gu, G. Q.; Han, C. B.; Lu, C. X.; He, C.; Jiang, T.; Gao, Z. L.; Li, C. J.; Wang, Z. L. Triboelectric Nanogenerator Enhanced Nanofiber Air Filters for Efficient Particulate Matter Removal. *ACS Nano* **2017**, *11* (6), 6211−6217.

(62) Liu, G.; Nie, J.; Han, C.; Jiang, T.; Yang, Z.; Pang, Y.; Xu, L.; Guo, T.; Bu, T.; Zhang, C.; Wang, Z. L. Self-Powered Electrostatic Adsorption Face Mask Based on a Triboelectric Nanogenerator. *ACS Appl. Mater. Interfaces* **2018**, *10* (8), 7126−7133.

(63) Wang, X.; Niu, S.; Yi, F.; Yin, Y.; Hao, C.; Dai, K.; Zhang, Y.; You, Z.; Wang, Z. L. Harvesting Ambient Vibration Energy over a Wide Frequency Range for Self-Powered Electronics. *ACS Nano* **2017**, *11* (2), 1728−1735.

(64) Bai, Y.; Han, C. B.; He, C.; Gu, G. Q.; Nie, J. H.; Shao, J. J.; Xiao, T. X.; Deng, C. R.; Wang, Z. L. Washable Multilayer Triboelectric Air Filter for Efficient Particulate Matter PM2.5 Removal. *Adv. Funct. Mater.* **2018**, *28* (15), 1706680.

(65) Qiu, S.; Xue, M.; Zhu, G. Metal−organic framework membranes: from synthesis to separation application. *Chem. Soc. Rev.* **2014**, *43* (16), 6116−6140.

(66) Li, J.; Zhang, D.; Yang, T.; Yang, S.; Yang, X.; Zhu, H. Nanofibrous membrane of graphene oxide-in-polyacrylonitrile composite with low filtration resistance for the effective capture of PM2.5. *J. Membr. Sci.* **2018**, *551*, 85−92.

(67) Chen, Y.; Zhang, S.; Cao, S.; Li, S.; Chen, F.; Yuan, S.; Xu, C.; Zhou, J.; Feng, X.; Ma, X.; Wang, B. Roll-to-Roll Production of Metal-Organic Framework Coatings for Particulate Matter Removal. *Adv. Mater.* **2017**, *29* (15), 1606221.

(68) Koo, W.-T.; Jang, J.-S.; Qiao, S.; Hwang, W.; Jha, G.; Penner, R. M.; Kim, I.-D. Hierarchical Metal−Organic Framework-Assembled Membrane Filter for Efficient Removal of Particulate Matter. *ACS Appl. Mater. Interfaces* **2018**, *10* (23), 19957−19963.

(69) Hao, Z.; Wu, J.; Wang, C.; Liu, J. Electrospun Polyimide/Metal-Organic Framework Nanofibrous Membrane with Superior Thermal Stability for Efficient PM2.5 Capture. *ACS Appl. Mater. Interfaces* **2019**, *11* (12), 11904−11909.

(70) Lee, D. H.; Jung, J. H.; Lee, B. U. Effect of Treatment with a Natural Extract of Mukdenia Rossii (Oliv) Koidz and Unipolar Ion Emission on the Antibacterial Performance of Air Filters. *Aerosol Air Qual. Res.* **2013**, *13* (2), 771−776.

(71) Woo, C. G.; Kim, H.-J.; Kim, Y.-J.; Han, B. Enhanced Antimicrobial Activity on Non-Conducting and Conducting Air Filters by Using Air Ions and Grapefruit Seed Extract. *Aerosol Air Qual. Res.* **2017**, *17* (7), 1917−1924.

(72) Komaladewi, A. A. I. A. S.; Khoiruddin, K.; Surata, I. W.; Subagia, I. D. G. A.; Wenten, I. G. Recent advances in antimicrobial air filter. *E3S Web Conf.* **2018**, *67*, 03016.

(73) Baranwal, A.; Srivastava, A.; Kumar, P.; Bajpai, V. K.; Maurya, P. K.; Chandra, P. Prospects of Nanostructure Materials and Their Composites as Antimicrobial Agents. *Front. Microbiol.* **2018**, *9*, 422.

(74) Beyth, N.; Houri-Haddad, Y.; Domb, A.; Khan, W.; Hazan, R. Alternative Antimicrobial Approach: Nano-Antimicrobial Materials. *Evidence-Based Complementary Altern. Med.* **2015**, *2015*, 246012.

(75) Lakshminarayanan, R.; Ye, E.; Young, D. J.; Li, Z.; Loh, X. J. Recent Advances in the Development of Antimicrobial Nanoparticles for Combating Resistant Pathogens. *Adv. Healthcare Mater.* **2018**, *7* (13), 1701400.

(76) Binas, V.; Venieri, D.; Kotzias, D.; Kiriakidis, G. Modified TiO2 based photocatalysts for improved air and health quality. *Journal of Materiomics* **2017**, *3* (1), 3−16.

(77) Rudramurthy, G. R.; Swamy, M. K.; Sinniah, U. R.; Ghasemzadeh, A. Nanoparticles: Alternatives Against Drug-Resistant Pathogenic Microbes. *Molecules* **2016**, *21* (7), 836.

(78) Lee, N.-Y.; Ko, W.-C.; Hsueh, P.-R. Nanoparticles in the Treatment of Infections Caused by Multidrug-Resistant Organisms. *Front. Pharmacol.* **2019**, *10*, 1153.

(79) Slavin, Y. N.; Asnis, J.; Häfeli, U. O.; Bach, H. Metal nanoparticles: understanding the mechanisms behind antibacterial activity. *J. Nanobiotechnol.* **2017**, *15* (1), 65.

(80) Sánchez-López, E.; Gomes, D.; Esteruelas, G.; Bonilla, L.; Lopez-Machado, A. L.; Galindo, R.; Cano, A.; Espina, M.; Ettcheto, M.; Camins, A.; Silva, A. M.; Durazzo, A.; Santini, A.; Garcia, M. L.; Souto, E. B. Metal-Based Nanoparticles as Antimicrobial Agents: An Overview. *Nanomaterials* **2020**, *10* (2), 292.

(81) Dizaj, S. M.; Lotfipour, F.; Barzegar-Jalali, M.; Zarrintan, M. H.; Adibkia, K. Antimicrobial activity of the metals and metal oxide nanoparticles. *Mater. Sci. Eng., C* **2014**, *44*, 278−284.

(82) Durán, N.; Durán, M.; de Jesus, M. B.; Seabra, A. B.; Fávaro, W. J.; Nakazato, G. Silver nanoparticles: A new view on mechanistic aspects on antimicrobial activity. *Nanomedicine* **2016**, *12* (3), 789−799.

(83) Feng, S.; Li, D.; Low, Z.-x.; Liu, Z.; Zhong, Z.; Hu, Y.; Wang, Y.; Xing, W. ALD-seeded hydrothermally-grown Ag/ZnO nanorod PTFE membrane as efficient indoor air filter. *J. Membr. Sci.* **2017**, *531*, 86−93.

(84) Zhao, Y.; Low, Z.-X.; Feng, S.; Zhong, Z.; Wang, Y.; Yao, Z. Multifunctional hybrid porous filters with hierarchical structures for simultaneous removal of indoor VOCs, dusts and microorganisms. *Nanoscale* **2017**, *9* (17), 5433−5444.

(85) Hiragond, C. B.; Kshirsagar, A. S.; Dhapte, V. V.; Khanna, T.; Joshi, P.; More, P. V. Enhanced anti-microbial response of commercial face mask using colloidal silver nanoparticles. *Vacuum* **2018**, *156*, 475−482.

(86) Goh, S. S.; Guduguntla, S.; Kikuchi, T.; Lutz, M.; Otten, E.; Fujita, M.; Feringa, B. L. Desymmetrization of meso-Dibromocycloalkenes through Copper(I)-Catalyzed Asymmetric Allylic Substitution with Organolithium Reagents. *J. Am. Chem. Soc.* **2018**, *140* (23), 7052−7055.

(87) Borkow, G.; Gabbay, J. Copper, An Ancient Remedy Returning to Fight Microbial, Fungal and Viral Infections. *Curr. Chem. Biol.* **2009**, *3* (3), 272−278.

(88) Borkow, G.; Zhou, S. S.; Page, T.; Gabbay, J. A Novel Anti-Influenza Copper Oxide Containing Respiratory Face Mask. *PLoS One* **2010**, *5* (6), No. e11295.

(89) Li, Y.; Leung, P.; Yao, L.; Song, Q. W.; Newton, E. Antimicrobial effect of surgical masks coated with nanoparticles. *Journal of Hospital Infection* **2006**, *62* (1), 58−63.

(90) Ganguly, P.; Byrne, C.; Breen, A.; Pillai, S. C. Antimicrobial activity of photocatalysts: Fundamentals, mechanisms, kinetics and recent advances. *Appl. Catal., B* **2018**, *225*, 51−75.

(91) Li, P.; Li, J.; Feng, X.; Li, J.; Hao, Y.; Zhang, J.; Wang, H.; Yin, A.; Zhou, J.; Ma, X.; Wang, B. Metal-organic frameworks with photocatalytic bactericidal activity for integrated air cleaning. *Nat. Commun.* **2019**, *10* (1), 2177.

(92) Ekabutr, P.; Chuysinuan, P.; Suksamrarn, S.; Sukhumsirichart, W.; Hongmanee, P.; Supaphol, P. Development of antituberculosis melt-blown polypropylene filters coated with mangosteen extracts for medical face mask applications. *Polym. Bull.* **2019**, *76* (4), 1985−2004.

(93) Woo, C. G.; Kang, J.-S.; Kim, H.-J.; Kim, Y.-J.; Han, B. Treatment of Air Filters Using the Antimicrobial Natural Products Propolis and Grapefruit Seed Extract for Deactivation of Bioaerosols. *Aerosol Sci. Technol.* **2015**, *49* (8), 611−619.

(94) Huang, R.; Pyankov, O. V.; Yu, B.; Agranovski, I. E. Inactivation of Fungal Spores Collected on Fibrous Filters by Melaleuca alternifolia (Tea Tree Oil). *Aerosol Sci. Technol.* **2010**, *44* (4), 262−268.

(95) Chong, E.-s.; Hwang, G. B.; Nho, C. W.; Kwon, B. M.; Lee, J. E.; Seo, S.; Bae, G.-N.; Jung, J. H. Antimicrobial durability of air filters coated with airborne Sophora flavescens nanoparticles. *Sci. Total Environ.* **2013**, *444*, 110−114.

(96) Choi, J.; Yang, B. J.; Bae, G.-N.; Jung, J. H. Herbal Extract Incorporated Nanofiber Fabricated by an Electrospinning Technique and its Application to Antimicrobial Air Filtration. *ACS Appl. Mater. Interfaces* **2015**, *7* (45), 25313−25320.

(97) Hwang, G. B.; Sim, K. M.; Bae, G.-N.; Jung, J. H. Synthesis of hybrid carbon nanotube structures coated with Sophora flavescens nanoparticles and their application to antimicrobial air filtration. *J. Aerosol Sci.* **2015**, *86*, 44−54.

(98) Hwang, G. B.; Heo, K. J.; Yun, J. H.; Lee, J. E.; Lee, H. J.; Nho, C. W.; Bae, G.-N.; Jung, J. H. Antimicrobial Air Filters Using Natural Euscaphis japonica Nanoparticles. *PLoS One* **2015**, *10* (5), No. e0126481.

(99) Sim, K. M.; Lee, H. J.; Nho, C. W.; Bae, G.-N.; Jung, J. H. Effects of Surrounding Temperature on Antimicrobial Air Filters Coated with Sophora flavescens Nanoparticles. *Aerosol Sci. Technol.* **2014**, *48* (3), 324−332.

(100) Shen, M.; Forghani, F.; Kong, X.; Liu, D.; Ye, X.; Chen, S.; Ding, T. Antibacterial applications of metal−organic frameworks and

their composites. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19* (4), 1397−1419.

(101) Bhardwaj, N.; Pandey, S. K.; Mehta, J.; Bhardwaj, S. K.; Kim, K.-H.; Deep, A. Bioactive nano-metal−organic frameworks as antimicrobials against Gram-positive and Gram-negative bacteria. *Toxicol. Res.* **2018**, *7* (5), 931−941.

(102) Nishide, M.; Tsujimoto, K.; Uozaki, M.; Ikeda, K.; Yamasaki, H.; Koyama, A. H.; Arakawa, T. Effects of electrolytes on virus inactivation by acidic solutions. *Int. J. Mol. Med.* **2011**, *27* (6), 803−809.

(103) Lombardi, M. E.; Ladman, B. S.; Alphin, R. L.; Benson, E. R. Inactivation of Avian Influenza Virus Using Common Detergents and Chemicals. *Avian Dis.* **2008**, *52* (1), 118−123.

(104) Quan, F.-S.; Rubino, I.; Lee, S.-H.; Koch, B.; Choi, H.-J. Universal and reusable virus deactivation system for respiratory protection. *Sci. Rep.* **2017**, *7* (1), 39956.

(105) Isquith, A. J.; McCollum, C. J. Surface kinetic test method for determining rate of kill by an antimicrobial solid. *Appl. Environ. Microbiol.* **1978**, *36* (5), 700−704.

(106) Sun, W.; Wu, F.-G. Two-Dimensional Materials for Antimicrobial Applications: Graphene Materials and Beyond. *Chem. - Asian J.* **2018**, *13* (22), 3378−3410.

(107) Zhu, J.; Wang, J.; Hou, J.; Zhang, Y.; Liu, J.; Van der Bruggen, B. Graphene-based antimicrobial polymeric membranes: a review. *J. Mater. Chem. A* **2017**, *5* (15), 6776−6793.

(108) Stanford, M. G.; Li, J. T.; Chen, Y.; McHugh, E. A.; Liopo, A.; Xiao, H.; Tour, J. M. Self-Sterilizing Laser-Induced Graphene Bacterial Air Filter. *ACS Nano* **2019**, *13* (10), 11912−11920.

(109) Jindal, S.; Gopinath, P. Nanotechnology based approaches for combatting COVID-19 viral infection. *Nano Express* **2020**, *1* (2), 022003.

(110) Campos, E. V. R.; Pereira, A. E. S.; de Oliveira, J. L.; Carvalho, L. B.; Guilger-Casagrande, M.; de Lima, R.; Fraceto, L. F. How can nanotechnology help to combat COVID-19? Opportunities and urgent need. *J. Nanobiotechnol.* **2020**, *18* (1), 125.

(111) Palmieri, V.; Papi, M. Can graphene take part in the fight against COVID-19? *Nano Today* **2020**, *33*, 100883.

(112) Talebian, S.; Wallace, G. G.; Schroeder, A.; Stellacci, F.; Conde, J. Nanotechnology-based disinfectants and sensors for SARS-CoV-2. *Nat. Nanotechnol.* **2020**, *15* (8), 618−621.

(113) Kumar, S.; Karmacharya, M.; Joshi, S. R.; Gulenko, O.; Park, J.; Kim, G.-H.; Cho, Y.-K. Photoactive Antiviral Face Mask with Self-Sterilization and Reusability. *Nano Lett.* **2020**.

(114) Lin, Y.-C.; Chen, C.-P. Thermoregulation and thermal sensation in response to wearing tight-fitting respirators and exercising in hot-and-humid indoor environment. *Building and Environment* **2019**, *160*, 106158.

(115) Yip, W.; Leung, L.; Lau, P.; Tong, H. The Effect of Wearing a Face Mask on Body Temperature. *Hong Kong Journal of Emergency Medicine* **2005**, *12* (1), 23−27.

(116) Zhong, H.; Zhu, Z.; Lin, J.; Cheung, C. F.; Lu, V. L.; Yan, F.; Chan, C.-Y.; Li, G. Reusable and Recyclable Graphene Masks with Outstanding Superhydrophobic and Photothermal Performances. *ACS Nano* **2020**, *14* (5), 6213−6221.

(117) Drewnick, F.; Pikmann, J.; Fachinger, F.; Moormann, L.; Sprang, F.; Borrmann, S. Aerosol filtration efficiency of household materials for homemade face masks: Influence of material properties, particle size, particle electrical charge, face velocity, and leaks. *Aerosol Sci. Technol.* **2021**, *55* (1), 63−79.

(118) Lai, A. C. K.; Poon, C. K. M.; Cheung, A. C. T. Effectiveness of facemasks to reduce exposure hazards for airborne infections among general populations. *J. R. Soc., Interface* **2012**, *9* (70), 938−948.

(119) Jung, H.; Kim, J. K.; Lee, S.; Lee, J.; Kim, J.; Tsai, P.; Yoon, C. Comparison of Filtration Efficiency and Pressure Drop in Anti-Yellow Sand Masks, Quarantine Masks, Medical Masks, General Masks, and Handkerchiefs. *Aerosol Air Qual. Res.* **2014**, *14* (3), 991−1002.

(120) Sickbert-Bennett, E. E.; Samet, J. M.; Clapp, P. W.; Chen, H.; Berntsen, J.; Zeman, K. L.; Tong, H.; Weber, D. J.; Bennett, W. D. Filtration Efficiency of Hospital Face Mask Alternatives Available for Use During the COVID-19 Pandemic. *JAMA Internal Medicine* **2020**, *180* (12), 1607−1612.

(121) Rodriguez-Palacios, A.; Cominelli, F.; Basson, A. R.; Pizarro, T. T.; Ilic, S. Textile Masks and Surface Covers-A Spray Simulation Method and a "Universal Droplet Reduction Model" Against Respiratory Pandemics. *Front. Med.* **2020**, *7*, 260.

(122) Verma, S.; Dhanak, M.; Frankenfield, J. Visualizing the effectiveness of face masks in obstructing respiratory jets. *Phys. Fluids* **2020**, *32* (6), 061708.

(123) Neupane, B. B.; Chaudhary, R. K.; Sharma, A. A smartphone microscopic method for rapid screening of cloth facemask fabrics during pandemics. *PeerJ* **2020**, *8*, e9647.

(124) Yu, S.; Kim, S.; Kang, J. Face Mask Policies in South Korea in Response to COVID-19. *Asia Pac J. Public Health* **2020**, *32* (8), 497−499.

(125) Baluja, A.; Arines, J.; Vilanova, R.; Cortiñas, J.; Bao-Varela, C.; Flores-Arias, M. T. UV light dosage distribution over irregular respirator surfaces. Methods and implications for safety. *J. Occup. Environ. Hyg.* **2020**, *17* (9), 390−397.

(126) Viscusi, D. J.; King, W. P.; Shaffer, R. E. Effect of Decontamination on the Filtration Efficiency of Two Filtering Facepiece Respirator Models, *J. Int. Soc. Respir. Prot.***2008**, *24*, 93−107.

(127) Lin, T.-H.; Tang, F.-C.; Hung, P.-C.; Hua, Z.-C.; Lai, C.-Y. Relative survival of Bacillus subtilis spores loaded on filtering facepiece respirators after five decontamination methods. *Indoor Air* **2018**, *28* (5), 754−762.

(128) Kumar, A.; Kasloff, S. B.; Leung, A.; Cutts, T.; Strong, J. E.; Hills, K.; Vazquez-Grande, G.; Rush, B.; Lother, S.; Zarychanski, R.; Krishnan, J. N95 Mask Decontamination using Standard Hospital Sterilization Technologies. *medRxiv (Infectious Diseases (except HIV/AIDS))*, 2020, 2020.04.05.20049346.https://doi.org/10.1101/2020.04.05.20049346 (accessed 2021-01-13).

(129) He, W.; Guo, Y.; Gao, H.; Liu, J.; Yue, Y.; Wang, J. Evaluation of Regeneration Processes for Filtering Facepiece Respirators in Terms of the Bacteria Inactivation Efficiency and Influences on Filtration Performance. *ACS Nano* **2020**, *14* (10), 13161−13171.

(130) Banerjee, R.; Roy, P.; Das, S.; Paul, M. K. A hybrid model integrating warm heat and ultraviolet germicidal irradiation might efficiently disinfect respirators and personal protective equipment. *Am. J. Infect. Control* **2020**, DOI: 10.1016/j.ajic.2020.07.022.

(131) Weiss, C.; Carriere, M.; Fusco, L.; Capua, I.; Regla-Nava, J. A.; Pasquali, M.; Scott, J. A.; Vitale, F.; Unal, M. A.; Mattevi, C.; Bedognetti, D.; Merkoçi, A.; Tasciotti, E.; Yilmazer, A.; Gogotsi, Y.; Stellacci, F.; Delogu, L. G. Toward Nanotechnology-Enabled Approaches against the COVID-19 Pandemic. *ACS Nano* **2020**, *14* (6), 6383−6406.

(132) Jones, S. T.; Cagno, V.; Janeček, M.; Ortiz, D.; Gasilova, N.; Piret, J.; Gasbarri, M.; Constant, D. A.; Han, Y.; Vuković, L.; Král, P.; Kaiser, L.; Huang, S.; Constant, S.; Kirkegaard, K.; Boivin, G.; Stellacci, F.; Tapparel, C. Modified cyclodextrins as broad-spectrum antivirals. *Sci. Adv.* **2020**, *6* (5), No. eaax9318.

(133) Lemire, J. A.; Harrison, J. J.; Turner, R. J. Antimicrobial activity of metals: mechanisms, molecular targets and applications. *Nat. Rev. Microbiol.* **2013**, *11* (6), 371−384.

(134) Jenkins, J.; Mantell, J.; Neal, C.; Gholinia, A.; Verkade, P.; Nobbs, A. H.; Su, B. Antibacterial effects of nanopillar surfaces are mediated by cell impedance, penetration and induction of oxidative stress. *Nat. Commun.* **2020**, *11* (1), 1626.

(135) Cloutier, M.; Mantovani, D.; Rosei, F. Antibacterial Coatings: Challenges, Perspectives, and Opportunities. *Trends Biotechnol.* **2015**, *33* (11), 637−652.

(136) Ghatak, B.; Banerjee, S.; Ali, S. B.; Bandyopadhyay, R.; Das, N.; Mandal, D.; Tudu, B. Design of a self-powered triboelectric face mask. *Nano Energy* **2021**, *79*, 105387.

(137) El-Atab, N.; Qaiser, N.; Badghaish, H.; Shaikh, S. F.; Hussain, M. M. Flexible Nanoporous Template for the Design and Develop-

ment of Reusable Anti-COVID-19 Hydrophobic Face Masks. *ACS Nano* **2020**, *14* (6), 7659−7665.

(138) Yahyaei, H.; Makki, H.; Mohseni, M. Superhydrophobic coatings for medical applications. In *Superhydrophobic Polymer Coatings*; Samal, S. K., Mohanty, S., Nayak, S. K., Eds.; Elsevier, 2019; Chapter 14, pp 321−338, DOI: 10.1016/B978-0-12-816671-0.00015-1.

(139) Jokinen, V.; Kankuri, E.; Hoshian, S.; Franssila, S.; Ras, R. H. A. Superhydrophobic Blood-Repellent Surfaces. *Adv. Mater.* **2018**, *30* (24), 1705104.

(140) Wang, D.; Sun, Q.; Hokkanen, M. J.; Zhang, C.; Lin, F.-Y.; Liu, Q.; Zhu, S.-P.; Zhou, T.; Chang, Q.; He, B.; Zhou, Q.; Chen, L.; Wang, Z.; Ras, R. H. A.; Deng, X. Design of robust superhydrophobic surfaces. *Nature* **2020**, *582* (7810), 55−59.

(141) Schutzius, T. M.; Jung, S.; Maitra, T.; Graeber, G.; Köhme, M.; Poulikakos, D. Spontaneous droplet trampolining on rigid superhydrophobic surfaces. *Nature* **2015**, *527* (7576), 82−85.

(142) Yang, P.; Wang, X. COVID-19: a new challenge for human beings. *Cell. Mol. Immunol.* **2020**, *17* (5), 555−557.

(143) Zhou, P.; Yang, X.-L.; Wang, X.-G.; Hu, B.; Zhang, L.; Zhang, W.; Si, H.-R.; Zhu, Y.; Li, B.; Huang, C.-L.; Chen, H.-D.; Chen, J.; Luo, Y.; Guo, H.; Jiang, R.-D.; Liu, M.-Q.; Chen, Y.; Shen, X.-R.; Wang, X.; Zheng, X.-S.; Zhao, K.; Chen, Q.-J.; Deng, F.; Liu, L.-L.; Yan, B.; Zhan, F.-X.; Wang, Y.-Y.; Xiao, G.-F.; Shi, Z.-L. A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature* **2020**, *579* (7798), 270−273.

(144) Zhong, H.; Zhu, Z.; You, P.; Lin, J.; Cheung, C. F.; Lu, V. L.; Yan, F.; Chan, C.-Y.; Li, G. Plasmonic and Superhydrophobic Self-Decontaminating N95 Respirators. *ACS Nano* **2020**, *14* (7), 8846−8854.

(145) Huang, L.; Xu, S.; Wang, Z.; Xue, K.; Su, J.; Song, Y.; Chen, S.; Zhu, C.; Tang, B. Z.; Ye, R. Self-Reporting and Photothermally Enhanced Rapid Bacterial Killing on a Laser-Induced Graphene Mask. *ACS Nano* **2020**, *14* (9), 12045−12053.

(146) Herrera Melián, J. A.; Doña Rodríguez, J. M.; Viera Suárez, A.; Tello Rendón, E.; Valdés do Campo, C.; Arana, J.; Pérez Peña, J. The photocatalytic disinfection of urban waste waters. *Chemosphere* **2000**, *41* (3), 323−327.

(147) Nasr, M.; Eid, C.; Habchi, R.; Miele, P.; Bechelany, M. Recent Progress on Titanium Dioxide Nanomaterials for Photocatalytic Applications. *ChemSusChem* **2018**, *11* (18), 3023−3047.

(148) Horváth, E.; Rossi, L.; Mercier, C.; Lehmann, C.; Sienkiewicz, A.; Forró, L. Photocatalytic Nanowires-Based Air Filter: Towards Reusable Protective Masks. *Adv. Funct. Mater.* **2020**, *30* (40), 2004615.

(149) Fadare, O. O.; Okoffo, E. D. Covid-19 face masks: A potential source of microplastic fibers in the environment. *Sci. Total Environ.* **2020**, *737*, 140279.

(150) Klemeš, J. J.; Fan, Y. V.; Jiang, P. The energy and environmental footprints of COVID-19 fighting measures - PPE, disinfection, supply chains. *Energy (Oxford, U. K.)* **2020**, *211*, 118701.

(151) Behnam, B.; Oishi, S. N.; Uddin, S. M. N.; Rafa, N.; Nasiruddin, S. M.; Mollah, A. M.; Hongzhi, M. Inadequacies in Hospital Waste and Sewerage Management in Chattogram, Bangladesh: Exploring Environmental and Occupational Health Hazards. *Sustainability* **2020**, *12* (21), 9077.

(152) Köhler, A. R. Challenges for eco-design of emerging technologies: The case of electronic textiles. *Mater. Eng.* **2013**, *51*, 51−60.

(153) Scarano, A.; Inchingolo, F.; Lorusso, F. Facial Skin Temperature and Discomfort When Wearing Protective Face Masks: Thermal Infrared Imaging Evaluation and Hands Moving the Mask. *Int. J. Environ. Res. Public Health* **2020**, *17* (13), 4624.

(154) Kinzig, A. P.; Ehrlich, P. R.; Alston, L. J.; Arrow, K.; Barrett, S.; Buchman, T. G.; Daily, G. C.; Levin, B.; Levin, S.; Oppenheimer, M.; Ostrom, E.; Saari, D. Social Norms and Global Environmental Challenges: The Complex Interaction of Behaviors, Values, and Policy. *BioScience* **2013**, *63* (3), 164−175.

(155) Mackenzie, J. S.; Jeggo, M. The One Health Approach-Why Is It So Important? *Trop Med. Infect Dis* **2019**, *4* (2), 88.

(156) Jung, S.; Lee, S.; Dou, X.; Kwon, E. E. Valorization of disposable COVID-19 mask through the thermo-chemical process. *Chem. Eng. J.* **2021**, *405*, 126658.

(157) Chughtai, A. A.; Seale, H.; Macintyre, C. R. Effectiveness of Cloth Masks for Protection Against Severe Acute Respiratory Syndrome Coronavirus 2. *Emerging Infect. Dis.* **2020**, *26* (10), 1−5.

(158) Hill, W. C.; Hull, M. S.; MacCuspie, R. I. Testing of Commercial Masks and Respirators and Cotton Mask Insert Materials using SARS-CoV-2 Virion-Sized Particulates: Comparison of Ideal Aerosol Filtration Efficiency versus Fitted Filtration Efficiency. *Nano Lett.* **2020**, *20* (10), 7642−7647.