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 μm (fine particle aerosols) present in the air or those larger than 5 μm (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 μm) 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...
spread through patient-derived bio-aerosols. The bio-aerosols remain viable for 72 h on plastic and stainless steel surfaces containing a 50% tissue-culture infectious dose \([\text{TCID}_{50}]\), with a reduction in infectious titer from \(10^{3.5}\) to \(10^{2.7}\) TCID\(_{50}\) per liter of air. This virus can be spread through three major routes: contact, droplet, and aerosol.

2.1. Contact Transmission. Contact transmission can be either direct or indirect. 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.

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.

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.

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...
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 super-spreaders.\(^2\)\(^6\)\(^7\)\(^8\) Particle emission rates are directly proportional to the speed and loudness of spoken sounds.\(^2\)\(^4\) Covering or masking the speaker’s mouth can reduce droplet emissions to low levels, as observed by laser light scattering.\(^2\)\(^2\) Hence, masks act as barriers that prevent droplets from symptomatic and asymptomatic carriers.

This study reveals that masks play two important roles.\(^1\)\(^1\) First, they prevent gas cloud formation during sneezing and coughing, which simplifies rapid turbulent jets of aerosol toward individuals or the environment.\(^2\)\(^8\) Second, the layer present in the mask filters the aerosol and prevents it from entering the nasopharyngeal region.\(^1\)\(^2\) 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.\(^2\)\(^4\) 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).\(^1\)\(^1\) Respirators and medical masks fall under the certifi ed 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).\(^1\)\(^1\) 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.\(^2\)\(^4\) 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 fi rst Class (Korea), and DS (Japan) are respirator equivalents to FFP2. N95 respirators comprise four layers, which include inner, support, fi lter, and mask-fi lter layers, respectively.\(^2\)\(^5\) The outer layer comprises hydrophobic non-woven polypropylene (PP), which resists external moisture. The fi lter layer consists of two layers of melt-blown nonwoven PP that absorb oil- and non-oil-based particles. This fi lter 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 fi ltration efficiency.\(^2\)\(^6\) These are tightly fi tted 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 fi tted and disposable, and are regarded as medical devices by the Food and Drug Administration.\(^1\)\(^1\) 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 fi lter that fi lters air particles and prevents particles of specifi c dimensions from entering both sides of the facemask. The outer layer is hydrophobic; hence, it repels aerosols and water droplets from the outer environment.\(^2\)\(^7\) This type of mask is not closely fi tted to the face; therefore it is effective against large coarse droplets rather than small ones.\(^2\)\(^8\) However, various studies have shown that medical masks are able to prevent coronaviruses and the infl uenza 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.\(^2\)\(^9\) 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 μm 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. Filtration efficiencies of common fabrics made of polyester, cotton, silk, and nylon were found to be 5–25%. 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%. These masks are good alternatives, as medical masks are scarce in a pandemic. 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. However, N95 respirators and surgical facemasks provide the best protection in a high-risk environment. 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. Table 1 lists materials used to prepare cloth masks.

| Material          | Fiber Composition          |
|-------------------|---------------------------|
| T-shirt           | 100% cotton               |
| fleece sweater    | 100% cotton               |
| pillowcase A      | air-jet down-proof fabric |
| pillowcase B      | jet satin                 |
| pillowcase C      | jet satin                 |
| down jacket       | 100% polyurethane         |
| jeans             | cotton and polyurethane   |
| medical gauze     | absorbent cotton          |
| scarf             | polyester                 |
| tea towel         | linen                     |
| handkerchief      | cotton                    |
| napkin            | silk                      |
| exercise pants    | nylon                     |
| paper towel       | cellulose                 |
| tissue paper      | cellulose                 |
| toddler wrap      | polyester                 |
| towel             | 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. Medical masks effectively block different types of influenza virus, depending on their size, whereas the rhinovirus was not blocked. 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. 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. 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. Approximately 97% of particles penetrate cloth masks, whereas 44% and <0.01–0.1% penetrate medical masks and respirators, respectively. Respirators are 50- and 25-fold more reliable than homemade and medical masks, respectively. Cloth masks can be reused many times, which increases the risk of infection due to the effectiveness of cleaning and moisture-retention properties. 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. 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). In particular, PP is in high demand due to its nonabsorbent properties and the ability to repel humidity. 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). Other fibers, such as polyester rayon, glass, and cellulose are also utilized; however, these fibers are less efficient than PP. 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.

Combining these polymers with nanofiber filters can increase air flow efficiency. The nanofibers used on nanoporous polyethylene increase the capture efficiency of particulate matter (PM) to 99.6% (Figure 4a). Polycrylonitrile 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. Nonwoven PP substrates containing electret poly(ether sulfone)/barium titanate nano-fibrous 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. The melt-blown and nanofiber filters used in N95 masks possess high filtration efficiencies. 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.
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.

Table 2. Comparison of the Filtration Efficacy and Pressure Drop of a Variety of Materials

| mask type     | material used | structure | filtration efficiency (%) | ΔP (Pa)\(^b\) | reusable |
|---------------|---------------|-----------|---------------------------|---------------|----------|
| certified mask medical mask | polypropylene (no gap) | nonwoven | 76 ± 22 | 2.5 | no |
| respirator    | polypropylene (gap) | nonwoven | 50 ± 7 | 2.5 | no |
|               | 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 ft³/min (CFM), and the average particle size range was <300 nm ± error. \(^b\)ΔP = 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.
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.50

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. The method can fabricate polyacrylonitrile nanofibers (diameter ~ 200 nm) used for air purification that can capture PM less than 2.5 mm in size (PM2.5).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.\(^1\) The aforementioned technology demonstrated promising potential regarding fine particulate filtration, with an efficiency of 99.985% for PM\(_{1.05}\) 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.\(^1\)

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.\(^3,5\) When magnesium stearate is used, 98.94% of PM\(_{1.5}\) was filtered at a surface potential of 4.78 kV. Similarly, SiO\(_2\) NPs demonstrate this effect at 12.4 kV.\(^{53,58}\) Further, corona charging enhanced the PM\(_{2.5}\) 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.\(^5\) 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 rotator (R-TENGs) provides continuous charge to the filter and enables the fabrication of interconnected nanonets with large surface area, resulting in high efficiencies of up to 88.335% and 89.67% for the removal of PM\(_{1.5}\) and PM\(_{10}\), respectively.\(^{54,63}\) 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.\(^64\)

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.\(^70\) 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.

#### 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.\(^73\) 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.\(^79\) Silver NPs bind to thiol groups and exhibit antimicrobial properties.\(^80\) 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.\(^53\) Similarly, Ag@MWCNTs incorporated in Al\(_2\)O\(_3\) 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(1) 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, Cu-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.\(^9\) Similarly, a combination of CuO and Ag\(_2\)O 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%.

5.4.2. Use of Natural Extracts. Natural product extracts of olive, mangosteen, grapefruit seed, tea tree, and Sophora flavescens (S. flavescens) exhibit antimicrobial properties that are due to flavonoids. A mixture of poly(vinylpyrrolidone) and ammonium chloride and related products, are used to surface-

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. The combination of MOFs and cellulose fibers (CFs, ZIF-8@CF) exhibited a 99.99% photocatalytic biocidal effect against E. coli, with the removal of 96.8% PM_{2.5} at a low pressure drop. The bactericidal effect is due to the production of ROS because the photoelectrons at Zn^{2+} centers become trapped. 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.

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 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,nanoﬁbres 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 periods 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. Conductive microporous graphene can trap microbes and use electrical charges to destroy them; this is also applicable to SARS-CoV-2. Apart from their photothermal and photodynamic properties, these kinds of nanomaterial generate reactive oxygen species (ROS) as part of their intrinsic antiviral mechanism.

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. SARS-CoV-2 particles are transmitted from person to person by aerosols that are exhaled during breathing, coughing, or talking, with the largest droplets influenced by gravity. Therefore, the majority of droplets precipitate before contacting the target; however, a small fraction (<3 μm) are primarily governed by diffusion and

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electrostatic interactions. 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. 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. To quantify efficiency, various metrics are used:

filtration efficiency:

\[
FE = \frac{C_{\text{up}} - C_{\text{down}}}{C_{\text{up}}} \times 100\%
\]

where \(C_{\text{down}}\) and \(C_{\text{up}}\) are the downstream and upstream filter concentrations, respectively. The formula describes the fraction of particles filtered by the filter.
mask were examined and performed by Sickbert-Bennet et al. Various commercial masks were compared to N95 and surgical masks. The results revealed that mask efficiency is important for protecting against airborne pathogen transmission. 

Table 3. Comparison of the Decontamination Methods for Facemasks

| Decontamination Type             | Advantages                                                                 | Disadvantages                                                                                       | Ref   |
|---------------------------------|----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-------|
| UV irradiation                  | • simple and robust method                                                  | • timing and energy of exposure should be appropriate; otherwise mask can be damaged                 | 125–130|
|                                 | • can be done in everyday settings                                          | • may not cover the whole area                                                                      |       |
|                                 | • provides good decontamination                                            |                                                                                                     |       |
| Dry heating                     | • simple and robust method                                                  | • heat can easily damage mask and increase the particle penetration                                 | 126, 127|
|                                 | • can be done in everyday settings                                          |                                                                                                     |       |
|                                 | • can cover the whole mask area                                             |                                                                                                     |       |
|                                 | • provides good decontamination                                            |                                                                                                     |       |
| Steam heating                   | • simple and robust method                                                  | • if temperature is too high, mask fibers may be damaged                                           | 126, 127|
|                                 | • can be done in everyday settings                                          |                                                                                                     |       |
|                                 | • can cover the whole mask area                                             |                                                                                                     |       |
|                                 | • provides good decontamination                                            |                                                                                                     |       |
| Hydrogen peroxide vapor         | • can cover the whole mask area                                             | • requires special equipment                                                                        | 126, 127|
|                                 | • high capacity                                                             |                                                                                                     |       |
| Organic solvents (ethanol, isopropanol), bleach | • can be done in everyday settings                                          | • increases the particle penetration of the mask                                                    | 126, 127|
|                                 | • can be done in everyday settings                                          |                                                                                                     |       |
|                                 | • removes the fiber charge; increases the particle penetration               |                                                                                                     |       |
| UV + microwave                  | • provides good decontamination                                            | • increases the particle penetration of mask                                                       | 129, 130|

Protection degree:

$$PD = \left( 1 - \frac{\int(C_{\text{ref}}/C_D) \, dt}{\int(C_{\text{ref}}/C_D) \, dt} \right) \times 100\%$$

where $C_{\text{ref}}$ and $C_D$ 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. 

Penetration:

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

This criterion identifies which portion of the particles penetrating the filter. 

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). 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. 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. 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.

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. 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. 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...
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). 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).

7. DECONTAMINATION

In 2020, the global COVID-19 pandemic resulted in the widespread use of personal protection equipment, such as facemasks, in public places. 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.

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/cm², 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. Another method of decontamination involves heating, which includes, but is not limited to, the use of microwaves, rice cookers, and autoclaves. 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.

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.

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. Also, compared to other chemical methods, hydrogen peroxide is readily decomposed; therefore, it does not leave harmful residuals on the mask. 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. 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. Shaffer et al. used 1 g/L 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 fibercharge. 

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. 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. 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. 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. 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 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). 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. 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 μm.

8.3. Facemask Modification Using Photothermal Materials. SARS-CoV-2 can be deactivated at 56 °C within 15 min. Consequently, mask surfaces have been modified using nanomaterials to enable self-sterilization. Plasmmonic heating has recently been used to deactivate the virus. During plasmmonic 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 to enable 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. Plasmmonic photothermal deactivation was studied using solar energy (600 W/m²), which resulted in a 60 °C increase in temperature; such a high temperature sufficiently inactivated SARS-CoV-2 (Figure 6c). 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.

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. TiO2-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. Recently, a TiO2 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 TiO2 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.

9. FUTURE PERSPECTIVES AND CONCLUSION

Since the World Health Organization (WHO) recommended wearing facemasks in public areas, the global demand for 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). 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.
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. 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. 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. 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.

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.

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. Our new social norms require the same thought as to where our actions are interconnected, which extend beyond boundaries and cultural heterogeneity. 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.

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. 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. The preparation of polypropylene, which is used to make disposable masks, emits toxic dioxin to the environment, which is a cause of air pollution. Reusable, sustainable, and environmentally friendly masks provide a solution to this problem. Cloth masks are alternatives to polypropylene masks; 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. 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. Critical analyses of alternative sources will effectively enhance waste management while limiting COVID-19 transfer.

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, super-hydrophobicity, transparency, self-cleaning, and detection capabilities.

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Notes

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