

Recent Progress in Modified Polymer-Based PPE in Fight Against COVID-19 and Beyond

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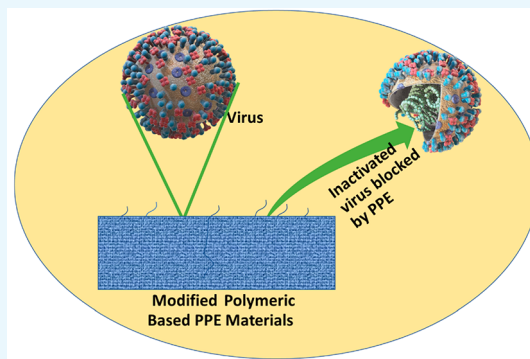
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ABSTRACT: The increasing concerns about human-health-related microbial infections and the need for the development of personal protective equipment (PPE) is becoming a major challenge. Because of their light weight and ease of processing, polymeric materials are widely used in designing and fabricating PPE that are being used by healthcare workers and the general population. Among the available PPEs, face masks have been widely developed from polymeric materials such as polypropylene, polycarbonate, and poly(ethylene terephthalate). However, currently, many of the face masks are not antimicrobial, which can pose a great risk for cross-infection as discarded masks can be a dangerous source of microbes. To prevent the spread of microbes, researchers have prompted the development of self-sterilizing masks that are capable of inactivating microbes via different mechanisms. Hence, this review provides a brief overview of the currently available antimicrobial-modified polymer-based PPE, and it mainly focuses on the different types of nanoparticles and other materials that have been embedded in different polymeric materials. The possibility of inhaling microplastics from wearing a face mask is also outlined, and the effects of various modifications on the health of face mask users are also explored. Furthermore, the effects of the disposed masks on the environment are underlined.



1. INTRODUCTION

The emergence of the novel severe acute respiratory syndrome coronavirus (SARS-CoV-2), which initially started in Wuhan located in China,^{1a} received global attention due to its rapid widespread infection. Many nations were unprepared for such a pandemic that emerged rapidly. As the world is now a global village, the virus spread rapidly throughout many countries, resulting in a serious global health problem. As it is airborne and infectious, the movement of people internationally is strictly regulated. Most countries announced partial and full lockdowns to protect their citizens from this deadly disease. Therefore, the pandemic has caused major disruptions economically, politically, and socially, and many people have died due to the illness and complications linked to COVID-19.^{1b} Hence, people are now being encouraged to observe strict social distance regulations, use of face masks, and COVID-19 vaccines to minimize the spread of the virus and subsequently the death of people.^{1c} Several vaccines have been developed, and their efficacies and mode of operation have been made public. Despite the introduction of vaccines, there is still a plethora of challenges in vaccine distribution. In third-world countries, main challenges include cold storage for vaccines as well as procurement of vaccines, resulting in few people being vaccinated. Therefore, currently, it is of paramount importance to promote the use of personal protective equipment (PPE). Wearing PPE, such as face

masks, is a viable method for mitigating the transmission of the novel SARS-CoV-2 virus. Face masks protect users against aerosols that contain the SARS-CoV-2 virus.^{1d} Polymeric materials such as polypropylene (PP) are currently being used to fabricate surgical masks, which play a significant role in mitigating the spread of the virus. The main disadvantage of the present face masks and other related PPEs is that they are incapable of killing microbes present on their surfaces. This has led researchers to modify PPE, especially face masks, thereby enabling them to self-sterilize. Modifications in face masks enable users to wear masks for a long period and prevent cross-contamination. This can be of great importance to frontline medical health workers who are exposed to many disease-causing organisms.

A review article focusing on different types of polymeric materials and processing methods used in fabricating face masks has been recently published.^{1e} The article further explores natural and synthetic additives that can be coated on

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the face mask to make them antimicrobial. However, this review article further explores the journey of polymeric materials and their modifications to achieve antimicrobial properties to prevent the spread of COVID-19 and other diseases. A plethora pool of different antibacterial and antiviral additives that can be incorporated into polymeric materials has been explored. The review also focuses on any possible cytotoxic effects of different nanomaterials used to render PPE antimicrobial. It also further highlights the impact of face masks when disposed of in the environment.

2. POLYMER-BASED FACE MASKS IN PREVENTING THE SPREAD OF COVID-19

Polymers have played a significant role in the fabrication of masks and respirators, especially during the COVID-19 pandemic.^{16g} Surgical masks are PPE that are currently being used by healthcare workers and the population at large for protection against SARS-CoV-2 aerosols/droplets. They are made of three layers: outer, middle, and inner. The outer layer prevents the entrance of liquid droplets, the melt-blown middle layer acts as a filter, and the inner layer acts as an absorber of moisture coming from the wearer.²

Surgical masks are used widely because they are affordable and highly comfortable to wear. Their filtration efficiency is good in comparison to the present popular cloth mask but less than that of the N95 mask. The main disadvantage of N95 masks is that they are not recommended for people with breathing problems and are expensive especially in developing countries. Surgical masks are mainly fabricated from PP, a hydrophobic thermoplastic polymer. Its hydrophobic nature makes it ideal for preventing aerosols from penetrating through the mask to the nasal passage. However, their main disadvantages are that they do not have any antimicrobial properties, are not reusable, and are discarded after use. Researchers have developed different modifications that enable the self-sterilization of surgical masks. Various nanoparticles (NPs) have been incorporated into different masks and other polymeric materials to impart antimicrobial properties.² Many researchers have modified surgical masks and other polymeric materials so that they can be reused and increase their efficiency against SARS-CoV-2 and other emerging diseases. The self-sterilization mechanism by the NPs is a better way to disinfect the masks as compared to other harsh methods such as the use of autoclave and ethanol treatment, which may damage and affect the overall performance of the mask.

3. MODIFIED POLYMER-BASED PPE

3.1. Graphene and Its Derivatives. Graphene and its derivatives have been extensively investigated for their antimicrobial properties, and their properties have been extended to COVID-19, which has become a global concern. Ye et al.³ went on to study the antiviral activity of graphene oxide (GO) and investigated the antiviral mechanism of GO in both RNA and DNA virus models. The authors used Pseudorabies virus (PRV), a DNA virus, and porcine epidemic diarrhea virus (PEDV), an RNA virus. They reported that, in the presence of 6 $\mu\text{g}/\text{mL}$ of GO, the NPs showed inhibitory properties against PRV. They also investigated the effect of GO on PEDV, an RNA-based virus, and the results showed that GO had antiviral properties against PEDV. The results proved that GO possesses antiviral properties against both DNA and RNA viruses. The authors also claimed that reduced GO

(rGO) showed antiviral properties similar to those of GO, indicating that functional groups may not be a significant determinant of antiviral properties. Regarding the antiviral mechanism, the authors claimed through their experimental studies that the negative charge and nanosheet structure were essential for the antiviral properties of GO. The above studies show that GO nanosheets are essential in the fight against the novel SARS-CoV-2 virus.

Graphene and its derivatives can be coated on the surface of the surgical mask because of their antimicrobial properties and good thermal conductivity. The high thermal conductivity of graphene enables the nanosheets to have good photothermal properties on exposure to direct sunlight. Reports have shown that the coronavirus can be inactivated at temperatures above approximately 65 °C.⁴ Zhong et al.⁵ further designed a surgical mask with self-cleaning and photothermal properties. A few layers of graphene were deposited on the surface of the commercial mask using the dual-mode laser-induced forward transfer method. The presence of graphene increased the hydrophobicity of the mask. This hydrophobic nature is important because it prevents the attachment of microbes on the surface of the mask, enabling self-cleaning. When exposed to the sun, the graphene-coated surgical mask's surface temperature rose to 80 °C, which made the masks self-sterilizable. Shan et al.⁶ further developed a graphene-coated self-sterilizable mask that was not sunlight-dependent. The face mask was modified in such a way that, at low voltage, the mask quickly generates heat, which is capable of killing viruses present on the mask surface. The authors claimed that the heat produced is capable of eliminating the water vapor produced when wearing a mask that makes the mask comfortable. These electrothermal masks are important because they are capable of self-sterilization as compared to cloth masks, which must be washed for reuse. Graphene/GO-coated masks are affordable compared to expensive disinfection methods, having prolonged filtration efficiency and cause less polymer pollution. Therefore, this modification is an economical, efficient, and environment friendly process that can serve as a good alternative to curb the spread of SARS-CoV-2 and other respiratory viruses.

3.2. Carbon Nanotubes. Other carbonaceous nanomaterials such as carbon nanotubes (CNTs) can be coated on the surface of PP surgical face masks to improve their hydrophobicity and make them self-sterilizable. In a recent work by Soni et al.,⁷ single-walled CNTs (SWCNTs) were spray-coated on surgical masks made of melt-blown PP. Figure 1 shows the spray-coating process of the SWCNTs on the mask. The presence of the SWCNTs improved the hydrophobic properties (contact angle) of the mask from 113.6 ± 3 to $156.2 \pm 1.8^\circ$. As mentioned previously, the hydrophobic nature is of great importance in preventing aerosols that might contain microbes to attach to the surface of the mask. When exposed to 1 sun illumination for 3 s, the coated mask exhibited an excellent photothermal response, increasing the surface temperature of the mask to above 90 °C. This temperature is sufficient to destroy various microbes that might be present on the surface of the mask.⁴ The CNT-coated mask also showed 99.9% antibacterial performance against *Escherichia coli* compared to the uncoated mask. In addition to the antibacterial properties, the coated mask also showed virucidal properties against virus-like particles.

3.3. Silver NPs. Silver (Ag) NPs are reported to have good antimicrobial properties. AgNPs inactivate bacteria via their

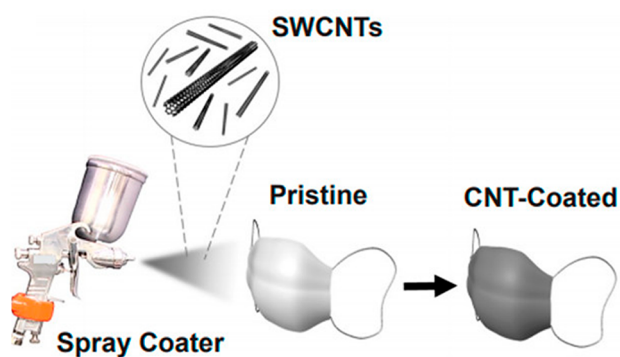


Figure 1. Spray-coating process of single-walled carbon nanotubes on the mask. Reprinted from ref 7. Copyright 2021 American Chemical Society.

interaction with the bacterial protein thiol groups. The NPs can penetrate inside the cell, and their interaction with phosphorus and sulfur, which constitutes the cell DNA, results in a snag of the DNA replication mechanism and also the reproduction process of the cells.⁸ Li et al.⁹ reported on the antimicrobial action of a combination of silver nitrate and titanium dioxide (TiO_2 NPs), which were coated on surgical masks. The NPs were tested against *E. coli* and *Staphylococcus aureus* (*S. aureus*). The NPs were coated onto the fabric used to develop the masks. The authors observed that the coated masks resulted in a 100% reduction in both *E. coli* and *S. aureus*. The antimicrobial mechanism was reported to be due to the destruction of the cell walls of the bacteria, which was a result of cytoplasmic content leakage and compromised metabolic pathways. Because of their size, AgNPs are capable of penetrating the cell walls of the bacteria and subsequently alter the cell membrane structure.¹⁰ The authors further investigated the effects of the NP-coated face masks and observed that there was no inflammation of the skin of the wearers.⁹ This study shows that a combination of both silver nitrate and TiO_2 NPs can be used to fabricate comfortable face masks that are capable of inactivating microbes.

3.4. Molybdenum Disulfide. Molybdenum disulfide (MoS_2) is a two-dimensional (2D)-layered material having exciting and unique properties and can be used in several different applications. Polycotton fabric can also be fabricated to impart antibacterial properties on their surfaces with 2D materials, as illustrated by Kumar et al.¹¹ in their study. The authors reported that the MoS_2 -coated fabrics had excellent antibacterial activity against Gram-positive and Gram-negative bacteria and possessed photothermal properties when exposed to sunlight. When exposed to sunlight, the surface temperature increased to $\sim 77^\circ\text{C}$, which makes it a good candidate for self-disinfection. This enabled the fabric to be reused after sunlight-induced disinfection. The modified fabrics maintained their antibacterial properties even after frequent washing, enabling them to be reused. The authors also mentioned that MoS_2 -modified polycotton fabric was able to increase the filtration efficiency when it was used as an additional layer without affecting breathability. The antibacterial mechanism of MoS_2 may be attributed to the sharp edges of MoS_2 , which punctures the membrane of the bacteria. The authors mentioned that the hydrophilic nature of the nanosheets aided in the antibacterial performance of the modified fabric. MoS_2 is reported to be capable of preventing micro-organism growth owing to both oxidative and induced membrane stress. The only challenge of

MoS_2 is its negatively charged surface, which can attract repelling bacteria to its surface. Therefore, the antibacterial efficiency of the nanosheets is decreased, which can be further enhanced by modifying the nanosheets.¹² These findings are important in developing PPEs that can be used by healthcare medical workers, especially during the COVID-19 crisis.

3.5. Copper. Copper is a frequently used antimicrobial material.¹³ Recently, Kumar et al.¹⁴ developed an antimicrobial nanocomposite that can be embedded on a face mask. The authors fabricated thin copper@ZIF-8 (zeolite imidazole framework 8) core-shell nanowires (Cu@ZIF-8 NWs), which were attached to PP filtration media (this filtration media can be used to fabricate medical-grade masks). The nanowires showed significant antibacterial activity against Gram-positive and Gram-negative bacteria. The hydrophobicity of the melt-blown PP was not significantly altered even after functionalization with the NWs. PPEs are generally made of hydrophobic materials to prevent the attachment of viruses transmitted via aerosols. The authors further checked whether there was any particle shedding during filtration and observed that there was a negligible loss of Cu@ZIF-8 NWs, which is a very significant property in fabricating PPEs that will be nontoxic and durable. Cu@ZIF-8 has been reported to show significant biocidal activity against *Streptococcus mutans* and *E. coli* strains. The Cu@ZIF-8 NWs were found to have antibacterial properties better than those of both Cu NWs and ZIF-8. The authors claimed that the presence of ZIF-8 on the NWs is important because it helps stabilize the NWs and ensures sustained liberation of Cu^{2+} from the copper NWs. The antibacterial action might be due to the release of Cu and Zn ions, as mentioned by the authors. The Cu@ZIF-8 NWs were also shown to have antiviral properties against SARS-CoV-2. These results are important in developing PPEs for medical care workers, especially during COVID-19. The authors were able to fabricate Cu@ZIF-8 NWs by using a simple method, which can be scaled up, especially from an industrial perspective, during this pandemic period. In another study, Jung et al.¹⁵ deposited a thin film of copper on the surface of a spunbond PP by vacuum coating. The polymer surface was pretreated first using an oxygen ion beam to improve the adhesion of the copper thin film on its surface. The copper thin film was then deposited on the PP surface using the DC magnetron sputtering method. The copper-coated PP filter medium was reported to inactivate SARS-CoV-2 virus, which was confirmed by immunostaining and real-time PCR.

3.6. Hexagonal Boron Nitride. Commercially available surgical masks are used by a large population; however, they become uncomfortable after prolonged use because of the heat produced during breathing. This is because of minimal diffusion of heat by the polymeric material used to fabricate the masks. Xiong et al.¹⁶ developed a mask that offers excellent comfort with outstanding antibacterial properties. Hexagonal boron nitride (h-BN) was used, which was functionalized via the immobilization of quaternary ammonium salt. Functionalized NPs were incorporated to increase the thermal conductivity and antibacterial properties of the nonwoven PP fibers. On thermal conductivity tests, the nanocomposites (QAC (quaternary ammonium salt)/h-BN/PP) showed thermal conductivity that was better than that of pristine commercial and homemade PP. Therefore, the addition of the NPs improves the thermal conductivity of PP, which is essential for fabricating comfortable masks because low

thermal conductivity can result in uncomfortable hot masks. The antibacterial properties of the nanocomposite material were also assessed against *E. coli* and *S. aureus*. It was observed that the incorporation of QAC/h-BN NPs imparts outstanding antibacterial properties. To ensure that the antibacterial materials do not release biocides that might be harmful to the wearers of the masks, the authors conducted a zone of inhibition test with the nanocomposites (QAC/h-BN/PP). They observed that the nanocomposites did not produce unfavorable biocides. Regarding the antibacterial mechanism, the authors claimed that positively charged QAC/h-BN NPs can attach to bacteria via electrostatic interactions. Figure 2 shows the proposed mechanism in which the QAC/h-BN inactivates the bacteria on the PP surface.

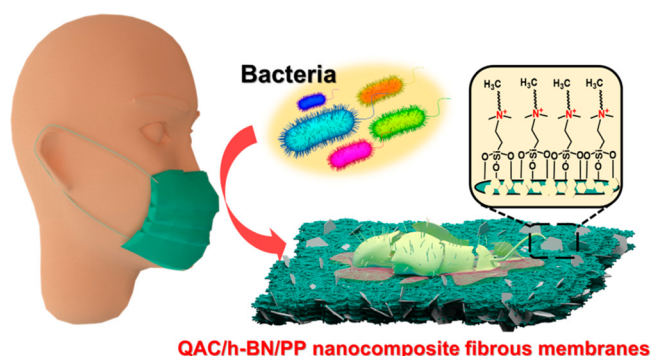


Figure 2. Mechanism in which the QAC/h-BN inactivates the bacteria on the PP surface. Reprinted from ref 16. Copyright 2020 American Chemical Society.

This enables the QAC hydrophobic chains to disrupt the cell membranes, thereby inactivating them. Quaternary ammonium salts have been reported to have excellent antimicrobial properties.¹⁷ Many healthcare workers deal with harmful microbes that are currently present and those that emerge in the future. This investigation is of paramount importance because it results in PPE, which has antibacterial properties.

3.7. N-Halamine Compounds. N-Halamine compounds can be used as antimicrobial coatings on different fabric materials. These compounds are potent biocides with a multiplicity of inhibitory activities.¹⁸ These compounds kill microbes by a mechanism assumed to be a result of a chemical reaction between the positive halogens of the N-halamine and the micro-organism receptors. This reaction disrupts metabolic processes, eventually leading to the death of the micro-organisms.¹⁹ The main advantage of N-halamine compared to other inorganic halogens is that they are less corrosive, release halogen compounds when in contact with microbes, and they are highly stable. Demir et al.^{20a} modified melt-blown nonwoven PP with an N-halamine compound. They synthesized 1-chloro-2,2,5,5-tetramethyl-4-imidazolidinone (MC) and dissolved it in ethanol. The nonwoven PP fabrics were then dipped for 10 min in a previously prepared solution. The coatings were tested against *E. coli* and *S. aureus*, and the coated fabrics showed excellent antimicrobial properties when exposed for 3 h to aerosol generation. Authors also observed that the coating had a minimal effect on the permeability of the fabrics. In another study,^{20b} hydantoin acrylamide anionic and cationic polyelectrolytes were synthesized and deposited on melt-blown nonwoven PP fabrics. The coatings showed about a 6-log reduction when in contact with the bacteria for 2–30

min depending on several factors. These fabrics can be used to fabricate face masks with antimicrobial properties.

3.8. Lignin. In an endeavor to avoid the use of NPs and carbon-based metallic materials, Kumaran et al.²¹ went a step further to fabricate antimicrobial substances that can either be spray- or dip-coated. The authors achieved this by chemically modifying lignin imparting it with multiple hydroxy and carboxylic groups, which enables conjugation to occur. The authors synthesized trimethylammonium chloride (TMAC) and adenine hexyl ammonium chloride (AHAC) antimicrobial substances and managed to conjugate them with lignin. They claimed that the UV-induced antimicrobial coating on the face mask was due to the quaternary ammonium group substitution in lignin 2,2',4'-terpyridine methylammonium chloride (LTMAC) and/or the multiple amine groups on the hydrophobic alkyl group in lignin adenine hexyl ammonium chloride (LAHAC), as shown in Figure 3.

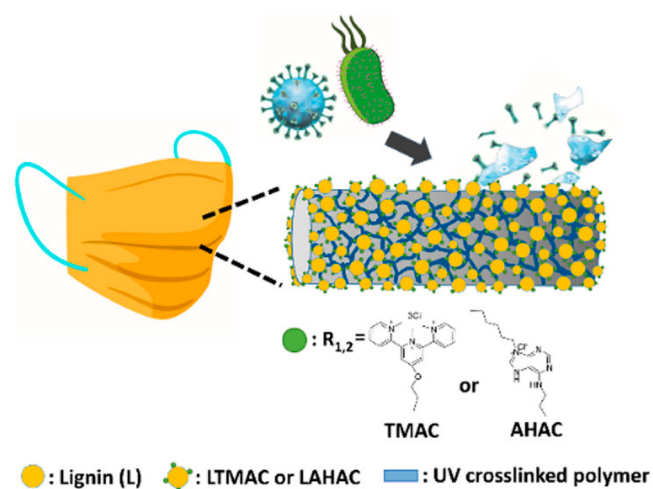


Figure 3. Antimicrobial coating on a face mask. Reprinted from ref 21. Copyright 2021 American Chemical Society.

3.9. Polyphenols. The surface of polymeric materials can be chemically modified with polyphenols to achieve antiviral properties. Polyphenols have antiviral properties, and their presence on polymeric materials may be of great use in fighting COVID-19. Catel-Ferreira et al.²² developed bio-based wipers and filters that have antiviral properties due to the presence of polyphenols. Polyphenols were attached to the surface of the nonwoven cellulose fibers using an enzymatic coupling agent. Chemically modified cellulosic fibers were tested against *Escherichia coli* B. The wipers grafted with catechin showed a 5-log reduction after 1 and 2 h in liquid media. The virucidal action of the catechin-grafted wipers was a result of the interaction between catechin and the bacteriophage. Catechin polyphenols are known to disrupt bacterial cell membranes.

4. ASSESSING THE HEALTH IMPLICATIONS OF WEARING NEAT AND MODIFIED POLYMER-BASED MASKS

4.1. Effect of Inhaling Microfibers from Masks. Due to the lack of resources and low incomes in developing countries, people tend to reuse their masks for a prolonged period. Therefore, it is important to investigate the effect of microfibers/plastics, which are produced during the continual use of masks and the disinfection method used. Microplastics

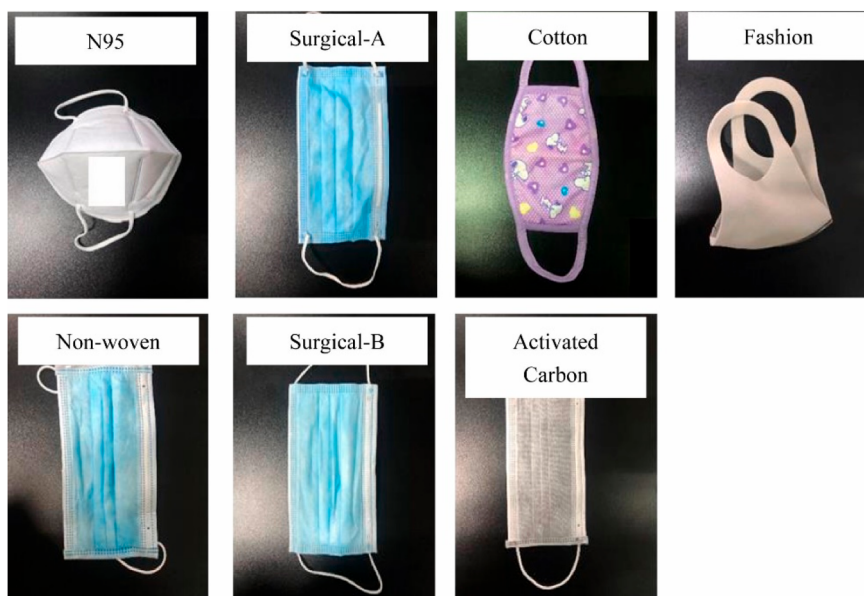


Figure 4. Different types of masks are used to investigate the effect of microplastic inhalation. Reprinted with permission from ref 25. Copyright 2021 Elsevier Science Ltd.

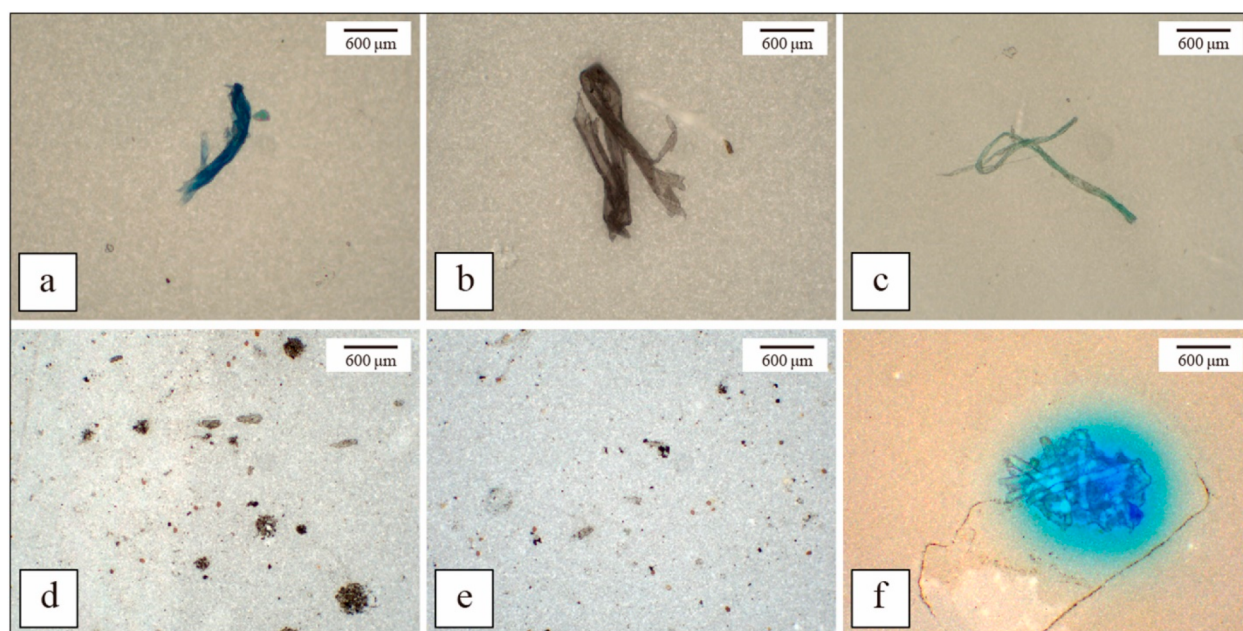


Figure 5. Microplastics observed from the selected masks (a) surgical mask, (b) activated carbon mask, (c) surgical mask C, (d) cotton mask, (e) nonwoven mask, and (f) fashion mask. Reprinted with permission from ref 25. Copyright 2021 Elsevier Science Ltd.

are small plastic materials that are less than 5 mm.²³ These plastic fragments can pass through cell walls and interact with the functions of the cells, resulting in increased cytotoxicity.²⁴ The misuse of the mask can lead to inhalation of microplastics via the nasal passage; microplastics can enter through face masks, and some are present in the atmosphere. Li et al.²⁵ investigated the risk of microplastic inhalation due to the use of different masks. The authors studied seven types of masks, namely, two surgical masks (A and B), which were obtained from different companies: N95 respirator, fashion, cotton, activated carbon, and nonwoven mask. Optical images of the various types of masks are shown in Figure 4.

Spherical and fiber-like microplastics were observed using a breathing simulation experiment, and the results are reported in Figure 5. It was further observed that wearing activated carbon, surgical, fashion, and cotton masks would result in higher fiber-like microplastic inhalation. After 720 h, the highest amount of fiber-like microplastics was recorded within the activated carbon mask, which was attributed to the inferior quality of the material used to produce the mask. The lowest amount of microplastics (fiber-like) was observed in the N95 respirators. N95 respirators were found to prevent the inhalation of fiber- and spherical-like microplastics present in the air in comparison to other masks. The authors further investigated the inhalation of microplastics of masks that had

been subjected to different disinfection methods such as UV radiation, sunlight exposure, washing with water, alcohol disinfection, and air blower treatment. They observed an increased microplastic inhalation risk for both fiber- and spherical-like microplastics after treatment. The UV radiation disinfection method was found to have a less detrimental effect on the inhalation of microplastics (fiber-like). Therefore, researchers will have to focus more on the effect of prolonged use of face masks and further investigate the health implications of inhaling microplastics on human health.

4.2. Effects of Carbonaceous Materials on Human Health. As highlighted previously, carbonaceous materials such as graphene and its derivatives are now being used to modify polymeric materials in the fight against COVID-19. It is of paramount importance to understand the health effects of graphene-related materials on human health in cases of leakage leading to accidental breathing or consumption. The toxicity of GO depends on several factors such as the dose, shape, size, carbon to oxygen ratio, and density of the functional groups. Because of their minute size, inhaled GO nanosheets can find their way to the lungs via the nasal passage. When inhaled, the GO nanosheets can interact with the pulmonary surfactant (PS), which coats the alveoli. GO nanosheets can cause pores on the PS films and negatively affect the biophysical properties and ultrastructure of the PS film.²⁶ Drasler et al.²⁷ studied the single exposure of GO and graphene nanoplatelets in a 3D human lung model. The authors realized that the single exposure of the nanosheets did not cause any adverse effects on the model. The inhalation of CNTs can also cause detrimental effects on human lungs, and there is a chance that these long and thin nanomaterials can cause lung cancer. The toxicity of CNTs is not yet conclusive since both different CNTs and animal species have been used in accessing the CNTs' pulmonary toxicity. It should be noted that the nanoparticle dosage and dimensions are the critical factors that induce detrimental effects to the lungs. More research is needed to investigate the effect of inhaling carbonaceous materials-based modified polymer masks, especially after long exposure.

4.3. Effect of AgNP Inhalation. The effects of AgNPs embedded in masks must be fully investigated. In the case of leakage, the NPs can be accidentally inhaled by the wearer of the masks. Many studies on the effects of AgNPs have been conducted in rodents. Sung et al.²⁸ studied the effect of inhaling AgNPs in Sprague–Dawley rats. The rats were exposed to fresh air, low (0.94×10^6 particle/cm³, 76 $\mu\text{g}/\text{m}^3$), middle (1.64×10^6 particle/cm³, 135 $\mu\text{g}/\text{m}^3$), and high dose (3.08×10^6 particle/cm³, 750 $\mu\text{g}/\text{m}^3$) of the NPs. After 2 weeks, there was no significant change in weight, and the authors also observed that there was no major difference in the lung function test between the rats exposed to AgNPs and those exposed to fresh air. In another study, Seiffert et al.²⁹ reported that AgNPs induced some characteristic features of asthma in rats. Further investigations are needed to analyze the possibility of AgNP leakage and its effects on human health when inhaled.

5. EFFECTS OF DISPOSED POLYMER-BASED PPE ON THE ENVIRONMENT

The use of masks and other polymeric PPE has increased since the emergence of COVID-19. Governments are now encouraging people to always wear masks, as they play a significant role in mitigating the spread of the virus.

Governments are still encouraging people to continue wearing masks despite the development of vaccines and many people taking the double jab of vaccines. Strict measures have been put in place for people to always wear their face masks, and even when traveling, many people are now wearing full PPE gear from bottom to top. The virus is evolving and mutating; therefore, people will continue wearing their masks. Although masks play a major role in mitigating the spread of the virus, when disposed, they become an environmental hazard. Of late, polymeric materials have been a problem in the environment, especially in aquatic animals, and the disposal of PPE further worsens the situation.

Disposed face masks can be a potential source of microplastics posing a danger to both the environment and micro-organisms. Chen et al.³⁰ investigated how microplastics are released from new and used face masks. It was observed that the users' face masks released microplastics to a greater extent compared to new face masks, which was mainly due to the abrasion and aging of the masks. Repeated use of these masks might cause inhalation of fibers, as stated previously, due to the loosely attached polymeric fibers. Careful management of the disposal of masks is required to create a balance by avoiding environmental pollution and mitigating the spread of SARS-CoV-2 virus. The effects of microplastics on micro-organisms have also been studied. Kwak et al.³¹ explored the production of nanofibers from polymeric melt-blown mask filters. From the results, the soil organisms (earthworms and springtails) ingested polymeric fragments from the melt-blown filter. This affected springtail reproduction and growth processes and prevented spermatogenesis in earthworms. Although the authors explained the limitations of their study, much attention has to be paid to the effect of microplastics on soil organisms. Microplastics can act as carriers of heavy metals, hydrophobic dyes, and antibiotics. A recent study by Anastopoulos et al.³² showed that disposed surgical masks have the potential to act as dye carriers in the aquatic environment. Even though face masks made from polymeric materials have helped to mitigate the spread of COVID-19, much more emphasis must be placed on preventing them to become a major environmental hazard.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

The COVID-19 outbreak caused by the novel SARS-CoV-2 virus disrupted the systematic setup of the world. Traveling and social gatherings have been banned, and people are now encouraged to wear face masks to avoid being infected by the virus. To curb the cross-contamination of the virus via a mask, researchers have modified the masks by making them antimicrobial. This specific modification enables the prolonged usage of face masks, especially in developing countries where resources are scarce. Different nanomaterials have been coated on various polymeric materials, making them antimicrobial or enabling the mask to have self-sterilization ability. Some of the nanomaterials currently being used by the researchers are carbon nanotubes, graphene oxide and its derivatives, and hexagonal boron nitride, just to mention a few. Since it is now expected that everyone wears face masks, the overview further explores the effects of inhaling microfibrils and the possibility of breathing different nanomaterials embedded on the face masks. Different types of disinfection methods have been found to damage the masks, leading to a higher risk of microplastic inhalation. The modification of masks and other related materials can prove to be a positive game changer in

preventing the spread of COVID-19 by minimizing cross-contamination and enabling prolonged use of face masks. However, the development of antimicrobial PPE, such as face masks, is an evolving process, and therefore, researchers have to put more emphasis on the safety of wearing masks and cost effectiveness. Moreover, the aspect that should be further explored is the effect of the disposal of PPEs in the environment.

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The manuscript was written through contributions of all the authors.

Notes

The authors declare no competing financial interest.

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