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SARS-CoV-2 airborne transmission: a review of risk factors and possible preventative measures using air purifiers

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The rapid spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and the resulting worldwide death toll have prompted worries regarding its transmission mechanisms. Direct, indirect, and droplet modes are the basic mechanisms of transmission. SARS-CoV-2 spreads by respiratory droplets (size range >10 μm size ranges), aerosols (5 μm), airborne, and particulate matter. The rapid transmission of SARS-CoV-2 is due to the involvement of tiny indoor air particulate matter ($PM_{2.5}$), which functions as a vector. SARS-CoV-2 is more contagious in the indoor environment where particulate matter floats for a longer period and greater distances. Extended residence time in the environment raises the risk of SARS-CoV-2 entering the lower respiratory tract, which may cause serious infection and possibly death. To decrease viral transmission in the indoor environment, it is essential to catch and kill the SARS-CoV-2 virus and maintain virus-free air, which will significantly reduce viral exposure concerns. Therefore, effective air filters with anti-viral, anti-bacterial, and anti-air-pollutant characteristics are gaining popularity recently. It is essential to develop cost-effective materials based on nanoparticles and metal–organic frameworks in order to lower the risk of airborne transmission in developing countries. A diverse range of materials play an important role in the manufacturing of effective air filters. We have summarized in this review article the basic concepts of the transmission routes of SARS-CoV-2 virus and precautionary measures using air purifiers with efficient materials-based air filters for the indoor environment. The performance of air-filter materials, challenges and alternative approaches, and future perspectives are also presented. We believe that air purifiers fabricated with highly efficient materials can control various air pollutants and prevent upcoming pandemics.

Environmental significance

Since the outbreak of the coronavirus disease in 2019 (SARS-CoV-2), questions have been raised regarding the transmission modes of the virus. In this work, we present a concise critical review of the major risk factors that have been found to contribute to the spread of SARS-CoV-2 and highlighted the role of particulate matters (PMs) as a carrier for transmission of the virus and their impact on the human body. In this regard, the need for air purifiers to filter all viral air is the greatest priority for cleaning the indoor air environment. However, most commercially available air purifiers are only able to remove a small proportion of airborne particles. The obstacles related to air purifiers inspired us to address the issues of the selection of effective materials-based air filters and the necessity for air purifiers in the indoor environment. We emphasize the fabrication of low-cost and highly potent disinfection-materials-based air filters for killing microorganisms and cleaning the air promptly. This review gives guidelines for the future development of commercial air purification materials and technologies to fight new virus strains in the future.

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1. Introduction

Coronavirus disease 2019, also known as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), (COVID-19) has altered the entire world's dynamics and perception of human lifestyle and health. The World Health Organization declared SARS-CoV-2 a pandemic on March 11, 2020.[1] The disease is constantly expanding, most likely due to viral mutation. Globally, over 609 million COVID-19 cases and over 60 million deaths had been documented by September 2022.[2] More recently, the novel SARS-CoV-2 variant Omicron (B.1.1.529) was discovered in South Africa and spread to other regions, including the Netherlands, Australia, North America, South Korea, and many areas of Europe.[2,3] Moreover, other variants include Alpha (B.1.17) found in the United Kingdom, Beta (B.1.351) detected in South Africa, Gamma (P.1) discovered among Brazilian visitors, and Delta (B.1.617.2) identified in India.[4,5]

SARS-CoV-2 is mostly transmitted between people by aerosols and droplets produced by coughing, sneezing, talking, and screaming.[6] When SARS-CoV-2 enters a live cell, its entrance and replication cycle is comprised of numerous phases: attachment and entry, translation of viral protein, genome transcription and replication, translation of structural proteins, and virion assembly and release.[7] After making viral copies, the

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next step is to infect other people *via* various modes. The possible transmission modes of SARS-CoV-2 are person-to-person, direct or indirect contact with an infected surface, and aerosol emission during coughing and sneezing.[8,9] However, the main transmission modes are airborne, such as mixing with $PM_{2.5}$, air-conditioning systems, and weather conditions. According to contemporary research, air conditioners can increase the risk of infection in an indoor environment by up to 85.2%.[10] The presence of $PM_{2.5}$ in the air is responsible for bad air quality and for transmitting SARS-CoV-2 over a longer distance within a short period.[11–13] New research suggests that tiny aerosol particles (5 μm) contain more copies of SARS-CoV-2 than coarse aerosols, suggesting that this might be a significant factor in viral transmission.[14] However, it is crucial to understand the ways in which air quality plays a fundamental role in the transmission of SARS-CoV-2 in the presence of pollutants and specific climatic conditions, because these pollutants act as carriers for airborne transmission as mentioned earlier.[15,16] SARS-CoV-2 infection has been reported for a range of particulate matter (PM), from sub- to super-micrometer sizes.[17,18] This indicates that the virus may be transmitted by solid aerosols. $PM_{2.5}$ particles have a particle diameter of ≤2.5 μm and are aerosols suspended in ambient air. There was no association between viral concentration and the diameter of particles in particulate matter. Nonetheless, positive connections have been reported between $PM_{2.5}$ and other respiratory viruses such as the influenza virus. This correlation shows that SARS-CoV-2 is transported *via* particulate particles.[19] Similarly, Nor *et al.*[20] found a strong relationship between $PM_{2.5}$ and virus concentration. $PM_{2.5}$ involvement in a closed environment can cause more acute infection of SARS-CoV-2. The majority of $PM_{2.5}$ dust particles come into the indoor environment from typical outside sources including automobiles, biomass burning, and industrial pollution.[21–23] This small particulate matter is readily dispersed by the minute turbulent air currents induced by human activity, such as walking.[24] SARS-CoV-2 has been shown to be viable on a variety of surfaces (*e.g.*, metal for 48 hours, plastic for 72 hours, cardboard for 24 hours, and copper for 4 hours). Therefore, surface viruses may become trapped in $PM_{2.5}$ and be carried back into the atmosphere.[25,26]

Intrinsically, the SARS-CoV-2 virus constitutes a significant threat to the public health. The virus can enter the upper–lower respiratory system and cause severe lung infection and chronic obstructive pulmonary diseases. In addition to respiratory

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disorders and organ damage, SARS-CoV-2 infection has been linked to a wide range of neurological and psychiatric symptoms, including neurocognitive syndrome, ischemic stroke, psychosis, depression, anxiety, headache, hyposmia, dizziness, and ataxia, among others.[27] Primarily, human coronavirus (HCoV) enters the central nervous system (CNS) through the blood and peripheral organs before spreading to the brain. HCoV could potentially infect the CNS *via* neuronal dissemination, a process in which the virus infects peripheral neurons and then CNS neurons using host cell machinery. Patients suffering from acute respiratory symptoms are more likely to develop neuropsychiatric and neurocognitive diseases such as depression, obsessive–compulsive disorder, Parkinson's disease, and Alzheimer's disease. Chronic HCoV infection may result in the development of a blood clot in the brain, which can be fatal.[27–30] Environmental sustainability, poor indoor air quality, and a pathogenic indoor air environment are particular attributes that increase the chances of the global outbreak of the virus again in future years. Therefore, numerous medical, social, and engineering methods have been recommended to address SARS-CoV-2. The World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), the National Institutes of Health (NHI), and others are investigating the etiology, structural variations, cell biology, and biological functions of SARS-CoV-2 in addition to methods of controlling the SARS-CoV-2 pandemic. These agencies have exerted maximum efforts, but it is still difficult to manage SARS-CoV-2 because of its dissemination and infectious characteristics. The use of preventative measures such as the adoption of face masks, immunizations, self-monitoring of health status, cleanliness, and public distancing have led, to a certain degree, to a decrease in the chain of transmission.[31–33] Furthermore, SARS-CoV-2 variations make this task more arduous as new virus strains are more infectious and deadly.[34]

Keeping these obstacles in consideration, further redesigned efforts and modern techniques are required to combat this deadly viral infection.[35] As addressed earlier, SARS-CoV-2 is propagated by airborne transmission. As a result, one of the new approaches to address this problem is to produce virus-free clean indoor air by capturing, eradicating, and destroying viruses including SARS-CoV-2 using air purifiers. Fig. 1 shows how SARS-CoV-2 spreads mostly by respiratory droplets, aerosols, particulates ($PM_{2.5}$), and airborne particles.[35–39]

There is universal concern about air quality and the availability of sufficient air filtering systems. Since SARS-CoV-2 was identified as a virus, air filters with anti-viral and anti-microbial characteristics have gained popularity. These filters are very efficient in preventing the transmission of viruses. Moreover, certain air filters based on electrospun nano-fibers, photocatalytic nanomaterials and fibers, metal–organic-framework (MOFs), and bead-based filters with anti-microbial and air-pollutant-removal characteristics are more effective. These materials can be used in face masks and air purifiers to clean the indoor environment and protect public health.[40–46] Today, semiconductor materials such as TiO_2 and ZnO, which are promising photocatalysts for air disinfection under UV light, are being used in air purifier filters. However, their disinfection effectiveness is still far from satisfactory, particularly when VOCs and PMs mix with high air flow velocity. According to scientific investigations, TiO_2 has a large energy band gap (3.2 eV). Therefore, TiO_2 can only absorb wavelengths shorter than 400 nm and cannot work well in the indoor environment.[47,48]

There have been several reviews of evaluations focused on preventing the spread of the transmission of SARS-CoV-2,

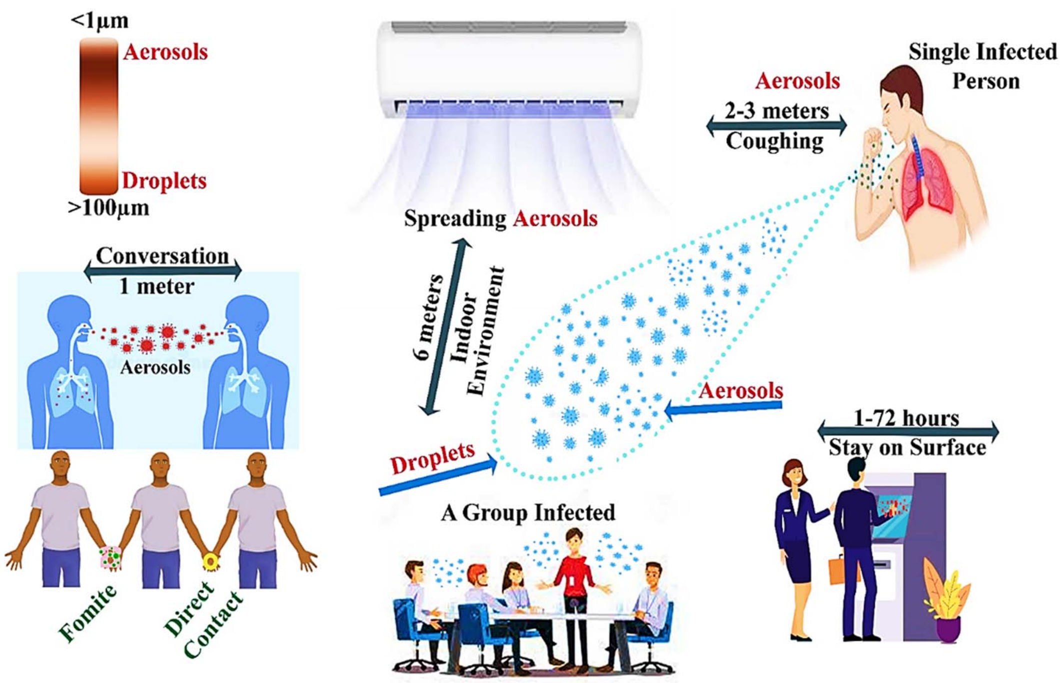

Fig. 1 Transmission modes of SARS-CoV-2.

including the effects of air quality on the transmission, replication, and virology of SARS-CoV-2, the role of $PM_{2.5}$ in its transmission, and the effect of weather variations on its spread.[49–52] However, there is a lack of awareness of air purifiers, the selection of efficient materials-based air filters, and the importance of air purifiers in the indoor environment, which has provided us with an opportunity to highlight this challenge.

In this review, we have provided a concise summary of the fundamental risk factors that have been proven to contribute to the spread of SARS-CoV-2 and highlighted the role of particulate matters (PMs) as a carrier for transmission of the virus and their impact on the human body. However, there is little information on air purification systems consisting of low-cost and highly potent disinfecting materials for microorganisms and air pollutants. Therefore, we have briefly described and emphasized the fabrication of various efficient materials-based air filters for air purifiers. This review provides guidelines for the continued development of air purification materials and technologies for commercial use in the future.

2. Methodology

Various search engines, including Google Scholar, Research Gate, Academia, and ScienceDirect, were used to perform a literature search. The targeted keywords SARS-CoV-2, airborne transmission, $PM_{2.5}$, indoor pollution, nanomaterials, metal–organic frameworks (MOFs), air cleaning materials, and air purifiers were used to identify relevant articles. The selected articles also focus on transmissibility mechanisms *via* $PM_{2.5}$ as a carrier. The articles were coded into different themes through an iterative process, followed by classification into four categories: mechanism of SARS-CoV-2 transmission; respiratory problems due to exposure to $PM_{2.5}$ and viral air; cumulative effects of airborne transmission of COVID-19 through PMs; and preventative measures using air purifiers containing efficient nanomaterials, fibers, and MOFs porous material.

3. Discussion

3.1. Major transmission modes of SARS-CoV-2

Since the commencement of the viral outbreak, research has mostly focused on controlling and combating the pandemic; therefore, many studies have been carried out regarding the etymology, symptoms, modes of transmission, and mortality of the virus. The well-established route of viral infection is through respiratory droplets and contact with COVID-19-infected people.[53] According to current statistics, the predominant mechanisms of SARS-CoV-2 transmission in the current pandemic are direct (contact with an infected person), indirect (by touching a viral surface), and, significantly, through aerosols (by inhaling viral air).[54] To prevent the infection from spreading directly, strict monitoring and testing are required. In general, SARS-CoV-2-infected people will transmit the infection to people with whom they come into contact. Many SARS-CoV-2 infected patients are asymptomatic and may act as carriers, unintentionally transmitting the virus.[55]

3.1.1. Contact (direct). Direct contact transmission occurs when humans directly touch virus-infected people *via* their mouth, nose, or eyes.[56] The principal source of infectious particles conveyed by physical contact is thought to be spores. SARS-CoV-2 transmission may be reduced by frequent hand-washing with an alcohol-based sanitizer and avoiding contact with the eyes, nostrils, and face. Although the SARS-CoV-2 virus is not primarily airborne, it is transmitted *via* exhalation when infected persons cough and sneeze, resulting in pollution of the environment with viral aerosols.[52] Aerosol transmission is not restricted to those with symptoms; asymptomatic COVID-19-positive individuals are also among the sources of infection. In addition, the virus-containing aerosol may persist in the air for extended periods of time and in high concentrations in close surroundings, thus significantly boosting the transmission rate.[57] This virus has the ability to survive in aerosols for at least three hours, but it can survive on stainless-steel and plastic surfaces for 48–72 hours.[58]

3.1.2. Droplets. In most cases, respiratory air includes multiple droplets of respiratory fluids, the majority of which are saliva, that have a diameter of more than 10 micrometers. These droplets are sufficiently sized to transmit respiratory viruses such as SARS-CoV-2, which may persist in open space and on surfaces for several hours.[59] Infected people expel infectious droplets of varying sizes by breathing, coughing, and sneezing. They also generate feces with a high concentration of SARS-CoV-2 virus. During speaking and breathing, up to 200 droplets of sizes varying from 1 to 24 m may be expelled, and these droplets can spread across a distance of 1 m.[60,61] Depending on their size, these droplets may travel up to three feet before settling on the surfaces with which they come into contact. Large droplets have a greater chance of being infected with a virus than smaller ones. Large droplets are capable of transforming into small droplets that remain suspended for longer durations. Viruses can be spread by the contact of hands that have been contaminated with viruses with the mucous membranes of the mouth, nose, and eyes (fomite transmission).

Massive numbers of virus particles may be transmitted in droplets with a diameter between 10 and 100 μm, leading to a severe case of COVID-19 infection. Consequently, it is pivotal to take essential protective measures to prevent droplet-based transmission (DBT) of SARS-CoV-2. Using a face mask (not necessarily N95) and disinfectants to clean a contaminated surface may prevent droplet-based transmission (DBT).[62] In addition, transmission relies on the turbulence and flow of air, and droplet nuclei may remain in the air for long periods of time and travel enormous distances. Depending on air flow velocity, turbulence, temperature, and humidity, airborne particles with a diameter smaller than 5 μm may remain suspended for several hours.[63] When they mix with other particles, such as dust or $PM_{2.5}$, they can stay airborne for up to several months. As a result, coating surfaces with antiviral and antibacterial nanomaterials such as Cu, Ag, TiO_2, *etc.*, is a great method for preventing fomite transmission.[62]

3.1.3. Aerosols. Aerosols are considered one of the major routes of transmission of SARS-CoV-2. The transmission of

SARS-CoV-2 by aerosols is the most severe and well-studied mode of transmission. Virus-containing aerosol droplets of respiratory fluid are smaller than 5 μm and can travel up to 6 feet in the air. Aerosols are produced when an expiratory event takes place, such as coughing or sneezing. The majority of the time, these two events release hundreds of microscopic droplets that contain a large number of virus particles into the air. These droplets have the potential to cause significant infection when inhaled by someone who is in close proximity to an infected person. A variety of environmental conditions impact viral transmission through aerosols. Aerosols may travel a distance of up to 30 feet under some specific conditions. Additionally, ambient humidity and temperature may enhance the survivability of an aerosolized virus, enabling it to persist for a longer period of time.[59,62] A typical mask may not capture some virus-containing particles. As a result, higher-quality masks (N95 and nanoparticle-coated masks), appropriate circulation, and air purifiers are required to avoid aerosol-transmitted infectious diseases.[64]

3.1.4. Indoor airborne transmission. The prevalence of close interactions and the probability of touching highly infected items in indoor environments, especially educational institutions, places of worship, health care facilities, and day-care centers, can be an extremely high risk for the spread and transmissibility of SARS-CoV-2.[65] Because people spend so much time inside (over 90% of their time), the spread of disease is a major concern. Ventilation/air-conditioning systems are often linked to viral transmission of up to 6 m, and increase the infection risk in indoor environments. The size of the aerosols is still debatable; however, it has been measured at the genome level in hospitals and found to be 0.2 μm. The tiny particles can remain suspended in the air for an extended period of time, increasing the probability of inhalation, particularly in closed spaces.[33,36,38] A recent study reported that aerosols could transmit at speeds of more than 2 m s^{-1}, and that droplets could be transmitted with a high possible speed of between 1 and 1.9 m s^{-1}. When the velocity is between 0.9 and 0.25 m s^{-1}, there is no chance that the droplets will be transmitted speedily. This is the primary basis for classifying SARS-CoV-2 viral infection as having airborne transmission.[66] Contemporary research has been focused on ways to manage this form of transmission under various environmental circumstances. There is a chance that the airflow in buildings may allow virus particles to travel further than usual. Temperature and humidity may also contribute to the longevity of virus particles in a given space. It is vital to eradicate these particles from contaminated air in order to avoid the spread of a particularly dangerous infection.[67] However, at present, the biggest challenge is how to remove viruses from the air. Effective air purifiers that collect and destroy viruses might be a solution for airborne infection management.

3.2. Plausible role of particulate matter in the transmission of SARS-CoV-2

Microscopically sized solid or liquid particles that float in the air are called particulate matter (PM). The particles that make up particulates may be coarse or fine in terms of dimensions. PM_{10} and $PM_{2.5}$ are the most often used PM indices, and indicate the overall concentrations of particles having diameters of ≤10 and ≤2.5 μm, respectively.[68] An indicator, known as the PM index, measures the quantity of $PM_{2.5}$ in a given volume of air. Several primary, natural, and man-made sources of $PM_{2.5}$ are volcanic gases, sand, rock erosion, forest fires, pollens, lichen propagules, incinerators, cement plants, industrial gases, household heating, manufacturing facilities, steel plants, and coal or heavy crude power plants, as examples of facilities that rely on fossil fuels for energy.[69–71] Many virologists have recently raised concerns about particulate-assisted viral transmission, which is unsurprising.[38,72] Likewise, virus durability with the $PM_{2.5}$ in the atmosphere (airborne transmission) is high, as compared to the direct (sneezing, coughing) and indirect (infected surfaces) transmission modes. To demonstrate this phenomenon, investigators used a three-jet collision nebulizer to produce particles that were sufficiently small (5 μm) that they stayed suspended in aerosols.[72] Consequently, active new SARS-CoV-2 was discovered in aerosols for up to 3 hours after aerosolization, 4 hours on copper, and 7 days on other substrates. In aerosols, the half-lives of novel SARS-CoV-2 and SARS-CoV-1 were comparable, with median values of roughly 2.7 hours. Eventual SARS-CoV-2 aerosol transmission is conceivable, given that the virus may survive in aerosols for many hours and even days on substrates. As a result of the fact that aerosol-borne viruses float in the air, there is a possibility that aerosols in the air may adsorb other particles (such as $PM_{1.0}$, $PM_{2.5}$, and PM_{10}). These particles consist of tiny chemical particles, biological particulates, and biopolymers such as hair, animal dander, dead skin cells, and several others. They act as a suitable medium for viruses, which can prolong their survival time. Thus, particulate matter is the primary cause of SARS-CoV-2 air transmission and long-range coverage, and it increases the death rate of those infected by the virus.[73] Table 1 summarizes multiple research articles to strengthen the hypothesis that increased $PM_{2.5}$ leads to a higher mortality rate and more reported cases in this outbreak. Another study reports that a 0.7% increase in the mortality rate may be caused by an average rise of 10 μm m^{-3} in $PM_{2.5}$ in the atmosphere when there are no viral droplets in the air. Additionally, at present, in viral air, an increase of only 1 μm m^{-3} in $PM_{2.5}$ in the air can lead to a 9% increase in the mortality rate.[74]

Particulate-matter-contaminated air contains an extreme viral load of SARS-CoV-2, which can directly infect the human lungs, cause acute infection, and lead to death. Fig. 2 illustrates the comparative adverse effects of viral and polluted air. Fig. 2(1) shows that respiration in clean air is associated with healthy lungs and the proper exchange of gases. Fig. 2(2) demonstrates that respiration in viral air can damage the wall and lining of the alveoli and capillaries, resulting in thickening of the lining. This thickening can lead to difficulty in breathing, cytokine release syndrome, and vasoconstriction. However, viral air alone can cause mildly infected lungs with inflammation.[75–77] Fig. 2(3) shows that the inhalation of $PM_{2.5}$ can cause moderate infection in the lungs. This infection mainly causes breathing difficulty, irritation of the airways,

Table 1 Association between $PM_{2.5\ (\mu m)}$ in viral air and mortality rate/reported cases

Main objective	Data sources for COVID-19 deaths and reported cases	Period of research	Reported new infection cases	Reported cases of death	Data sources for PM in the air	Analysis	Key findings	Reference
To explore the relationship between PM in air and mortality and infectivity rate in England	Public Health England and the National Health Service	1st February–8th April 2020	103 409	32 903	European Environmental Agency and Department of Food, Environment, and Rural Affairs Website	Exploratory analysis by statistics	A single unit increase in $PM_{2.5}$ is associated with 8% more COVID-19 cases in England	116
To investigate long-term exposure to fine particles. $PM_{2.5}$ is associated with an increased risk of COVID-19 deaths in the U.S	Johns Hopkins University, and the Centre for System Sciences and Engineering Coronavirus Resource Center	March 22nd 2020–April 22nd 2020	—	45 817	Environmental Protection Agency, Center for Disease Control and Prevention	Detrimental and sensitive analysis by statistics	An increase of only 1 $\mu g\ m^{-3}$ in $PM_{2.5}$ is associated with an 8% increase in the COVID-19 death rate in the United States	117
To evaluate the effects of long-term exposure to $PM_{2.5}$ on COVID-19-related mortality	Medical Research Council and National Institutes of Health	March 2019–June 30th, 2020	38 573	—	Environmental Protection Agency	Sensitivity analyses by statistics	There is a 4.4% rise in COVID-19-related mortality due to association with $PM_{2.5}$ in England	118
To prove that $PM_{2.5}$ acts as a carrier to spread the coronavirus and virus-related mortality in Italy	National Institutes of Health	February 24th, 2020–March 13th, 2021	4 million	17 660	European Environment Agency (EEA) air quality database	An observational study by statistical analysis	In the 110 Italian provinces, a positive correlation has been revealed between the demographic makeup of daily $PM_{2.5}$ emissions and the preliminary spread of COVID-19	119
To evaluate the impacts of the Saharan desert on the concentration of $PM_{2.5}$ and their association with COVID-19-related mortality	Johns Hopkins Coronavirus Resources Center	June 15th–July 12th 2020	250 000	32 796	National Oceanic and Atmospheric Administration, and Atlantic Oceanographic and Meteorological Laboratory	Correlation & statistical analysis	There is a 6.4% rise in COVID-19-related mortality due to the association with $PM_{2.5}$ in the Saharan desert	120

Table 1 (*Contd.*)

Main objective	Data sources for COVID-19 deaths and reported cases	Period of research	Reported new infection cases	Reported cases of death	Data sources for PM in the air	Analysis	Key findings	Reference
To determine the possible role $PM_{2.5}$ plays in coronavirus spread, morbidities, and mortalities	Google Scholar, PubMed, Sci-Hub	March 2019–April 2021	950 000	22 034	Air quality index data	Meta-analysis of secondary data	The effect of PM fumes and virus transmission among humans has been studied and investigated in a variety of global zones, with many incidences. In long-term exposure to $PM_{2.5}$, the COVID-19 mortality rate increased by 15% for every 1 $\mu g\ m^{-3}$ increase in $PM_{2.5}$	51
To evaluate the association between $PM_{2.5}$ and COVID-19-related deaths in 49 cities in China and their dependence on the weather variants	The National Health Commission and the Provincial Health Commissions	January 15th, 2020–February 29th, 2020	82 214	3206	China Meteorological Data Sharing Service System	Statistical analysis	For every 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ concentration, COVID-19 increased by 0.26%. The less significant association is due to weather variants of lower temperature and greater humidity	121
To determine the association between mortality by COVID-19 and ambient $PM_{2.5}$ in northern Italy	WHO website and Health Research Center	January 1st–April 30th, 2020	230 000	30 000	European Environmental Agency's (EEA) air monitoring database and Environmental Protection and Research	Empirical analysis by statistics	A 1 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ concentration is associated with a 9% increase in COVID-19 related mortality	74

acute bronchitis, and asthma due to the inhalation of fine particles of particulate matter, which directly enter the lungs and damage the alveoli, resulting in bronchoconstriction and restriction in the air exchange between lungs and air.[78,79] Fig. 2(4) demonstrates that when the human body inhales a mixture of $PM_{2.5}$ and aerosols, it can cause severe lung infection. This mainly affects the upper and lower respiratory tracts, and causes damage to alveoli and bronchoconstriction. The infection can be more severe when $PM_{2.5}$ are spread in the viral air, because it directly affects the heart, and can cause cardiovascular diseases, such as stroke.[80,81]

The transmission mechanism of SARS-CoV-2 encapsulated in particulate matter must be investigated further. Maintaining a virus-free and hygienic indoor environment will aid in the battle against the pandemic. As mentioned previously in reference to airborne viral transmission, air purifiers are one of the most recommended approaches to catch particulates using nanofiber filters and simultaneously neutralize the virus protein, destroy volatile organic compounds using nanomaterials under UV light, and produce air that is devoid of SARS-CoV-2.

3.3. Preventative measures before infection (state-of-the-art indoor air purifiers)

The quality of the air within the indoor environment is a constant source of concern, and numerous studies have been conducted to monitor the presence of volatile organic compounds (VOCs) and dust particles in the indoor environment. However, indoor air quality meeting international standards could not be maintained due to a lack of awareness related to indoor air quality and limited availability of air purification technology. However, the novel SARS-CoV-2 pandemic has startled the world and compelled global health authorities to establish better management to control infectious diseases, enhance medical infrastructure, and educate the general public on the significance of clean air.[82–85] Another challenge is long COVID; according to a recent Italian survey, 87% of recovered patients discharged from hospitals had at least one symptom persist and 55% had three or more symptoms 60 days after SARS-CoV-2 infection. Another study found that COVID-19 patients who were discharged from the hospital still had dyspnea and extreme fatigue three months later. Unsanitary air, inadequate ventilation, and co-morbidities may all contribute to the development of post-COVID-19 syndrome, the most serious risk associated with long COVID. Effective materials-based air purifiers can maintain a sanitary indoor environment, destroy virus particles and particulate matter, and reduce the risk of air pollution in these circumstances. As a result, an air purifier can provide additional protection to post-COVID patients. Therefore, it is even more important to take preventative measures before an infection occurs.[86–90] As a consequence, the demand for virus-free indoor air and modern air purification technologies has increased. The primary concerns of air purifier makers are technological and commercial considerations. Such devices considerably enhance indoor air quality and significantly improve health quality by limiting airborne infection. The goal of air filtration technology is to capture and destroy air contaminants, particularly SARS-CoV-2, in a single pass.

Decades-long efforts have been undertaken to enhance the performance of air purifiers by upgrading filter efficiency and

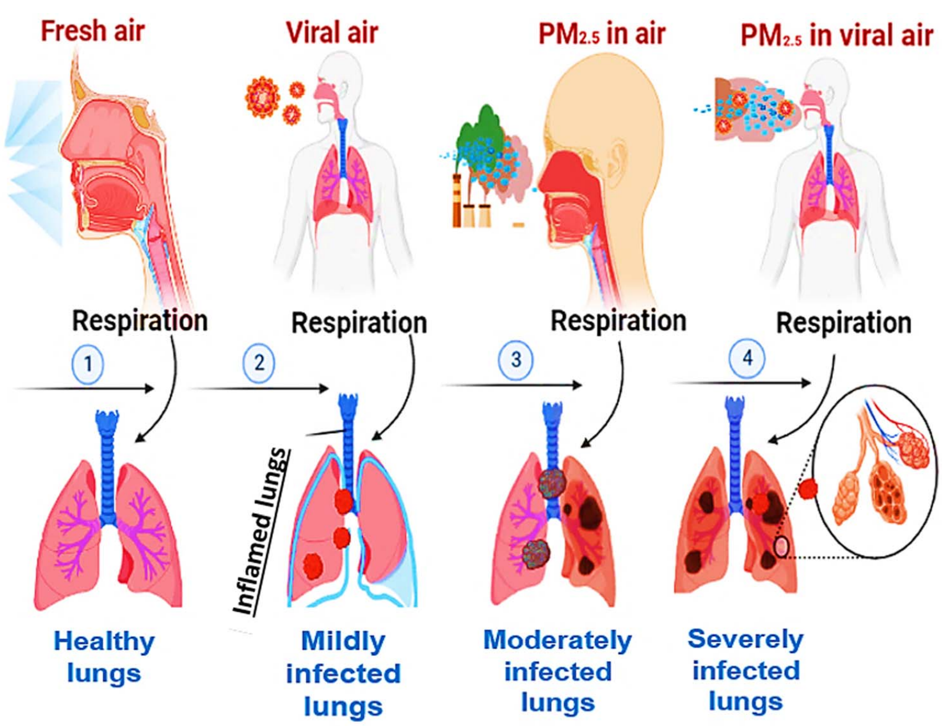

Fig. 2 Effects of the inhalation of SARS-CoV-2 and $PM_{2.5}$ mixtures on the respiratory system.

device design to make them suitable for a variety of environments. The market for air purifiers in the United States continues to expand annually. It is expected to reach billions of dollars by 2028 (4.47 billion dollars). The annual growth is approximated to reach 8.6% in the years 2020 to 2028.[91] Despite the growing investment and health advantages, existing air purifiers consistently exhibit limitations such as limited filter performance, high power consumption, and lower efficiency in larger premises. After the SARS-CoV-2 outbreak, it has become very necessary to develop highly efficient filters for air purifiers, due to the fact that most commercially available air purifiers can only remove a small subset of airborne particles, namely particulate matter ($PM_{2.5}$ and PM_{10}) and volatile organic compounds (VOCs). Trapping PM_{10} and killing bio-active particles (allergens, germs, deadly viruses, *etc.*) along with molds is a remaining issue. Consequently, there is an immediate need to develop or add additional filters to air purifiers that are capable of catching pollutants effectively and killing small, deadly viruses promptly.[83]

Fig. 3a demonstrates an effective air purifier with different stages of filters, and Fig. 3b shows antimicrobial materials and their mechanism of action. There are three common types of air filters in the air purifiers that are available on the market: (i) pre-filters to remove coarse particles, (ii) activated carbon, which is a prominent ingredient in chemical air filters because of its ability to absorb noxious chemicals, and (iii) high-efficiency particulate air (HEPA) filters for the removal of fine dust particles.[92] The key component of an air purifier, *i.e.* the heart of the air purifier device, is an effective filter that can capture and kill the bio-contaminants in air instantly. It has been suggested that anti-microbial filters could be used in commercial air purifiers. These filters can be made using various nanomaterials or metal–organic frameworks (MOFs). These materials show rapid destruction efficiency under visible light instead of UV light. Although UV-light irradiation can improve photocatalytic activity and durability, it also generates ozone, which causes secondary air pollution and is harmful to the environment.[93–95]

3.3.1. Outstanding nanomaterials for air purification.

In response to recent epidemic diseases like SARS-CoV-2, new air filters with anti-viral and antibacterial capabilities have been discovered and developed to battle infections and protect public health. According to the most recent findings from various studies, airborne droplets or aerosols are the transmitters of the SARS-CoV-2 virus. Aerosols typically exhibit two dimensions: sub-micron and super-micron dimensions, which correspond to the 0.25 to 1.0 μm range and the >2.5 μm ranges.[96] Furthermore, data from published research reports has confirmed that particulate matter ($PM_{2.5}$) contains viruses, bacteria, and organic contaminants, as we have discussed earlier. These tiny particles can float in the air, enter the human body by inhalation, and inflict permanent harm. Consequently, medical

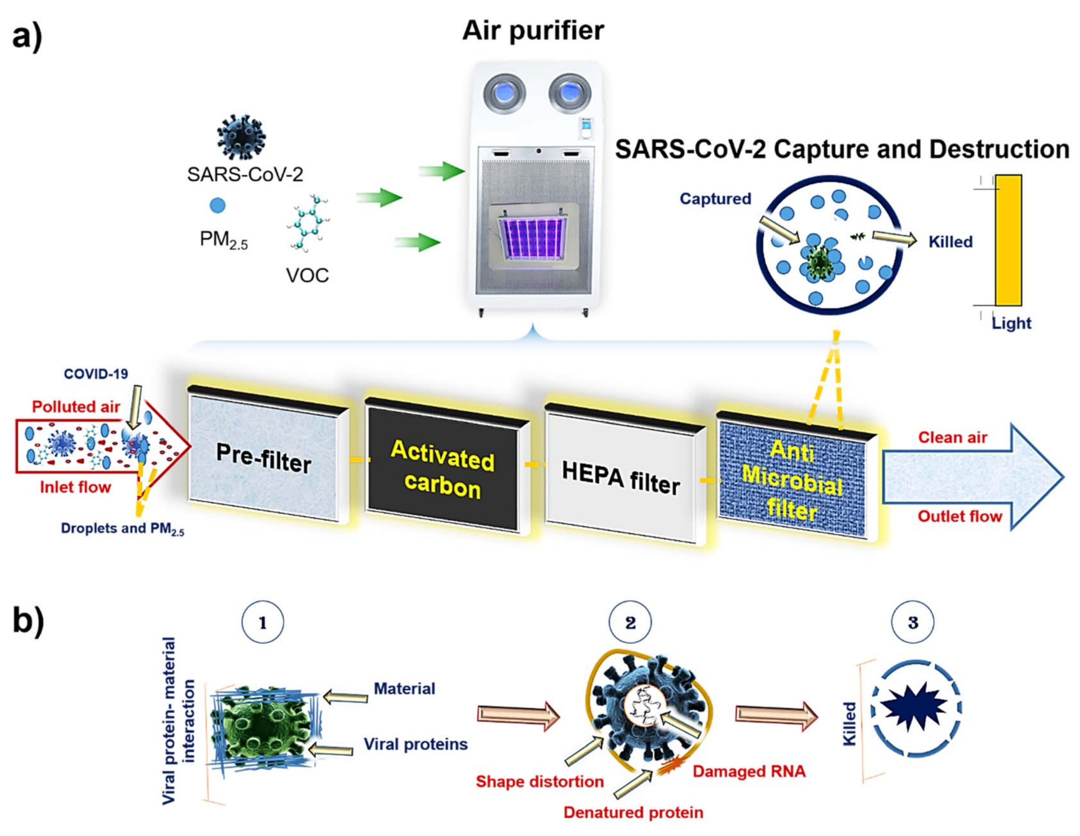

Fig. 3 Inside view of efficient materials-based state-of-art air purifier. (a) Air purifiers with a variety of filters. (b) Capture and destroy system mechanism of SARS-CoV-2.

masks and air purifier units should have appropriate filters made with efficient nanomaterials for the removal of nano-aerosols or ultrafine submicron particles. Therefore, nano-technology is one of the savior technologies that can protect us from inhaling viral air.

Due to their superior characteristics, metallic nanoparticles containing silver (Ag) have effective anti-viral and anti-bacterial activities and may be a useful option for the construction of air filters. In this regard, Kang *et al.*[97] reported a contemporary method for the fabrication of novel Ag-doped TiO_2 nanofibers using electrospinning and a post-treatment method. The synthesis of Ag/TiO_2 requires a silver nitrate ($AgNO_3$), titanium isopropoxide (TTIP), and polyvinylpyrrolidone (PVP) composite solution. The step-by-step preparation of Ag/TiO_2 NFs is depicted in Fig. 4. First, external electric potential ion separation was used, which caused the ions to migrate in a certain direction, as illustrated in Fig. 4a. When the nozzle was subjected to a negative electric potential, the Ag^+ and NO_3^- ions moved to the outer and inner sides of the nozzle, respectively. As a result, electrospun $AgNO_3$/TTIP/PVP NFs with a significant concertation of Ag at the surface were produced, as shown in Fig. 4b. Lastly, nanoparticles (NPs) were generated through electrospray and powerfully dispersed by coulombic repulsion force. All the components in the solution were mixed uniformly and then underwent a pyrolysis process. Finally, the authors tested the Ag/TiO_2 NFs in an air filtration experiment under visible light for the inactivation of airborne pathogens (H1N1, H3N2, multi-drug resistant bacteria), and the photocatalytic oxidation of VOCs was also thoroughly studied (Fig. 4c). As a consequence, Ag/TiO_2 NFs with 0.5% Ag-doping showed remarkable performance in killing the pathogenic bacteria and viruses under visible and UV light. Additionally, the Ag/TiO_2 NFs showed the highest methylene blue (MB) and acetaldehyde removal efficiency due to their lowest bandgap energy, smaller Ag size, and lower photoelectron recombination rate, and are expected to act as the best visible light photocatalyst. Therefore, Ag/TiO_2 NFs have a promising future for airborne pathogen inactivation and effective VOC oxidation under visible light. This could be a game-changer for the development of a new air filters for commercial air purifiers.

In another study, Kim *et al.*[98] suggested the latest methodology for air purification using a titania–zeolite composite. The major purpose of this investigation was to hybridize TiO_2 with porous adsorbents and test the TiO_2/H-ZSM5 bead-based filter in an air purifier. They investigated the filter durability and its efficiency for simultaneous treatment of VOCs and microorganisms. The authors chose the concept of hybridizing TiO_2 because this is an effective method to increase the photocatalytic adsorption capability. Activated carbon also seems to be a promising option for this kind of hybridization. However, it has been established that activated carbon hinders the vast majority of incoming UVA radiation and lowers the proportion of light available to TiO_2.[99,100] However, hybridization of TiO_2 with H-ZSM5, which possesses hydrophobic surfaces, may considerably enhance the removal of VOCs such as formaldehyde, acetaldehyde, and toluene.[100–102] Subsequently, the unpredicted SARS-CoV-2 epidemic seriously affected the world and pushed researchers to develop novel strategies for the removal of SARS-CoV-2 from indoor environments. Therefore, Sungwon Kim and their co-workers successfully synthesized

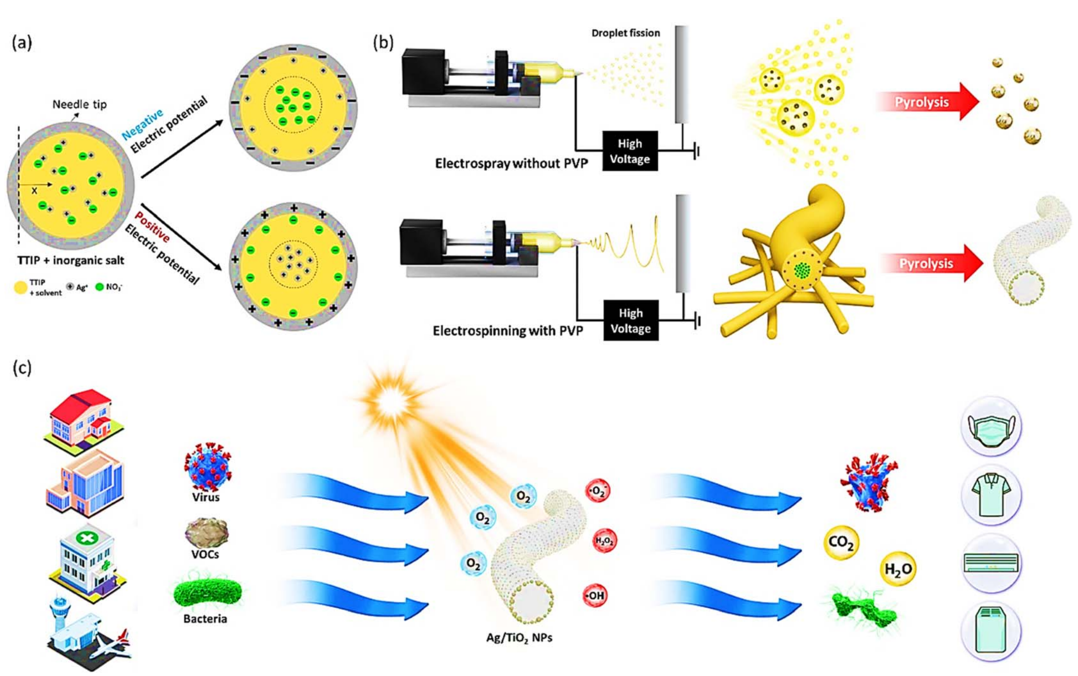

Fig. 4 Diagrammatic presentation of (a) the distribution of inorganic salts at various electric potentials and (b) the synthesis method for the Ag/TiO_2 nanoparticles (NPs) and nanofiber (NF). (c) Using Ag/TiO_2 NFs for integrated air cleaning. (Reprinted with permission from ref. 97, copyright © 2022 Elsevier B.V. All rights reserved).

a TiO_2/H-ZSM5 composite using spherical beads with diameters of 4 ± 0.5 mm that were fabricated by combining and granulating TiO_2 in an aqueous medium with various quantities of H-ZSM5 powder. Various powder weight percentages were used (0 to 7 wt%) in the granulator. The beads were heated at 150 °C for 2 hours, sorted to obtain the appropriate size, and then heat-treated at 550 °C for 2 hours. Finally, 1.3 kg of the manufactured beads was decorated in a filter frame 325 mm (W) × 345 mm (L) × 20 mm (T) and loaded in a purifier, and the experiment began under UVA light, as shown in Fig. 5a–c. The experiment showed that the photocatalytic air purifier with the TiO_2/H-ZSM5 composite bead filter gave an outstanding performance for the removal of VOCs and viruses. The performance of the TiO_2/H-ZSM5 filter was dramatically improved as compared to that of bare TiO_2, as depicted in Fig. 5d. Furthermore, the photocatalytic air purifier effectively removed aerosolized viruses (phi-X174) in a 60 m^3 chamber. Using photocatalytic oxidation, all the viruses on the filter beads were eradicated. The efficient TiO_2/H-ZSM5 composite beads had a nonselective virucidal effect on serval pathogenic coronaviruses, including PEDV, HCoV-NL63, and SARS-CoV-2. The infectivity was reduced *via* oxidative RNA destruction. The findings of this study show that an air purifier packed with a TiO_2/H-ZSM5 hybrid bead filter has potential for rapid commercialization for the reduction of VOCs and pathogens in indoor environments.[98]

Public health on a global scale is equipped to tackle the threats posed by airborne microbes and bioaerosols. When these aerosols mix with SARS-CoV-2 or other microorganisms, they can cause subsequent respiratory infection and lead to death. The easiest

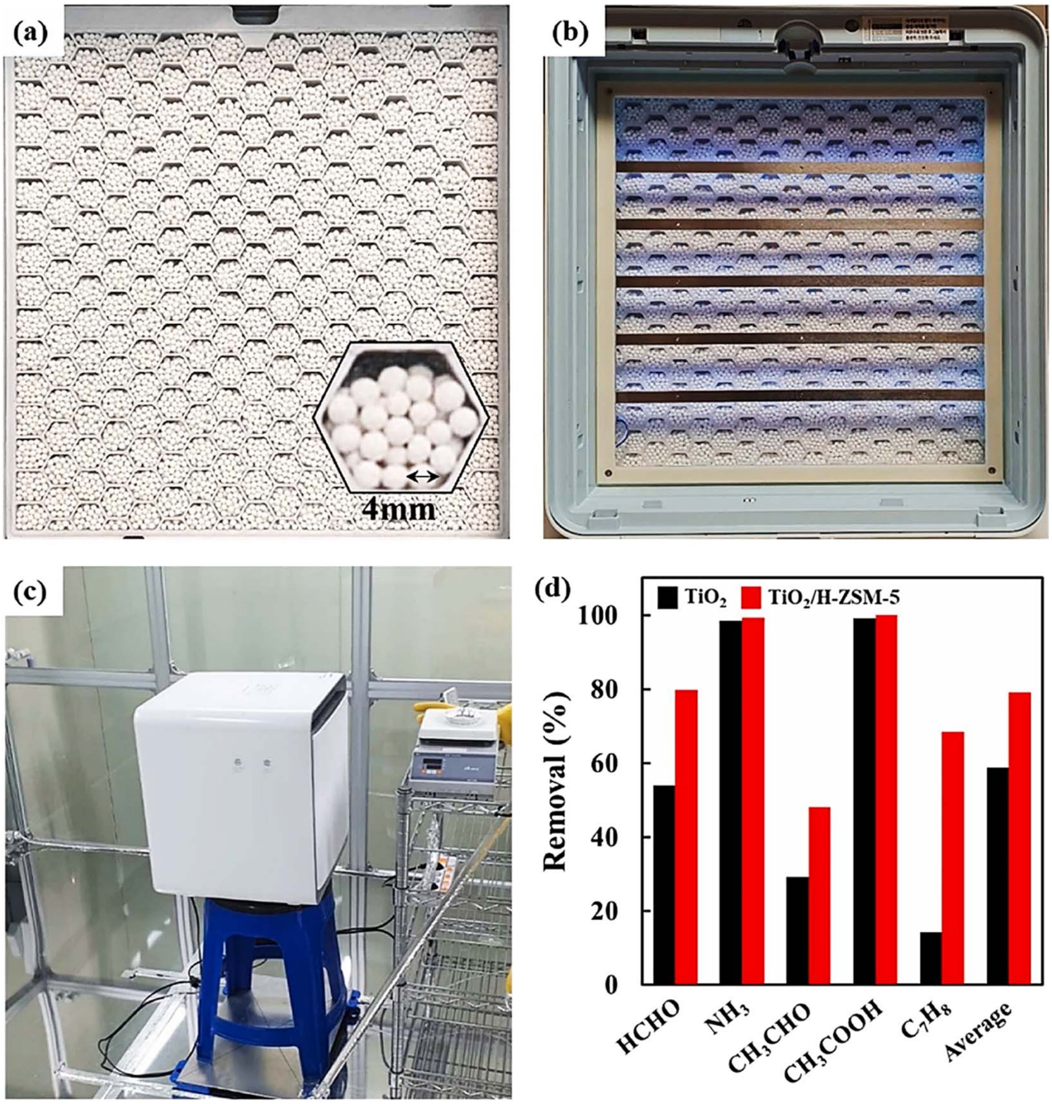

Fig. 5 Photographs of (a) a TiO_2/H-ZSM-5-based composite bead filter and (b) a composite bead filter illuminated by UVA-LED modules (AX9500 Samsung). (c) The test chamber (8 m^3) was equipped with an air purifier for the VOC removal test. (d) Bar graph illustrating the VOC removal efficiency using bare TiO_2 and TiO_2/H-ZSM-5 composite bead filter, assessed according to the air purifier standard procedure (SPS-KACA002-132) ($[VOC]_0 = 10$ ppmv in 8 m^3, 23 ± 2 °C, 45 ± 5% RH, reaction time of 30 min, TiO_2/H-ZSM-5 with 5 wt% H-ZSM-5). (Reprinted with permission from ref. 98, copyright © 2021 Elsevier Inc. All rights reserved).

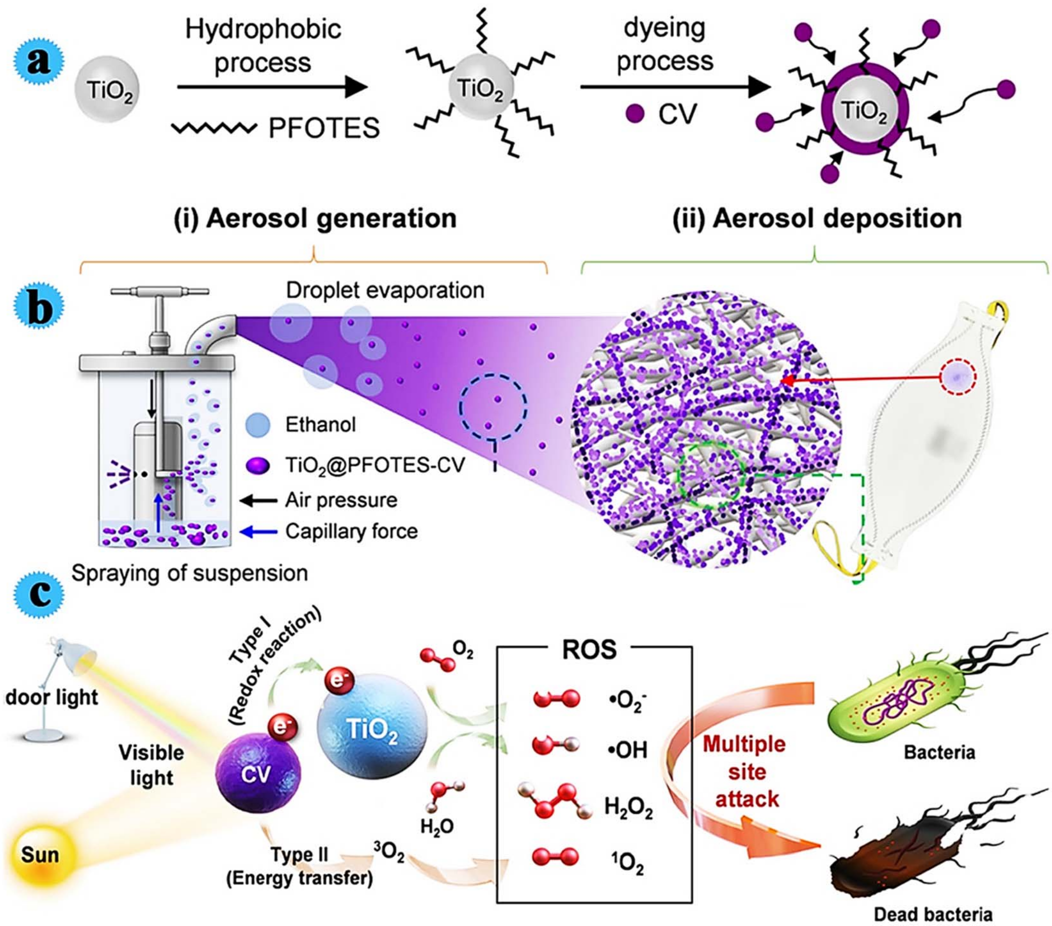

Fig. 6 (a) Schematic illustration of the synthesis of TiO_2@PFOTES-CV nanoparticles and (b) schematic diagram of the aerosol deposition process for the VLA antimicrobial air filter. (c) Schematic of the VLA inactivation mechanism based on the production of ROS and $^1O_2$. (Reprinted with permission from ref. 103, copyright © 2020 American Chemical Society).

approach to keep this under control is to use proper breathing masks and air purifiers in the indoor environment. The improper usage of masks and unhygienic indoor air quality can increase disease prevalence. In recent years, the inactivation of bioaerosols by visible-light-activated sterilization has received increased interest from the general public and scientists. In fact, the photocatalytic process can be used to kill microorganisms at any time and any place. The formation of reactive oxygen species (ROS, powerful germicidal agents) inactivates germs by causing damage to the cell membrane and DNA in this mechanism. Taking this into consideration, in 2021, Heo *et al.* developed a water-repellent, cost-efficient, and practical visible-light-activated antimicrobial nanostructure as an antimicrobial air filter to eliminate airborne microorganisms. TiO_2, the organic dye crystal violet (CV) as a visible light sensitizer, and the hydrophobic molecule 1*H*,1*H*,2*H*,2*H*-perfluorooctyltriethoxysilane (PFOTES) were used in this research for the synthesis of a 3D nanostructure. The TiO_2@PFOTES-CV fabrication process can be seen in Fig. 6a. Following that, TiO_2@PFOTES-CV was applied to the filter using a simple aerosol deposition technique. Aerosol deposition of TiO_2@PFOTES-CV nanoparticles resulted in the formation of a visible-light-activated antimicrobial filter (Fig. 6b). As shown in Fig. 6c, with photoexcited electrons traveling from CV to TiO_2, a redox process (type I) was initiated, and ROS (O_2, H_2O_2, and $^{\bullet}OH$) were formed. Furthermore, the CV molecule triggered the formation of $^1O_2$ *via* energy transfer (type II). Microorganisms were killed by active species produced by the synergistic action of TiO_2-CV. The antimicrobial air filter showed a spectacular inactivation rate (99.98%) and filtration efficiency (99.9%) against numerous bioaerosols. Furthermore, the constructed filter showed humidity resistance owing to the hydrophobic barrier provided by PFOTES, suggesting its potential usage in the real world in many conditions including humidity, exhaled air, and rain.[103] In our opinion, this filter can be used in air purifiers as they are cost-effective and environmentally friendly for killing SARS-CoV-2 and the removal of volatile organic compounds (VOCs) from the indoor environment.

Nanomaterials have also been extensively studied for their potential to clean the air. In Table 2, we have provided the most up-to-date, condensed overview of all materials that are inexpensive, simple to mass-produce (commercialization), and effective, thanks to their distinctive construction, exceptional mechanical strength, chemical stability, and exceptional capacity for killing viruses and bacteria simultaneously.

Table 2 Performance of various efficient and economical disinfectant nanomaterials to deactivate the virus and air pollutants

Main objective	Disinfectant material	Mechanism of action	Targeted virus	Key findings	Efficiency	Reference
To investigate the antiviral activity of Ag NP/polymer composites against H1N1 influenza virus	Silver nanoparticles (Ag NPs)	Nano Ag combined with virus releases Ag ions and reacts with viral proteins, inactivates them, or responds to viral nucleic acids to prevent viruses from replicating or oxidizing the virus to damage its structure. All the mechanism pathways depend on the concentration of the Ag NPs	H1N1 influenza virus	The Ag NP composite has a high level of efficacy against the H1N1 flu virus. To regulate the airborne virus particles, the anti-viral activity of the Ag NPs composites increased as the quantity of Ag NPs rose. Nano Ag binds to the outer membrane or surface protein, disrupting the virus's interaction with the cell receptor, and therefore preventing the virus from entering the cell	81%	122
To synthesize the reusable photocatalytic active filter paper from TiO_2 nanowires to disinfect viruses and bacteria	TiO_2-nanowire-based filter paper	TiO_2-based photocatalytic materials efficiently generate the ROS, which are hydroxyl radicals ($OH^•$), hydroperoxyl radicals ($H_2O^•$) hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), and superoxide radicals ($O_2^{-•}$) and ROS during UV light	Corona and Ebola viruses	Reusable and easily serializable masks can be fabricated using TiO_2 NWs, and they can provide strong protection from SARS-CoV-2 and bacteria with the highest efficiency rate. Moreover, the filter pore size can be controlled during the processing of TiO_2NWs, and they also have the potential for bulk production and use as an air purifier filter	100%	123
To determine the filtration efficiency of an anti-viral filter that is coated with SiO_2–Ag material	SiO_2–Ag	The silica particles were decorated with silver nanoparticles. This mixture interacts with the proteins of the virus, and exposes its RNA outside the membrane. Interactions like interlinking take place and lead to complete damage. The denatured proteins of the virus, which were responsible for the enzyme synthesis and damaged RNA, inactivated the bacteriophage	Bacteriophage virus	The SiO_2–Ag NP coating did not affect the pressure drop. The filtration efficiency increased with the number of SiO_2–Ag NPs for a given media velocity	99.99%	124
To determine the alumina filter's anti-viral ability and to evaluate the performance of the alumina nano-filter for the removal and retention of viral aerosols	Alumina	Because of electrostatic interactions between the electropositive fiber surface and the electronegative MS2 particles, viruses were successfully trapped in the nanofiber filter, according to the mechanism	Bacteriophage virus	The ability of this new alumina nanofiber filter to effectively remove and retain MS2 aerosol is shown	98.87%	125
			Bacteriophage MS2		92%	126

Table 2 (*Contd.*)

Main objective	Disinfectant material	Mechanism of action	Targeted virus	Key findings	Efficiency	Reference
To determine the aerosolized, charged, and injected efficiency to capture the virus and the filtration power of CNTs to purify the air of air-transmitted virus	Carbon nanotubes (CNTs)	The corona charger highly charges the carbon nanotubes (CNTs) *via* a voltage of −8 kV. The chemical adsorption mechanism is associated with electronic sharing or electronic exchange of covalent forces at the surface between nanomaterials and viruses to denature its structure and prevent replication		Carbon nanotube (CNT) filters made at atmospheric pressure and room temperature utilizing an electro-aerodynamic coating of aerosolized CNTs showed higher filtering effectiveness for aerosolized bacteriophage MS2 than medium air filters with a minimal pressure drop. The efficiency of carbon nanotubes (CNTs) in capturing the virus particles is 92%		
To investigate the antiviral activity of nanosized CuI particles against pandemic (H1N1) 2009 influenza virus	Copper iodide	CuI, when reacting with viral aerosol, damaged the viral functional proteins, such as hemagglutinin and neuraminidase. These denatured proteins are not able to replicate and transmit the virus, resulting in the killing of the virus	H1N1 influenza virus	Cu^{+} probably produces both ·OH and $O_2^{\cdot-}$, resulting in the degradation fragmentation of viral proteins. CuI appears to inactivate influenza viruses by degrading the functional proteins and potent oxidation activity	50%	127
To determine the effectiveness of a Ni- containing filter to remove SARS-COV-2 particles from the air, and to prevent the airborne transmission of coronavirus	Ni foam	A Ni-foam-containing filter in an air conditioner is heated to a high temperature of up to 250 °C in the cycling air, which can efficiently kill the coronavirus in a short time	SARS-CoV-2	Commercial Ni foam has been shown to effectively remove 99.8% of SARS-CoV-2 from circulating air in indoor environments, such as aircraft, airports, hospitals, schools, and churches. As a result, the Ni foam filter is immensely effective for limiting the growth of COVID-19 and blocking the transfer of highly infectious pathogens, such as anthrax spores and coronavirus, through the air	99.8%	128
To demonstrate a simple, cost-effective, and robust strategy for anti-influenza filter development by introducing the natural anti-viral compound TA onto the surface of polypropylene (PP) HEPA filter fabric, combining the material-independent coating and virus-capturing properties of tannic acid	Tannic acid	Hemagglutinin (HA), the most common protein on the surface of influenza viruses, binds to tannic acid molecules. The molecular weight of the HA–TA interaction increased, as did its strength. The TA–HF material may facilitate the adsorption of IAV onto the filter surface through TA–HA interaction, according to this study. Hydrogen bonding, metal chelation, and electrostatic interaction are all present in the interaction. The contact caused the influenza virus's RNA to be destroyed and the protein	Influenza virus	It has been concluded that based on the strong relationship between TA and IAV, the simple and environmentally friendly method of TA–HF preparation provides unique efficiency for IAV capture	87%	129

Table 2 (*Contd.*)

Main objective	Disinfectant material	Mechanism of action	Targeted virus	Key findings	Efficiency	Reference
		to be denatured, resulting in the virus's death				
To evaluate the antibacterial and anti-viral properties of Chinese medicine ingredients in the purification of air of airborne virus	Chlorogenic acid, ZnO and TiO_2	Still not investigated	Influenza A virus strain PR8	The testing results show that *Staphylococcus aureus*, *Colibacillus*, and *Candida albicans* all show 100% anti-bacteria rates, while influenza also has a 100% anti-viral rate with the nanomaterial	100%	130
To study the development of face mask media that integrate high PM and bioaerosols filtration efficiency and excellent antibacterial properties	Ag/Zn@cotton fabric with PVFD/PS	Due to external moisture and Ag^+/Zn^+ release, the construction of a microcurrent owing to the high-throughput electric simulation generation inside the composite fabric leads to killing the bacteria	*Escherichia coli* and *Staphylococcus aureus*	In conclusion, the filter showed high performance because of the small pore size, high porosity, and low basis weight of PVDF/PS nanofiber. The Ag/Zn@cotton layer provides strong structural stability as well as a higher removal rate of bacteria and excellent filtration of PMs	*Escherichia coli* (99.64%), *Staphylococcus aureus* (98.75%), $PM_{0.3}$ (99.1%)	131
The goal of this work was to explore the photocatalytic efficacy of the Cu/TiO_2 under UVA light to inactivate the deadly HuNoV	Cu/TiO_2 non-woven fabric (NWF)	ROSs and h^+ generated by photocatalysts, as well as the toxicity of metal ions released by metal-containing photocatalysts, induce morphological damage to viruses	HuNoV genogroup II genotype 4 (HuNoV GII.4)	The author suggested that viral particles of HuNoVs can be successfully destroyed using Cu/TiO_2 NWF due to irradiation with UVA-LED light and generation of $OH^•$ radicals, which leads to breakdown of the virus's viral protein or distortion of the viral shape	Higher than 90%	132

3.3.2. Selective metal–organic framework materials for air purifier filters. Metal–organic frameworks (MOFs), a novel class of porous crystalline materials, have attracted considerable interest in the fields of gas storage, separation, and catalysis.[104] In recent years, several research teams, including our research group, have looked at the potential of metal–organic frameworks (MOFs) as adsorbents and catalysts for regulating air pollution.[44,105–109] MOFs-based materials possess a large surface area and high porosity along with well-distributed active centers. MOF materials have tunable functionalities, which make them not only suitable for air filtration but also promising for heterogonous catalysts for the oxidation of air pollutants. Incredibly, MOFs provide molecular-level tuning of the photocatalytic efficiency by rationally altering the metal clusters or organic linkers.[110–112] MOF-based air filters can be used for different purposes, such as in air purifiers, the production of masks, and ventilators, among others. MOF air filters have strong PM filtration capability and can generate reactive oxygen species (ROS) such as hydroxyl radicals ($^{\bullet}OH$), superoxide ($^{\bullet}O_2^-$), singlet oxygen ($^1O_2$), and hydrogen peroxide (H_2O_2). These ROS are potent oxidants for destroying dangerous and deadly microorganisms. Fig. 7 depicts a MOF-based filter and the applications of such filters for air cleaning. Furthermore, some metal-based MOF materials have strong antimicrobial properties. In recent years, since the SARS-CoV-2 outbreak, various new studies have been published regarding the inactivation of microorganisms for air sterilization using economical and efficient MOFs.[44,90]

Among the reported MOFs, copper-based CPP (Cu-CPP), which is produced from Cu ions and benzene-1,3,5-tricarboxylic acid, is one of the most famous and extensively investigated MOFs due to its high surface area, large pore volume, and Cu^{2+} charge, which may promote VOC adsorption and kill microbes.[90] Unfortunately, the widespread availability of CPP-based air filters is hampered by the fact that CPPs are often found in powder form. Water resistance is another essential characteristic for the practical use of Cu-CPP. To overcome this issue, the authors have chosen Al_2O_3 as a support to grow Cu-CPP in order to increase the water resistibility of Cu-CPP/Al_2O_3 due to the hygroscopic nature of porous alumina. Likewise, Van *et al.*[44] prepared an eco-friendly and low-cost Cu-CPP material *via* the *in situ* growth of copper coordination polymer particles on Al_2O_3 beads (Cu-CPP/Al_2O_3). Fig. 8a schematically illustrates the synthesis of the Cu-CPP/Al_2O_3 beads in two steps; firstly, Cu-CPP was impregnated into Al_2O_3 beads by treating them with a solution rich in organic ligands and Cu species. Secondly, the impregnated Al_2O_3 was hydrothermally grown with Cu-CPP to generate composite Cu-CPP/Al_2O_3 beads. After the reaction, the color of the Al_2O_3 beads changed from white to blue, indicating that Cu-CPPs had been successfully integrated. After that, Cu-CPP/Al_2O_3 fabricated beads were decorated in a filter installed in an air purifier and then tested for the removal of VOCs and killing of pathogens. The filter is demonstrated in Fig. 8b. The Cu-CPP/Al_2O_3 bead air filter showed excellent performance for the removal of the VOCs formaldehyde (99.5%), toluene (99.5%), acetic acid (100%), and ammonia (100%). Similarly, *E. coli* bacteria was found to be inactivated after 120 minutes of exposure with Cu-CPP/Al_2O_3 beads. The filter had a 97.02% killing ability for bacteria due to the Cu^{2+} ions from the Cu-CPP framework, which can

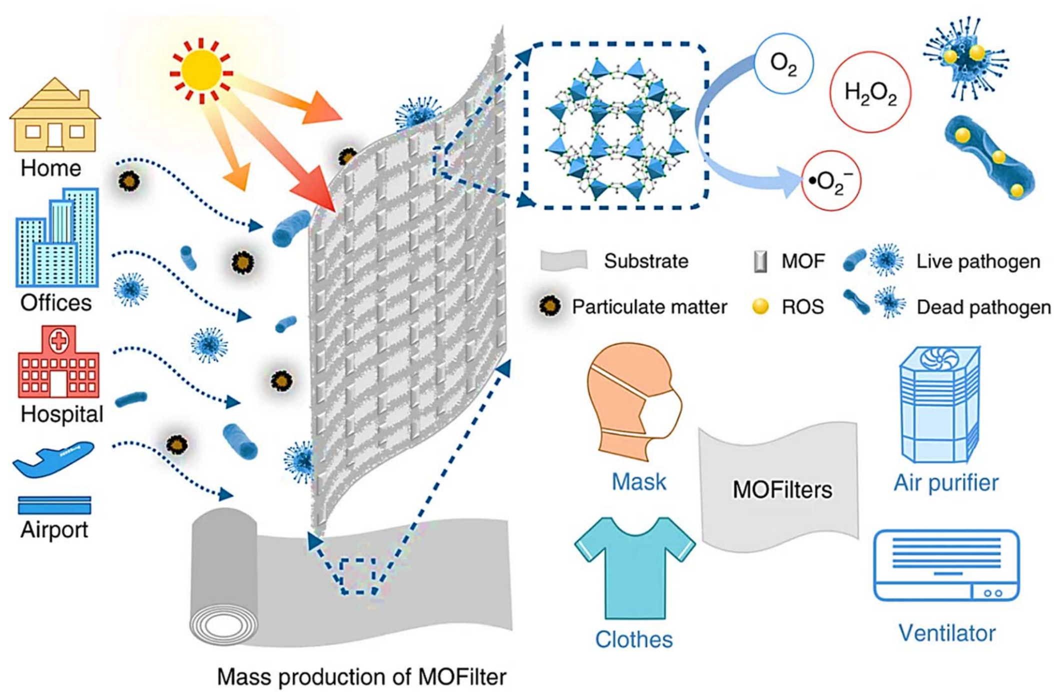

Fig. 7 Schematic of a metal–organic framework (MOF)-based filter and schematic illustration of the MOF-based filter (MO filter) for integrated air cleaning. (Reprinted with permission from ref. 90, copyright © 2019, Li *et al.*).

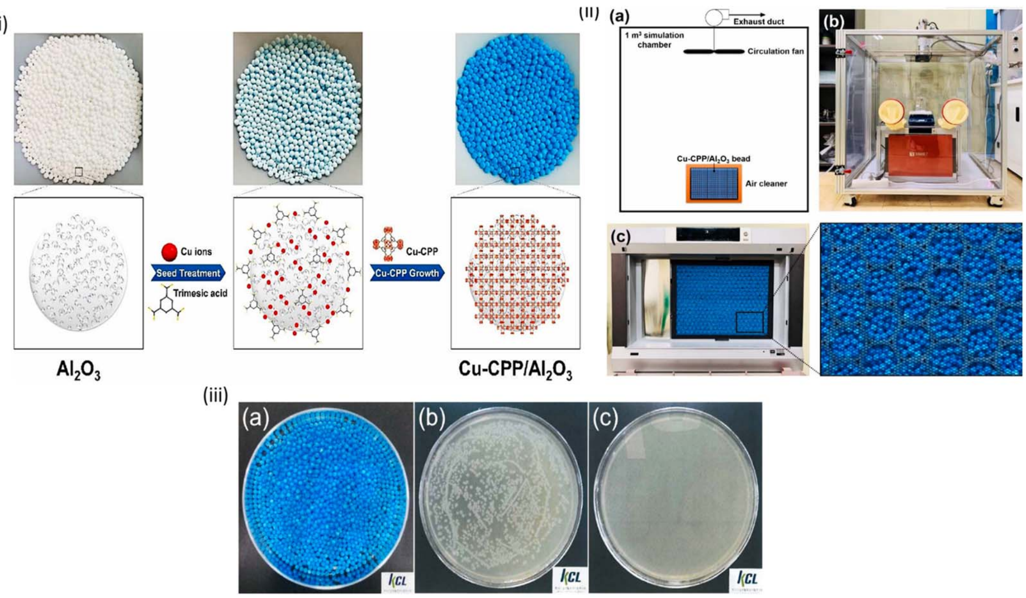

Fig. 8 (i) Schematic illustration of the fabrication of Cu-CPP/Al_2O_3 bead air filter and (ii) (a) schematic and (b) digital camera image of the 1 m^3 simulation chamber for the air cleaner performance tests. (c) Inside view of an air cleaner (Air Cure 7, Bentech) equipped with a Cu-CPP/Al_2O_3 bead filter with a size of 364 (*w*) × 282 (*h*) × 10 (*t*) mm^3. (iii) (a) Camera image of Cu-CPP-Al_2O_3 bead sample; digital images of cultivated *E. coli* colonies on agar culture plates of (b) blank and (c) Cu-CPP/Al_2O_3 beads after 24 h following the Korea Conformity Laboratories standard method (KCL-FIR-1002:2021). (Reprinted with permission from ref. 44, copyright © 2022 Elsevier Ltd. All rights reserved).

accumulate within bacterial cells and damage the cell membranes of the bacteria energetically. The agar culture plates are displayed in Fig. 8c. This air filter can be used for commercial air purifiers in the real world because of its low cost and multifunctional properties that can help in combating various pathogens and air pollutants.

For passive pollution management, air filtration is becoming a must. Most commercial air purifiers depend on thick fibrous filters, which are effective at removing particulate matter (PMs) but have low biocidal performance. These filters cannot kill microorganisms effectively. Therefore, a contemporary investigation was carried out by Li *et al.*[90] This study provides direction for the selection of efficient air filters. Herein, the authors compared the top five typical prominent, water-stable, and photocatalytic metal–organic frameworks (MOFs), which were listed as ZIF-8, ZIF-11, NH_2-UIO-66(Zr), MIL-100(Fe), and NH_2-MIL125(Ti). ZIF-8 (zinc-imidazolate MOF) was chosen from among the five MOFs because of the superiority of its

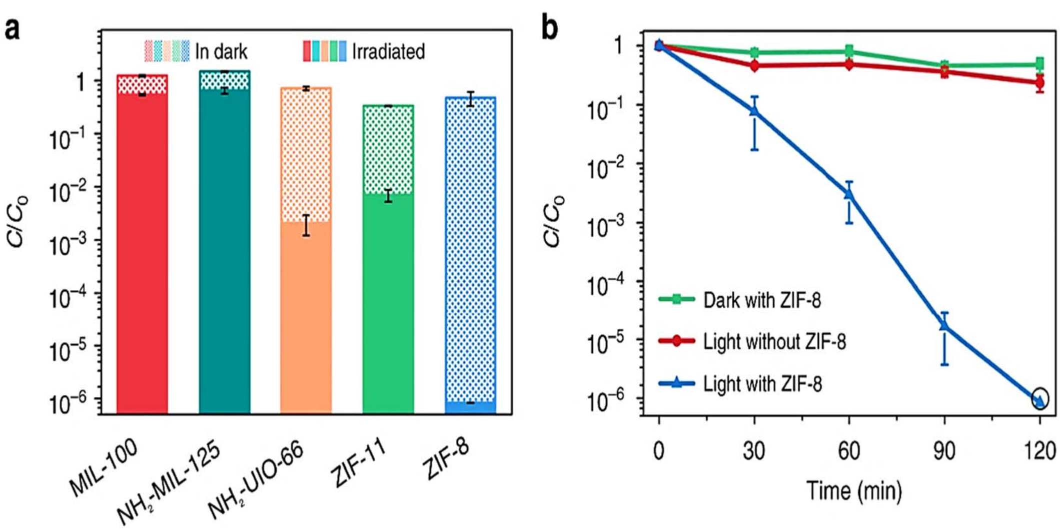

Fig. 9 Photocatalytic disinfection performance of ZIF-8 (zinc-imidazolate MOF). (a) Disinfection performance comparison among five metal–organic frameworks (MOFs). (b) Inactivation kinetics of *E. coli* in the presence of ZIF-8. (Reprinted with permission from ref. 90, copyright © 2019, Li *et al.*).

Table 3 Evaluation of the performance of different metal–organic framework (MOF)-based materials for air cleaning

Main objective	MOF material	Mechanism of action	Targeted air pollutants	Remarks	Efficiency	Reference
To fabricate a hybrid air filter using Cu-based CPPs on a melamine sponge as a filter substrate for capturing and disinfecting the bacteria	Copper-based coordination polymer particle incorporated on melamine sponge, Cu-CPP/MS	The porous nature of the melamine sponge as well as the incorporation of Cu-CPP microcrystals enhanced the electrostatic attraction between the negatively charged bacterial cell and positively charge imbalanced copper ion within Cu-CPP. Cu^{2+} ions are released and damage the bacterial membrane	*E. coli*	Our research group suggested an economical method for the preparation of air filters for capture and disinfection of airborne pathogens including SARS-CoV-2 using a Cu-CPP/MS-based air filter. It can be used as a replacement for conventional high-efficiency particulate air (HEPA) filters in air purifiers	Capture rate: (99.66%) Disinfection rate: (99.54%)	108
To accomplish this goal, an ammonia-derived UiO-66-NH_2 decorated with poly{2-(dimethyl decyl ammonium) ethyl methacrylate} (UiO-PQDMAEMA)-based nanofiber filter was prepared for killing bacteria and removing particulate matter (PM) from air	UiO-PQDMAEMA	The robust electrostatic interaction between the bacteria's anionic cell wall and the positively charged nitrogen (N^+) of UiO-PQDMAEMA is the primary cause of severe cell membrane disruption by a contact-killing mechanism which leads to bacteria death	*S. epidermidis* (Gram-positive) and *E. coli* (Gram negative)	This research opens up a new path for addressing air pollution control by utilizing quaternary ammonium compound (QAC)-modified MOF-based active filters for killing pathogens and filtration of fine particles simultaneously	Pathogens 100% PM filtration >95%	45
The nano-sized polypropylene@zeolitic imidazolate framework (PP@ZIF-8) membrane and proplyene@copper(II)benzene-1,3,5-tricarboxylate (PP@Cu-BTC) membrane were designed by *in situ* growth for removal of particulate matter (PMs)	PP@ZIF-8 PP@Cu-BTC	MOF nanocrystals of <100 nm can make defects to polarize the surface, and the polarized surface can freely interact with MOFs. In this procedure, the unbalanced metal ion gives a positive charge, which can increase the PM capture ability	$PM_{2.5}$ $PM_{1.0}$	This latest finding has interesting results for the filtration of particulate matter (PMs). Moreover, these fabricated filters showed excellent water resistance, recycling ability, and strong mechanical strength. Surprisingly, this study opens a new path for researchers to fabricate a double-layer air filter containing PP@ZIF-8 and PP@CuBTC, which can give not only PM filtration but also provide high anti-pathogen efficiency and VOC removal due to Cu^{2+} ion reservoirs in CuBTC	PP@ZIF-8 (98.35%) PP@CuBTC (99.5%)	46
Green synthesis of cellulose copper-based metal–organic framework (HUKST-1CF) by *in situ* growth to investigate the antibacterial activity	(HUKST-1/CF)	Due to the Cu^{2+} ions in HKUST-1, which could destroy the cell membrane of bacteria when microorganisms touched the surface of the HKUS-1/CF membrane, the Cu^{2+} ions penetrated the bacteria cell wall and death happened	*E. coli* and *Staphylococcus aureus*	The novel HKUST-1/CF composite exhibited remarkable antibacterial activity. This MOF-based cellulose could be favorable for air filter manufacturing	100%	133

Table 3 (*Contd.*)

Main objective	MOF material	Mechanism of action	Targeted air pollutants	Remarks	Efficiency	Reference
To investigate their antibacterial activity, photocatalytic Zr-based MOFs were prepared by using 4,8-diaminonaphthalene-2,6-dicarboxylic acid (NDC-$2NH_2$) as an organic linker and deposited on graphite paper	Zr-NDC-$2NH_2$	The anodic bias significantly reduced recombination of photo-generated electron–hole pairs, upgrading ROS production	*Staphylococcus aureus*	In this work, bacteria were completely inactivated in 60 min with a 99.4% efficiency rate. The addition of the $-NH_2$ group to the linker enhanced the light adsorption capacity	99.4%	134
To evaluate anti-pathogen and VOC removal in one shot using a copper-based MOF coating grown by an *in situ* method on Al_2O_3 beads for cleaning indoor air	Cu-CPP/Al_2O_3	Release of Cu^{2+} ions from the Cu-CPP framework. They can accumulate in the bacteria cell membrane and cause damage, and the leakage of intercellular substances happens to cause the death of the pathogen	*E. coli* and VOCs	Our research group successfully fabricated Cu-CPP/Al_2O_3 beads for a commercial air purifier filter. These beads can give greater efficiency for trapping of all VOC molecules in MOF cages and have a strong ability to kill pathogens	*E. coli* (97.02%) Formaldehyde (99.5%) Toluene (99.5) Acidic acid (100%) Ammonia (100%)	44
To develop a facile method for the synthesis of photocatalytic Ti/MOF/C material for killing pathogens	MIL-25	(i) ROS production (ii) Carbon and MIL-25 interaction modified the separation transmission of photo-generated charges to induce the generation of a greater quantity of ROS in response to light	*E. coli*	This study revealed a novel photocatalytic sterilizing procedure for disinfecting pathogens from all phases, water or air. Adding carbon to MIL-25, this strategy has the potential to speed up and improve the efficiency of the catalytic process because C can response to TiO_2 and reduce the reorganization rate of photogenerated electrons and holes, which leads to a superior photocatalytic-based MOF	98.7%	135

performance. ZIF-8 was synthesized using a $Zn(NO_3)_2 \cdot 4H_2O$ precursor with the H-MeIM ligand. The detailed synthesis process is reported in the literature.[113] The obtained ZIF-8 nanocrystals exhibit excellent characteristics with typical rhombic dodecahedron morphology and a large BET surface area of 1538 $m^2 g^{-1}$. The particle size of ZIF-8 ranged from 80 to 110 nanometers with an average diameter of 92 nm. The MO (metal–organic) air filter and MO filter mask were fabricated using the nanocrystals of ZIF-8. A disinfection experiment was carried out using five MOFs in 0.9% (w/v) saline with an initial *E. coli* cell density of 109 CFU mL^{-1} and catalyst dose of 500 mg L^{-1}. A 300 W Xe lamp connected to an AM 1.5 filter (300 nm < λ < 1100 nm) was used as a source of light with the optical powder density fixed at 100 mW cm^{-2}. The results of the experiment can be seen in Fig. 9. ZIF-8 nearly inactivated the bacteria completely and the efficiency was found to be >99.9999%, which is equivalent to $6.1 - \log_{10}(C/C_O)$ after 120 min of light illumination. In terms of photoinduced antibacterial activity, the performance of ZIF-8 was higher than those of the other four MOFs. A phenomenological study indicated that a photoelectron was trapped at the Zn^+ center within ZIF-8 *via* ligand-to-metal charge transfer. The ligand–metal charge transfer (LMCT) is responsible for oxygen-reduction-related reactive oxygen species (ROS) generation, which is the major disinfection mechanism. Furthermore, the ZIF-8 based air filter can give a higher removal rate of particulate matter (PMs) (>97%). This research has the potential to aid the effort to destroy the SARS-CoV-2 virus and in the development of air filters for air purifiers for large-scale production due to the strong photocatalytic antibacterial capacity, economical feasibility, and environmental friendliness of the product for public health protection. Table 3 summarizes all the low-cost and easily bulk-produced MOFs porous materials from published research articles, which can be used in air purifier filters in the shape of beads or fiber in the real world for the cleaning of indoor air.

4. Challenges and alternative approaches

Many air purifiers face the main challenge of air dispersion techniques. The majority of air purifiers absorb polluted air by directing it downward, filtering it, and then reintroducing it into the environment. Because the purified air must be discharged from the purifier at a greater distance than its intake, the wind speed at the outlet is greater than that at the intake. As a result of the relatively strong airflow at the exit, the pressure differential causes the air to ascend and disperse into the environment at a point farther away or higher in elevation than the intake.[114]

Another issue is that existing air filters, despite numerous improvements, still experience issues with air impermeability. Additional methods should be considered, as well as attention to the pressure drop of the filter and the issue of the detachment of material particles that can harm human health. Furthermore, current academic research is primarily focused on material discovery engineering and the commercialization of materials for air cleaning, but the most pressing practical challenges are photocatalyst fouling and preventing catalyst deactivation, as well as MOF water stability, and these concerns should be addressed. Making an air filter with visible-light-responsive materials is the ideal scenario for photocatalytic indoor air purification. Researchers should focus more on the development of new photocatalytic covalent and metal–organic frameworks in the future because of their biocompatibility, porous structure, and high surface-to-volume ratio, which can be more suitable for the production of effective air filters capable of instantly capturing and destroying air pollutants. As a result, there is no doubt that heterogeneous photocatalysis and MOF-based material filters with viral disinfection technology will be a tremendously active research topic in the near future, providing global comfort and trust to people.[90,109,115]

5. Conclusions

The purpose of this study is to give both an overview and a deeper understanding of the primary modes of SARS-CoV-2 transmission, as well as the usage of air purifiers as a preventative tool against the virus. Air pollution spreads faster and becomes more difficult to control. As a result, air pollution control and prevention present several challenges in both developed and developing countries since the SARS-CoV-2 pandemic outbreak. SARS-CoV-2 is the third human coronavirus infection to be identified as highly pathogenic. When the virus enters the host body *via* fusion of the envelope and cellular membrane, it controls the host machinery, makes more identical copies, and transmits. SARS-CoV-2 spreads in three ways: directly, indirectly, and by aerosols. Direct modes include sneezing, coughing, and speech; indirect modes include infected items and infected surfaces; aerosols include airborne transmission. Many studies have shown a direct and positive link between SARS-CoV-2 transmission and $PM_{2.5}$ in the air. $PM_{2.5}$ acts as a carrier to transmit the viral aerosols over longer distances and causes severe respiratory infections in people. In addition, this integration increases the residence time of the virus in the air, making this pandemic more deleterious and resulting in a higher mortality rate. After reviewing numerous articles, we concluded that $PM_{2.5}$, a consequence of human activity, has a direct influence on the concentration of SARS-CoV-2 viral RNA in the indoor environment, resulting in the deaths of several people.

It is most important to continue to promote the precautionary measures to combat this virus by vaccinations and installing air purifiers in indoor environments, especially in public places. Additionally, air filters are able to filter out viruses and other air contaminants. According to the available published data to date, it is apparent that the risk of an epidemic is significant in confined spaces with insufficient ventilation and without air purifiers in the breathing space. A variety of materials have been developed for air purification, but due to their high cost and lower efficiency rate, they have raised a big question for public health. In this review, we have summarized in detail all the efficient and economical antimicrobial nanomaterials, such as Ag, TiO_2-CV-PFOTES, and carbon nanotubes, and MOFs, such as copper, zirconium, and titanium-based MOFs, for fabricating highly effective air filters. These materials-based air filters for air purifiers can be installed to improve indoor air quality, but the primary issue is integration with $PM_{2.5}$. In these circumstances, it is critical to reduce $PM_{2.5}$ levels in the air, which can protect us from severe viral infections while also improving air quality.

Author contributions

Mahshab Sheraz (lead author): conceptualization, writing original draft, preparation, review and editing. Kaleem Anwar Mir: conceptualization, review and editing. Ali Anus: review and editing. Van Cam Thi Le: review and editing. Van Quyet Nguyen: review and editing. Seungdo Kim: funding acquisition, supervision. Woo Ram Lee: funding acquisition, supervision. All authors approved the final version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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