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A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality

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ABSTRACT

Airborne transmission arises through the inhalation of aerosol droplets exhaled by an infected person and is now thought to be the primary transmission route of COVID-19. Thus, maintaining adequate indoor air quality levels is vital in mitigating the spread of the airborne virus. The cause-and-effect flow of various agents involved in airborne transmission of viruses has been investigated through a systematic literature review. It has been identified that the airborne virus can stay infectious in the air for hours, and pollutants such as particulate matter (PM_{10}, $PM_{2.5}$), Nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), Carbon monoxide (CO), Ozone (O_3), Carbon dioxide (CO_2), and Total Volatile Organic Compounds (TVOCs) and other air pollutants can enhance the incidence, spread and mortality rates of viral disease. Also, environmental quality parameters such as humidity and temperature have shown considerable influence in virus transmission in indoor spaces. The measures adopted in different research studies that can curb airborne transmission of viruses for an improved Indoor Air Quality (IAQ) have been collated for their effectiveness and limitations. A diverse set of building strategies, components, and operation techniques from the recent literature pertaining to the ongoing spread of COVID-19 disease has been systematically presented to understand the current state of techniques and building systems that can minimize the viral spread in built spaces This comprehensive review will help architects, builders, realtors, and other organizations improve or design a resilient building system to deal with COVID-19 or any such pandemic in the future.

1. Introduction

The global outbreak of the highly infectious novel coronavirus SARS-CoV-2 has been rapidly progressing in India and other parts of the world since 2019. COVID-19 is primarily transmitted through the respiratory system via droplets, respiratory secretions, and direct contact between infected and non-infected individuals (van Doremalen et al., 2020a). The emergence of Severe Acute Respiratory Syndrome (SARS's) outbreak in 2002–03, the global prevalence of tuberculosis (TB), the threat of a highly pathogenic influenza pandemic, and the current COVID-19 pandemic serve as timely reminders of how airborne infectious diseases continue to pose a substantial risk to human health (Sockett, 1998; van Doremalen et al., 2020a; WHO, 2003; Yu et al., 2004).

Besides its primary spread through indoor bioaerosol droplets and infected surfaces, or direct human-to-human personal contact (WHO, 2020b; CDC, 2020; Noorimotlagh et al., 2021; Wei and Li, 2016), it has been highlighted that other disparate factors have a notable effect on the number of confirmed COVID-19 cases, new cases, and total deaths. These include air pollution, indoor air quality (IAQ), weather, meteorological parameters (temperature, humidity, precipitation, etc.), individual health, biological characteristics of the virus, and certain climate conditions (Domínguez-amarillo et al., 2020; Elsaid and Ahmed, 2021; Kumar, 2020; Lolli et al., 2020; Sobral et al., 2020; Wang et al., 2021; Wei and Li, 2016; Zoran et al., 2020). Additionaly, it has been pointed out that various socio-demographic factors such as living environment and accessibility to the basic amenities have a notable impact on the spread of the SARS-CoV-2 virus (Das et al., 2021).

A study by Qian et al. (2021) identified outbreaks from case reports of about 320 municipalities in China between January 4 - February 11, 2020, where it was found that home-based outbreaks were higher (254 of 318 incidents, accounting for 79.9% of all outbreaks), followed by transport-based outbreaks (108 of 318; 34% of total outbreaks) both signifying the role of indoor transmission. An experimental study done in the isolation ward of a hospital in Milan, Italy, by Razzini et al. (2020) has indicated the presence of virus in the indoor air samples from intensive care units, corridors, etc. A quantitative study by Rowe et al.

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Nomenclature

ACH	Air Changes per Hour
AHU	Air Handling Unit
AIIR	Airborne Infection Isolation Rooms
AOD	Aerosol Optical Depth
AQI	Air Quality Index
ASHRAE	American Society of Heating, Refrigeration, and Air conditioning Engineers
CADR	Clean Air Delivery Rate
CDC	Centre of Disease Control and Prevention
CO	Carbon monoxide
CO_2	Carbon dioxide
DCV	Demand Control Ventilation
DOAS	Dedicated Outdoor Air System
DT	Doubling Time
EEPF	Electrostatic Enhanced Pleated Filter
ESP	Electrostatic Precipitators
HEPA	High-Efficiency Particulate Air filters
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
MERV	Minimum Efficiency Reporting Value
NO_2	Nitrogen dioxide
O_3	Ozone
OR	Operating Rooms
PE	Protective Environments
PM	Particulate Matter
PPM	Parts Per Million
PV	Personalized Ventilation
REHVA	Federation of European Heating, Ventilation, and Air conditioning Associations
SARS	Severe Acute Respiratory Syndrome
SO_2	SN Sulphur dioxide Seeding Number
ST	Seeding Time
TB	Tuberculosis
TVOC	Total Volatile Organic Compounds
UVGI	Ultraviolet Germicidal Irradiation
VOC	Volatile Organic Compound
WHO	World Health Organization

(2021) assessed the outdoor versus indoor spread of SARS-CoV-2 and reported that the chances of being infected outdoors are substantially lower than that of being infected indoors. It was highlighted that only densely populated inversions with low wind velocity, a relatively steady atmosphere, and susceptibility to air pollution could generate an outside transmission similar to that of indoors. In the above-mentioned context, the outside air brought in from outside may already be "polluted" and strongly promote the indoor airborne spread of the virus (Rowe et al., 2021).

Experimental work by Taylor et al. (2020) confirmed that aerosolized SARS-CoV-2 virus stays infectious in the air for hours. Hence, SARS-CoV- virus spread through aerosol and fomite is possible since the virus can remain infectious in the form of aerosols for hours and on surfaces for days. It has been recognized by WHO (WHO, 2020a) that droplet particles with an aerodynamic diameter of <5 μm expelled from coughing or sneezing of the carrier may carry the virus and cause COVID-19 disease. The transmission routes of the SARS-CoV-2 have been shown in Fig. 1.

Multiple studies have identified the importance of IAQ for reducing the spread of the SARS-CoV-2 virus (Adams et al., 2015;

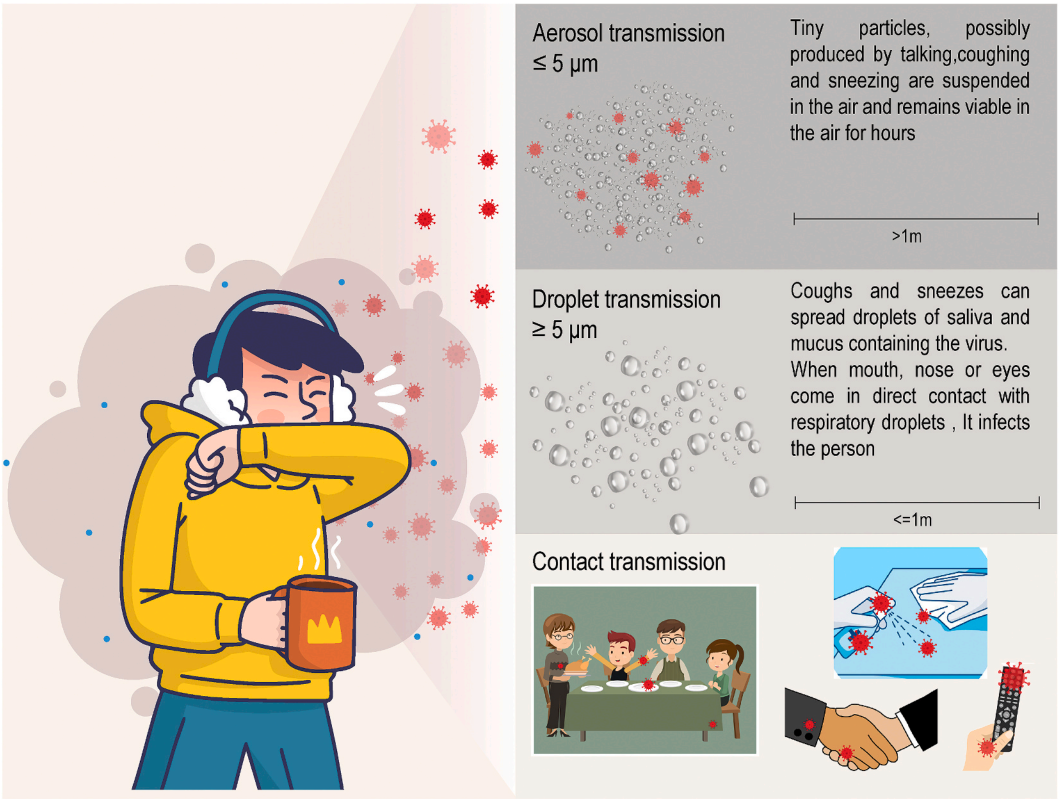


Fig. 1. Transmission routes of the SARS-CoV-2 virus.

Domínguez-amarillo et al., 2020; Qian and Zheng, 2018; Zoran et al., 2020). Anthropogenic activities that contribute to air quality degradation include agricultural activities, the use of fossil fuels in automobiles, power stations, a variety of industrial operations, and various other activities. These activities produce specific emissions such as PM_{10}, $PM_{2.5}$, NO_2, O_3, CO, and SO_2, which can become hazardous if it exceeds allowable levels and hastens the transmission of the infectious agents (Agarwal et al., 2021; Zoran et al., 2020). Furthermore, these contaminants, which have a negative impact on people's health, are being generated in indoor spaces via different anthropogenic activities like cooking, cleaning, usage of paints and electronic gadgets, etc. (Chang et al., 2021). The microbiota presence in indoor environments is also being discussed as a contributor to the degradation of IAQ (Adams et al., 2015).

With the ongoing pandemic and intermittent lockdowns imposed on most of the countries, it was noticed that the outside air quality improved due to a reduction in anthropological activities (reduced levels of PM, O_3, NO_2, CO, SO_2) (Albayati et al., 2021; Chauhan and Singh, 2020; Faridi et al., 2021). However, it was also observed that the individual's exposure to indoor pollution became typically more severe and extended during the lockdown period (Anthes, 2020). It was indicated by Domínguez-amarillo et al. (2020) that indoor pollution levels ($PM_{2.5}$, TVOC) in the indoor premises were comparably higher than the permissible healthy limits during the COVID-19 crisis, owing to concerns about household energy conservation, absence of adequate ventilation, and more frequent application of cleaning agents and disinfectants. Additionally, attempts to make dwellings airtight (for HVAC operations) to reduce energy consumption have resulted in buildings with lower outdoor ventilation rates, causing indoor contaminants to build up to dangerous levels that would typically be unacceptable outdoors (Milner et al., 2014).

Multiple studies across various regions also have reported a positive relationship between indoor air pollutants (particulate matter (PM_{10}, $PM_{2.5}$), NO_2, SO_2, CO, O_3, CO_2, and TVOCs) and incidence, spread, and mortality rates of COVID -19 disease (Cooper et al., 2021; Domínguez-amarillo et al., 2020; Wang and Li, 2021; Zhang et al., 2021; Zhu et al., 2020; Zoran et al., 2020). These pollutants should be dynamically tracked and must be kept within the minimum permitted limits to effectively manage and curb the rapid transmission of COVID-19 disease. Furthermore, several environmental factors, for instance, temperature, humidity, weather, climate, and ventilation, have a synergistic effect on the transmission trend of the COVID-19 in indoor places such as healthcare settings, restaurants, recreation facilities, residences, and other public places (Ganegoda et al., 2021; Mattiuzzi et al., 2021).

Multiple studies have demonstrated that adopting holistic and sustainable mitigation efforts can efficiently curb the rapid transmission of the SARS-CoV-2 virus. Different measures include control of air pollution, maintaining IAQ through air purification, air filtration, ventilation improvement, monitoring of environmental parameters, etc. Effective management and monitoring of these factors and parameters through integrated means of engineering and administrative approach, synchronously with appropriate human conduct in response to the evolving conditions, is critical for mitigating the indoor transmission of the viruses.

The ongoing pandemic is an evolving interdisciplinary problem where multiple branches of science and technology are acting upon. The built environment and the branch of building science can also play a vital role in managing the ongoing pandemic. This review article tries to shed light on the knowledge gap on the virus/infectious disease transmission risks in indoor built spaces and to provide fundamental insight into the significance of IEQ for viral load mitigation. Although IAQ has been widely discussed in the literature in terms of the overall health of an individual, but the influence of IAQ on viral transmissions risk, especially on COVID-19 related information, is limited. Complimentary effects of various meteorological parameters along with its role in IEQ and viral transmission risks are not widely discussed in the literature as per authors knowledge. A better understanding of the cause-and-effect flow of various agents/parameters involved in virus transmission is required to enable possible sustainable solutions. This study explores a diverse set of building strategies, associated components, and operation techniques from the recent literature pertaining to the ongoing spread of COVID-19 disease and is systematically presented to understand the current state of building systems that can reduce the transmission of the virus/infectious agents in the built environment. The topics discussed in this review range from the transmission routes of the viruses, the cause, and effects of multiple variables, and an in-depth review of strategies at the micro and macro level to curb the virus transmission. The results from the study will help various sectors to handle the ongoing COVID-19 pandemic in a better way and devise better mitigative strategies to deal with any future airborne infectious diseases.

2. Significance of indoor environmental quality in viral load mitigation

Several super-spreader events or cluster events at a particular location with high contamination rates have been characterized primarily as indoor events, such as incidents inside hospitals, restaurants, and other public places (Azimi et al., 2021; Lu, 2021; Razzini et al., 2020; Yang et al., 2020). According to recent research, in these events, the airborne transmission may be the most significant transmission mode of the SARS-CoV-2 virus (Y. Li et al., 2020; Morawska and Milton, 2020; Shen et al., 2020; Wilson et al., 2020). This prima-facie makes the SARS-CoV-2 virus transmission in buildings a critical issue to look upon if efficient recovery management of the COVID-19 pandemic is concerned. The emitted viral load is expressed as quanta emission rate (ERq, quanta h-1) (a quantum is described as the dosage of airborne droplet nuclei needed to infect 63% of susceptible individuals) (Buonanno et al., 2020; Miller et al., 2021). Buonanno et al. (2020) highlighted that an asymptomatic infectious SARS-CoV-2 individual vocalizing during light activities (i.e., slow strolling) could achieve high quanta emission rates ($>$100 quanta h^{-1}), whereas a symptomatic SARS-CoV-2 individual in a resting scenario had a lower quanta emission rate ($<$1 quantum h^{-1}). High emission levels were observed for an asymptomatic COVID-19 infected person in both the light exercise (when talking) and heavy exercise conditions when breathing through the mouth (Buonanno et al., 2020). It was also inferred by various researchers that a major percentage of SARS-CoV-2 virus transmission is due to airborne transmission of aerosols created by asymptomatic persons when breathing and speaking, especially in indoor spaces (Chen et al., 2021; IEES, 2006; Prather et al., 2020; Wang et al., 2020). Becchetti et al. (2021), in their review on quality of air and COVID-19 adverse effects, affirmed that the association between air pollution and COVID-19 pandemic outcome is solid and robust. This context makes it imperative to reduce the airborne transmission of the virus in order to bring a halt to the uncontrollable spread of the COVID-19 disease and other indoor airborne infectious diseases. To assess the virus's transmission under varied climatic and indoor environment settings, Raj et al. (2020) used an existing hypothesis of respiratory droplet drying to study COVID-19 spread and mortality. The study inferred that viruses contained in respiratory droplets become activated in some indoor circumstances due to a reduction in size in sessile and airborne droplet nuclei, resulting in an increased spread rate of the SARS-CoV-2 virus (Raj et al., 2020). Additionally, multiple international agencies such as WHO, CDC, and ASHRAE have all raised their concerns about the airborne viral transmission and highlighted on the need to maintain the IEQ to prevent the spread of diseases (ASHRAE, 2020a, CDC, 2021; WHO, 2021a).

Thus, after reviewing the articles mentioned above, it has been found that there is a need to identify the significance of various IEQ parameters and their role in indoor airborne virus transmission. Necessary measures have to be identified and accessed to tackle all these indoor environmental challenges to prevent the rising threats of the ongoing pandemic and other future pandemics. The role of different indoor air pollutants and other environmental variables has been carefully studied in the next two subsections.

2.1. Impact of air pollutants

Borro et al. (2020) conducted an evidence-based study to identify the relation between COVID-19 spread and air pollutants. Positive correlations were found between $PM_{2.5}$ levels and the incidence, mortality rate, and case fatality rate. The study by Amoatey et al. (2020) in middle-eastern countries identified the burning of incense sticks as a major reason for particulate matter (PM) in indoor environments. The study demonstrated that the presence of these indoor air pollutants along with lower levels of outdoor ventilation could accelerate the spread of virus droplets and particles in indoor spaces. SARS-COV-2 viral RNA was found in many PM_{10} samples collected from the outdoors air in Bergamo (Amoatey et al., 2020). Hence, the PM can be identified as a carrier of the virus, which boosts viral survivability outside the human body and thus pose a risk for virus transmission in indoor spaces (Setti et al., 2020a, 2020b). There has been an observed association between particulate matter pollution and disease outbreaks, particularly in Italy (Rohrer et al., 2020). It has been argued that polluted air can enhance the infection potential of the infectious agent through a synergistic effect by agglomerating airborne infective particles with PM present in the air (Zoran et al., 2020).

Aerodynamic analysis of the SARS-CoV-2 virus by Liu et al. (2020) has found a large concentration of viral RNA peaks in the sub-micrometer and super-micrometer particle ranges, indicating the possibility of SARS-CoV-2 transmission via aerosols inside two hospitals in Wuhan. New research has shown a relationship between COVID-19 mortality and exposure to high quantities of pollutants for an extended period, such as PM, SO_2, CO, NO_2, and O_3 (Coccia, 2020a; Ogen, 2020; Perone, 2021).

The time gap (days) between the index case (first case) and the date on which the cumulative number of confirmed cases achieved the seeding number (SN) is known as seeding time. The number of cases needed to “hatch” an epidemic in a nation is referred to as ’SN’ . It influences Doubling Time (DT) and can indicate the initially introduced risk at the start of an outbreak in a country. The number of days required to double the total cumulative number of cases can be used to measure the efficiency of preventive interventions (Zhou et al., 2020). In a survey-based study by Collivignarelli et al. (2021), correlations between PM and the SARS-CoV-2 spread-related Doubling time (DT) and Seeding time (ST) has been assessed using empirical model applications in Northern Italy. A strong positive relation was reported between DT and particulate matter ($PM_{2.5}$ and PM_{10}), which suggests the possibility of a link between the spread rapidity of COVID-19 and the PM presence. The study did not rule out the possibility of a collaborative effect with other factors (e.g., weather, climate, socio-economics, and culture) and the influence of other pollutants, meteorological parameters (e.g., temperature, solar radiation, and humidity) on viral transmission along with PM (Collivignarelli et al., 2021). A study by Li et al., (2020) based in Wuhan and XiaoGan demonstrated that the four variables that potentially increase the prolonged spread of the COVID-19 disease are the Air Quality Index (AQI), $PM_{2.5}$, NO_2, and temperature. The researchers looked into the link between long-term NO_2 exposure and COVID-19 mortality rates. The spatial analysis of regional-scale data indicated that the prolonged exposure to the NO_2 pollutant could significantly contribute to the increase in the mortality rate of COVID-19 disease.

Research by Coccia (2020a) established a link between COVID-19’s rapid and extensive diffusion in North Italy and air pollution as determined by days exceeding PM_{10} or ozone limits. The author concluded that urban areas in the hinterland with a high number of days surpassing PM_{10} limits and low wind speed have more infected individuals. In contrast, coastal cities with days surpassing PM_{10} or ozone limits but with high wind speed have a relatively less number of infected people. Furthermore, cities with >100 days of air pollution (above the PM_{10} standards) have a far higher average number of sick persons. In contrast, places with <100 days of air pollution annually have fewer infected individuals. The study also indicated that SARS-CoV-2 virus accelerated transmission dynamics are primarily due to “air pollution - human transmission” rather than “human-human transmission (Coccia, 2020b).

Existing literature suggests that indoor air pollutants significantly affect the incidence, spread rate, and mortality rates of COVID-19 infection.. Therefore, measures to improve indoor air quality through identification, regulation and mitigation of indoor air pollutants needs to be adopted. $PM_{2.5}$ and NO_2 has been reported with a higher association with COVID-19 when compared to $PM_{10.}$ This can be due to the atmospheric lifetime difference between PM $_{2.5}$ and PM_{10}. The atmospheric lifetime of $PM_{2.5}$ ranges from days to weeks, and for $PM_{10,}$ it’s just hours to days (Gugamsetty et al., 2012). Other pollutants such as SO_2, CO, CO_2, and O_3 were also positively correlated to COVID-19 transmission . Additionally, various research has indicated the detrimental effects of these pollutants on health and productivity of occupants in indoor environments. Hence, indoor air quality should be treated as an important parameter, and the potential sources of indoor pollutants should be identified and adressed. Special consideration to improve IAQ should be undertaken in policy making and health management specially in areas of high outdoor and indoor pollution, such as urban centers, slums, industrial areas, and low-income settlements.

2.2. Impact of meteorological indicators (temperature, humidity, rainfall, and wind speed)

Lin et al. (2020) assessed the effect of temperature, relative humidity (RH), and control measures on virus transmission using individual data from China, Singapore, and Hong Kong. Temperature was found to have a negative association with COVID-19 spread. On the other hand, the study also pointed out that the correlation of relative humidity (RH) is temperature-dependent. High humidity promotes virus spread when the temperature is low, and it inhibits the virus spread with high temperatures. (Lin et al., 2020). This makes the countries such as Indonesia, Singapore, Philippines, Malaysia, etc., with high temperature and high humidity throughout the year, innately capable of curbing COVID-19 transmission meteorologically. The countries where relative humidity decreases as the temperature increases, such as the US, Spain, etc., have to take extra precautions (non-pharmaceutical interventions) like social distancing and other restrictions to contain the spread, especially during the cold and dry seasons. Analysis based on everyday data on the meteorological condition, new cases, and new deaths were done by Wu et al. (2020); the findings revealed that a 1°C rise in temperature was associated with a 3.08% drop in daily new cases and 1.19% drop in daily new deaths. A 1% rise in relative humidity was linked to a 0.85% drop in daily new cases and a 0.51% drop in daily new deaths (Wu et al., 2020). High temperature and high humidity were found to inhibit viral transmission in Bangladesh (Haque and Rahman, 2020). Average temperature, the minimum temperature, was found to be correlated with the COVID-19 in New York, USA (Bashir et al., 2020). High humidity creates conformational changes on the membrane (polar membrane interactions) and causes a negative impact on lipid-enveloped viruses like the coronavirus, resulting in virus death and inactivation (Yang and Marr, 2012). A positive relationship between the diurnal temperature range and the negative association of absolute humidity (AH) was observed with COVID-19 mortality rate by (Ma et al., 2020) in a study done over 166 countries’ data.

A negative correlation between cases and rainfall was established by Raza et al. (2021) in Pakistan. No relationship between rainfall and pandemic was reported in a study conducted in New Delhi, India (Singh et al., 2021). The impact of weather on the SARS-CoV-2 virus spread has been established by Gupta et al. (2020); the study also highlighted the role of absolute humidity (AH) and temperature (T) in the transmission of the virus. The study observed that places in the United States with weather parameters range; AH (4–6 g/m^3) and T (4 °C–11 °C) helped the

COVID-19 spread. Data from 116 countries were analyzed by Islam et al. (2020), and results indicated that temperature, humidity, and wind speed are negatively related to the incidence rate of disease. Dry and cold environments were found more favorable by the study for viral spread. Temperature, humidity, and windspeed level increases were found to gradually reduce the spread rate in Brazil (Rosario et al., 2020).

Contrary to the above-mentioned studies, a positive correlation between temperature and cases, a negative association of humidity with mortality rate, and a feeble correlation were found between rainfall and the incidence of COVID-19 in major cities of Pakistan (Basray et al., 2021). Similarly, a positive correlation between maximum, minimum, and mean temperatures, relative humidity, evaporation, and wind speed was found with COVID-19 in a study conducted over a period of 90 days in Delhi, India (Singh et al., 2021). Mean temperature was found to be positively associated with COVID-19 incidence in a study conducted in China (Xie and Zhu, 2020). No significant relation or evidence was found between temperature and COVID-19 cases in a study conducted by (Briz-Redón and Serrano-Aroca, 2020) on data from Spain. No association between temperature and precipitation in COVID-19 deaths was reported by (Leslie et al., 2020). Relative humidity was positively related to the number of COVID-19 cases in Italy (Haghshenas et al., 2020), and no significant correlation between meteorological parameters such as rainfall and humidity was reported by Haghshenas et al. (2020) using data from Jakarta, Indonesia. Positive association of precipitation and COVID-19 viral infections was reported by (Sobral et al., 2020). A nonlinear association of wind speed was reported with COVID-19 incidence (Guo et al., 2021).

The relationship between meteorological variables and COVID-19 spread is ambiguous, and the results from various studies contradict each other. The majority of the studies reviewed display a negative correlation of meteorological variables such as temperature, humidity, etc., with the COVID-19 spread. But very few studies have reported positive correlations, and hence the relationship remains ambiguous with positive, negative, and mixed reviews. Hence further research is required to confirm the extent of the relationship. The influence of rainfall and windspeed has also been less studied and has to be explored more with extensive time series data to understand its actual effect on the spread of COVID-19 disease. Most of the studies have predicted the relationship between meteorological variables and COVID-19 transmission using real-life meteorological data using statistical analyses. More controlled experiments need to be conducted to confirm the relationship between these variables and virus transmission.

Nevertheless, all the above studies confirm the significance of IAQ and IEQ in viral load mitigation. Human beings spend approximately 90% (EPA, 2018) of their time inside buildings; hence, IEQ is a significant factor influencing occupants' health, comfort, pleasure, and productivity. Most developed countries follow certain IAQ regulations in the construction and operation phase of buildings, but it is not the case in developing or underdeveloped countries(Gall et al., 2013). Necessary policy initiatives should be taken to improve the indoor environment's quality, mainly focussing on IAQ to effectively minimize the transmission of the COVID-19 disease and other future pandemics. Table 1 summarizes the significance of IEQ parameters in COVID-19 transmission.

3. Indoor air quality improvement strategies

The majority of the population lives, works, and interacts in densely populated places, increasing their risk of contracting infectious diseases like the SARS-CoV-2 virus. However, depending on the exposure conditions, an infection can arise in variable degrees through multiple channels. Effective infection management is a multidisciplinary problem involving different branches of science, including the science of the built environment, that necessitates safeguarding the population from all possible exposure pathways. Multiple governments and international agencies are continuously trying to contain the current pandemic through various measures, which include quarantine, social distancing, disinfection, wearing of masks, better indoor air quality improvement (adequate ventilation for spaces, air purification, air filtration) as standard precautionary measures against SARS-CoV-2 infection (Agarwal et al., 2021; Alonso et al., 2021; Amoatey et al., 2020; CDC, 2020; Cooper et al., 2021; De Santoli et al., 2014; Elsaid and Ahmed, 2021; Morawska and Milton, 2020; WHO, 2021b). The presence of infectious agents in indoor settings can be minimized through building design and other engineering strategies, preventing occupants from getting infected through numerous transmission channels. It has been indicated by Morawska et al., (2020) that efficient IAQ strategies can minimize the risk of airborne transmission of viruses.

There are many potential sites for the spread of the virus in indoor spaces, including sick/infected persons, the presence of contaminated indoor air, and the threat of recirculated contaminated air through the Heating, ventilation, and air conditioning (HVAC) systems (Santos et al., 2020; Sloan Brittain et al., 2020). Researchers have spent a considerable amount of time figuring out how one can keep airborne infections out of their household premises or keep them at low levels to contain the infection spread. The most technically advanced interventions include pressurization, dilution, filtration, purification, and nanotechnology (Megahed and Ghoneim, 2021). The following measures have been recommended by various researchers for minimizing liquid droplets and airborne particles from indoor spaces to prevent the transmission of viruses, which includes increasing ventilation rates, reducing recirculation of stale contaminated air, implementing natural ventilation, personalized ventilation, personalized-exhaust systems, humidity regulation, and temperature control (Qian and Zheng, 2018; Raj et al., 2020; Sloan Brittain et al., 2020).

As discussed above, there are multiple strategies available at various scales for improving the IAQ in a building. These strategies require interventions at multiple levels, including the interventions to the building design, usage of various equipment, changes to occupant behavior, and various other policy measures to support these interventions. The following sub-section of the study provides a detailed focus on the ventilation, air purification/filtration strategies, along with other important strategies for improving indoor air quality to reduce virus transmission risk. IAQ improvement strategies can be primarily grouped into three; source control strategies, ventilation improvement strategies, and air filtration/purification strategies.

3.1. *Source control strategies*

Source control strategies refer to strategies that try to prevent or limit the virus transmissions with the source itself. Various source control strategies include the usage of masks, detecting, tracking and isolation of infected persons, and avoiding the spread and intake of the virus from its carriers to healthy individuals (Zhang, 2020). Controlling virus spread needs two steps: limiting sick persons' connections by physical separation along with other interventions and lowering the transmission probability per contact (Howard et al., 2021). Masks can be used to prevent/control the spread of bioaerosols from an infected person to spread to the immediate environment and to prevent the inhalation of these infected aerosols by a healthy individual. Masks are intended to reduce the spread of virus-laden droplets, which is especially critical for asymptomatic patients who are unaware of their infectious status. Wearing masks has been reported to minimize the inhalation of the infected bioaerosols by filtering the air at the source (Amoatey et al., 2020; Blocken et al., 2020; CDC, 2020).

Another improved source control strategy has been proposed by Melikov et al. (2020) in their study to reduce indoor airborne transmission of respiratory infectious diseases, which would be achieved by enforcing intermittent gaps in built space occupancy and recommending that all users should walk out of the space periodically (taking short breaks). The study by Sun and Zhai (Sun and Zhai, 2020) inferred that the combination of proper social distancing (which can be achieved by

Table 1
Significance of Indoor Environmental quality parameters in COVID-19 transmission.

Reference	Year	Objective	Parameters	Context	Method	Key finding	Notes
Zhu et al. (2020)	2020	Assess the link between ambient air pollution and COVID-19.	$PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3	China	Generalized Additive Model (GAM) based statistical analysis	• $PM_{2.5}$, PM_{10}, NO_2, and O_3 showed a positive relationship with the newly confirmed cases • Negative association of SO_2 with daily confirmed cases • 10-μg/m^3 rise in $PM_{2.5}$, PM_{10}, NO_2, and O_3 linked to a 2.24%, 1.76%, 6.94%, and 4.76% rise in the daily confirmed cases • 10-μg/m^3 rise in SO_2 was linked with a 7.79% reduction in confirmed cases	• Causal effects of air pollution on COVID-19 were not evaluated • Only the association between air pollutants and confirmed cases was assessed • Gender and age-specific analyses are not considered
Madewell et al. (2020)	2020	To investigate the relationship between long-term average exposure to fine PM and COVID-19 deaths	$PM_{2.5}$	USA	Negative binomial mixed model	1 μg/m^3 rise in $PM_{2.5}$ is linked to an 8% rise in death rates	A slight rise in long-term $PM_{2.5}$ exposure causes a significant rise in the death rate.
(Cole et al., 2020)	2020	To understand the association between long term air pollution exposure and COVID-19	$PM_{2.5}$, NO_2, SO_2	Netherlands (355 municipalities)	Negative binomial count model	1 μg/m^3 rise in $PM_{2.5}$ concentrations results in 9.4 times more cases, 3 times higher admission to hospitals, and 2.3 times more death.	
(Coker et al., 2020) (Borro et al., 2020)	2020	To assess the relationship between PM levels and incidence, mortality rate, and case fatality risk of SARS-CoV-2 virus.	$PM_{2.5}$	Italy	• Epidemiological analysis using geographical information and negative binomial regression • ACE-2 gene bioinformatics analysis	• 1 μg/m^3 rise in $PM_{2.5}$ is linked with a 9% rise in mortality • Positive correlations among $PM_{2.5}$ levels and the incidence, mortality rate, and case fatality rate	• Population density showed much lesser importance than PM
Collivignarelli et al. (2021)	2021	To ascertain whether PM was the main cause of SARS-CoV-2 spread rapidity	PM_{10}, $PM_{2.5}$, Air quality	Northern Italy	• Survey-based data collection and statistical correlation	• Excludes the possibility that PM alone was the main cause of SARS-CoV-2 spread rapidity. PM effect in synergy with other polluting elements, also conditions like sociability, liveability, and meteorological conditions accelerate the spread	• Spread rapidity was assessed using Seeding time (ST) and doubling time (DT)
(Setti et al., 2020a, 2020b)	2020	• To investigate the presence of SARS-CoV-2 presence on PM • To evaluate linkages between higher mortality rates and average PM_{10} concentrations exceeding 50 μg/m^3 daily limit	PM $_{10}$	Northern Italy	• Virus viability studies • Experimental with exploratory and statistical inference analysis	• The presence of SARS-CoV-2 RNA on PM • Geographical distribution of daily PM_{10} exceedances and the initial transmission of the virus were correlated	• The opportunity of considering PM as an ‘indicator’ for the expected impacts of virus transmission.
(H. Li et al., 2020)	2020	Investigate whether meteorological	• AQI	China (Wuhan and XiaoGan)	• Time-series analysis • Descriptive analysis	• Low AQI, $PM_{2.5}$, $PM_{10,}$ $_{NO2}$ could	• Short study period (Jan

(continued on next page)

Table 1 (*continued*)

Reference	Year	Objective	Parameters	Context	Method	Key finding	Notes
		variables and ambient air pollutants could increase the incidence of COVID-19 disease	• $PM_{2.5}$, PM_{10}, NO_2 and CO • Daily temperature, Highest temperature, Lowest temperature, Temperature difference, sunshine duration			enhance the incidence of COVID-19 • Temperature has an inhibitory influence on SARS-CoV-2 transmission • CO also showed a strong positive relation with Wuhan virus transmission	26th to Feb 29th in 2020) • Couldn't conclude on the effect of CO as the results vary in the case of two cities considered
van Doremalen et al. (2020b)	2020	To assess the stability of SARS-CoV-2 and SARS-CoV-1 in aerosols and on various surfaces	Aerosols		• Bayesian regression model	• SARS-CoV-2 transmission by aerosol and fomite is possible • The virus could remain alive and contagious inside aerosols for several hours and for days on surfaces	
(Peng and Jimenez, 2021)	2021	CO_2 based risk proxy expression derivation	• CO_2		• Wells−Riley model of aerosol infection	• Relative infection risk increases with excess CO_2 levels • Low CO_2 levels in spaces increase the efficiency of ventilation measures	CO_2 is the only infection risk proxy quantity that can be simply detected by fast and cheap sensors.
(Ahlawat et al., 2020; Ganegoda et al., 2021; Kumar, 2020; Yang and Marr, 2012)	2020,2021,2012	To assess the effect of humidity on Airborne Transmission of COVID-19	• RH, AH		• Statistical analysis with Epidemiological data, HYSPLIT Trajectory data, AOD and pollutants data, Weather data	A negative correlation was observed between AH and RH and daily cases of COVID-19	

reducing the occupancy) measures along with high ventilation effectiveness could significantly reduce the transmission risk of coronavirus. It was found that a reduction of 50% occupancy density can result in a reduction in infection rate by 20–40% (Sun and Zhai, 2020). Mokhtari and Jahangir, (2021) conducted a study to understand the impact of occupant distribution on energy usage and COVID-19 disease in a university building in Tehran. The study identified that an effective occupant distribution could decrease the number of infected individuals by up to 56%. Quanta generation can be conceived of as the emission of infectious doses of a virus by an individual (Kurnitski, 2020; Toparlar Yasin Gent van, 2020). The infection risk is highly sensitive to the quanta generation rate, indicating that a source control strategy (e.g., mask use, social distance, lesser occupancy, etc.) may be an appropriate and sensible technique for minimizing infection risk in the pandemic situation (Perazzo et al., 2021). Monitoring secondary $PM_{2.5}$ pollution, in conjunction with meteorological forecasts, in geographical areas prone to secondary $PM_{2.5}$ pollution, such as urban areas with high-density populations, could help in alarming the people of risk days and thereby mitigate the transmission of the viruses (Rowe et al., 2021). It was found by Shen et al. (2021) that installing partitions in indoor spaces has a 46% risk reduction efficiency potential and if used with displacement ventilation, it can result in 96% infection risk reduction. Partition walls in classrooms were found more effective in reducing bioaerosol spreading than wearing facemasks (Epple et al., 2021).

3.2. Ventilation improvement strategies

The main approach to minimize an individual's vulnerability or exposure duration to dangerous microorganisms in a confined place is to improve the air dilution rate. Ventilation is an efficient engineering strategy that provides air movement that contributes to the dilution and dispersion of aerosol particles (Nembhard et al., 2020; Santos et al., 2020). Ventilation, or the process of replacing contaminated indoor air with clean outdoor air, is the most crucial factor in ensuring adequate IAQ (CDC, 2021; EPA, 2021; Van Tran et al., 2020). Ventilation has been recognized as a vital strategy to manage the diffusion and transmission of airborne diseases like COVID-19 by international agencies such as ASHRAE, WHO, and REHVA (ASHRAE, 2020b; REHVA, 2020a; WHO, 2021a).

When considering the spread range (1–2 m) of coughs and sneezes, SARS-CoV-2 particle diameter characteristics, aerosol sedimentation velocity, and indoor airflow, ventilation of indoor spaces appear to be the most efficient strategy for reducing SARS-CoV-2 levels in aerosols ≤ 10 μm (Hayashi et al., 2020). In favorable conditions, the probability of tiny droplets (dia ≤ 60 μm) vaporizing into droplet nuclei (dia < 10 μm) are more, and the terminal settling velocity of a particle of < 10 μm in size is < 0.3 cm/s; thus, the infectious bioaerosols can be managed with appropriate indoor airflow strategies and adequate ventilation levels (Kenichi Azuma et al., 2020).

Wells– Riley equation states that (Atkinson et al., 2016; Riley et al., 1978; Wells, 1955),

$$P = \frac{D}{S} = 1 - \exp\left(\frac{-Ipqt}{Q}\right) \tag{1}$$

where;

P = probability of infection for susceptible
D = number of disease cases

S = number of susceptible
I = number of sick individuals
p = breathing rate/person (m^3/s)
q = quantum generation rate by sick individual (quanta/s)
t = total exposure time (s)
Q = outdoor air supply rate (m^3/s)

According to Equation (1), the air change rate is inversely proportional to the concentration of indoor pollutants. Hence adequate fresh air ventilation with an acceptable outdoor air exchange rate will help mitigate the transmission of the virus (ASHRAE, 2019; Widder and Haselbach, 2017). WHO has recommended a minimum ventilation rate for different built spaces to enhance and ensure standard ventilation levels in built spaces (WHO, 2021c). According to this equation, in high quanta producing conditions such as a health care setting with the aerosol-generating procedure, the projected likelihood of getting infected after 15 min of exposure in a space with 12 ACH will be less than 5% (Atkinson et al., 2016). The recommended ventilation rates by WHO are listed in Table 2 below.

Three main categories of ventilation exist, mechanical, natural, and hybrid ventilation. Mechanical ventilation uses mechanical equipment like fans or blowers to ventilate the spaces and typically requires electricity. On the other hand, natural ventilation is achieved without using any mechanical equipment (Chenari et al., 2016; Leslie et al., 2020). Nowadays, most buildings are mechanically ventilated, which increases energy consumption. The third type of ventilation is hybrid or mixed-mode ventilation (Ledo Gomis et al., 2021) which incorporates both mechanical and natural ventilation. In hybrid ventilation, mechanical ventilation using equipment such as fans and blowers is used when natural ventilation is not feasible for multiple reasons (Chenari et al., 2016).

Ventilation has been described as an easy-to-implement method that can help enhance vaccination efforts to endorsed levels (Melikov, 2020) and has a similar transmission risk-reducing effect as vaccine coverage of 50–60% (Smieszek et al., 2017). Opening windows has been found to be an efficient ventilation technique that will enhance the IAQ; it is preferable to open them wider and for extended periods. Opening a window in the main wind direction of the region and a window in the opposite facade allows air to travel through the indoor spaces more efficiently (Hayashi et al., 2020). The predominant airflow direction inside the room has to be from the fresh zone to the less fresh zones or contaminated areas; if not, strategies such as the stack effect, installation of wall/window air extractors, or whirlybirds should be adopted to rectify the airflow direction (WHO, 2021c). High-intensity natural ventilation has been found effective in reducing the viral transmission risk. It can be achieved by opening windows/doors on opposite facades if the weather conditions permits (Alonso et al., 2021; Amoatey et al., 2020; Bonell et al., 2020; Hayashi et al., 2020; Stabile et al., 2021). Shen et al. (2021) analyzed the efficacy of various control strategies in terms of their risk-reducing potential; the findings demonstrated that 100% outdoor air ventilation would result in a 27% reduction in infection risk, and doubling the total supply of airflow would result in a 26% reduction in infection risk.

According to Rowe et al. (2021), Africa, particularly Sub-Saharan Africa, has been less affected by the SARS-CoV-2 virus as rich mid-latitude nations. The study highlighted that this trend could be due to the climatic factors (volatile atmosphere) combined with an outdoor lifestyle, such as street markets instead of mechanically ventilated supermarkets (which recirculate contaminated air) in rich countries. It was also pointed out that air conditioning usage in African countries is far less widespread compared to affluent countries of the same latitude, which can also be a valid reason for this low COVID-19 case trend (Rowe et al., 2021).

Table 2
Recommended ventilation rates (WHO, 2021c).

Setting	Recommended Ventilation rate
1. Health care setting with the quarantine facility	
1a. With the aerosol-generating procedure	160 L/s or 12 ACH
1b. Without the aerosol-generating procedure	60 L/s or 6 ACH
2. Non-residential settings	10 L/s
3. Residential setting	10 L/s

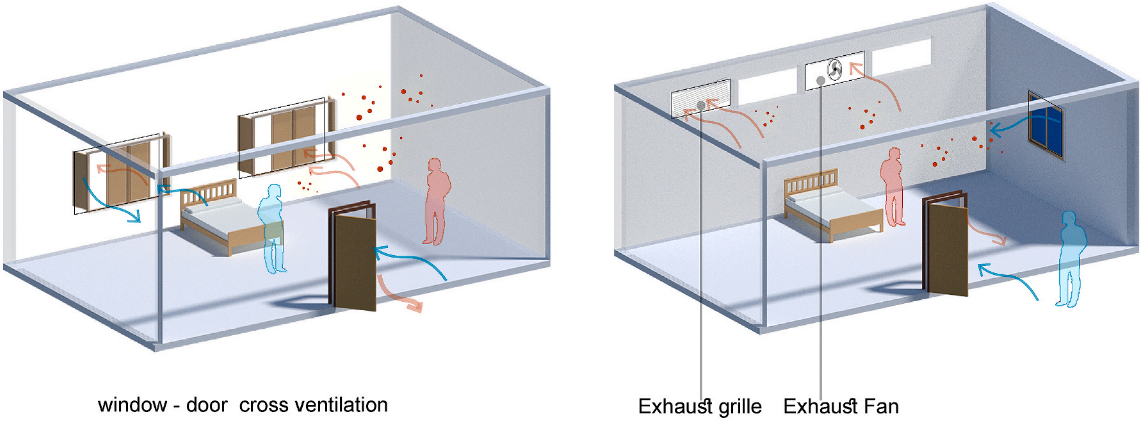
In air-conditioned settings, ceiling fans have been found to lower the incidence of cross-infection. The average contaminant concentration at the sampling point declined by 18% and 38%, respectively, when the number of air changes per hour rose from 4.5 to 5.6 and 7.5. With better aerosols' dispersion through mixing air and creating local air movements, the ceiling fan operation reduced the exposed individual's breathing zone concentrations by more than 20% (Li et al., 2021). Various natural, mechanical and hybrid mode ventilation strategies to reduce transmission risk are demonstrated in Fig. 2.

ASHRAE 62.1 recommended minimum ventilation rates might not be adequate to reduce the transmission of the SARS-CoV-2 virus in enclosed settings (Anand et al., 2022). HVAC systems should not be used as per the usual operation schedule and must be revised accordingly as there is a risk of increased air contamination in indoor spaces due to the ongoing pandemic. Various international agencies recommend that the ventilation system be turned 'on' before the room is occupied and should be kept on for as long as possible (ASHRAE, 2020a; CDC, 2021; REHVA, 2020b). In non-residential settings, HVAC systems should be running at nominal speed for at least 2 h prior to the space usage (occupancy) period and then at a lower speed for 2 h after the occupancy (CDC, 2021). It is also recommended that air-conditioning equipment should be running for longer periods of time, preferably for 24 h (ASHRAE, 2020a; REHVA, 2020b).

Personalized Ventilation (PV), which has been shown to compensate for total volume ventilation in order to enhance the local IAQ, could be used to minimize the spread of infectious aerosols in built spaces, thereby providing better protection for occupants exposed to a sick person (Ding et al., 2021; Li et al., 2013). The usage of PV in indoor spaces demonstrated an efficiency of 67% in reducing the infection risk (Shen et al., 2021). PV promises high ventilation effectiveness without any mixing with the contaminated air, and direct delivery of fresh air to the occupant's breathing zone thus can be considered as one of the promising strategies to reduce airborne transmission indoors (Chen, 2021; Melikov, 2020). As the potential of PV systems in COVID-19 pandemic management is huge and under-explored, particularly in small indoor spaces such as airplanes, office spaces, transport modes, etc., PV systems should be investigated more and employed wherever possible to enhance the IAQ and reduce inhalation of contaminated air by the occupants. The integration of PV to mixed ventilation systems in Fig. 3 demonstrates the incorporation of PV systems to the occupant desk to minimize the mixing of contaminated air with fresh air. A personalized exhaust system could be incorporated into the PV system at the occupant desk level, and that could provide better removal of stale indoor air in the breathing zone.

The objective of adaptive wall-based attachment ventilation is to supply fresh air directly to the occupant zones. When compared to a ceiling or upper sidewall air supply, this type of ventilation has been proven to produce a 15–17% reduction in average contaminant concentrations for a continuous release of contaminants at the same air exchanges per hour (ACH; 10 h^{-1}) (Ying et al., 2020).

There are two categories of building ventilation: displacement ventilation and mixing ventilation. In displacement ventilation, the outdoor air is provided at a lower speed through diffusers near the floor level and is withdrawn above the occupant zone, near the ceiling. Whereas in mixing ventilation, fresh outdoor air is provided at a high velocity outside the occupant zone, for example, through the ceiling. This new air will get mixed with contaminated indoor air to dilute concentrations of contaminants aerosols (Blocken et al., 2020). Zhang (2020) indicated that uniform distribution of air throughout the room



a. Natural Ventilation

b. Hybrid ventilation

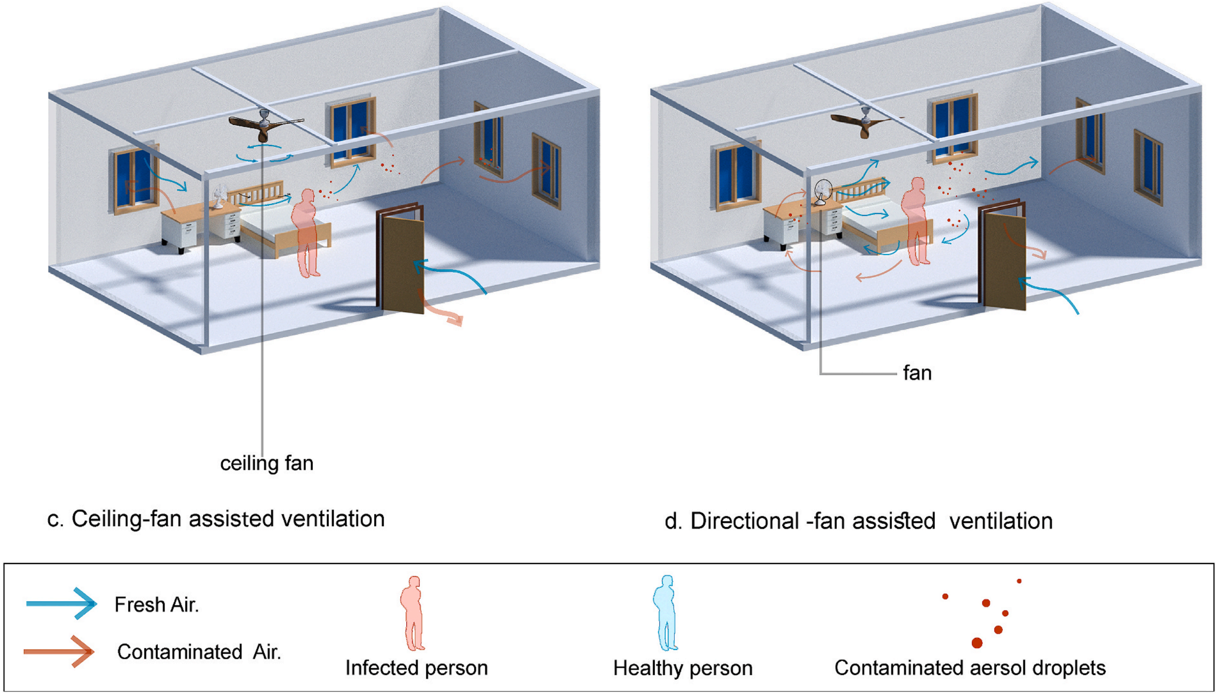


Fig. 2. Hybrid ventilation strategies to minimize the SARS-CoV-2 transmission risk.

through various ventilation strategies is essential for improving IAQ. In some situations, the ventilation system works through recirculation of air (like in mixing ventilation). A part of the expelled air is recirculated into the building, which is undesirable in the event of infectious diseases (Blocken et al., 2020; Leslie et al., 2020). Displacement ventilation should be preferred to properly ventilate an indoor space if sufficient buoyancy forces generate upward air movement (Lipinski et al., 2020; Noorimotlagh et al., 2021). The airflow pattern of displacement and mixed ventilation has been highlighted in Fig. 4.

Displacement ventilation (mechanical/natural) has been found to be a feasible option for negative pressure isolation chambers in hospitals, which commonly use mixing ventilation. Negative pressure is created in the occupied zone, which brings clean air in from the outside, and positive pressure is created towards the roof, which expels the hot, stale air (Lipinski et al., 2020; Rajesh and Bhagat, 2020; Sodiq et al., 2021). The hospitals' isolation chambers, when compared to corridor spaces and neighboring spaces, must use a negative differential pressure, quickly expelling room air to the exterior of the building to keep aerosolized viruses (from isolation spaces) out of circulation from shared spaces (Leslie et al., 2020; Qian and Zheng, 2018; Santos et al., 2020; Wei and Li, 2016). However, the same negative pressure might inadvertently expose room occupants to airborne infections from corridor area inhabitants. To counter this, . (Leslie et al.,(2020) suggested adding an anteroom to isolation rooms that would operate as a separator between common areas and isolated spaces, reducing disease transmission. A feasible intervention to improve IAQ in a mixed ventilated hospital isolation setting has been demonstrated in Fig. 5.

Demand control ventilation can be a useful energy-efficient feature in non-pandemic settings. However, in the event of an airborne pandemic or a threat of airborne infectious diseases, establishments should make every effort to maintain the air as clean as possible. Demand-controlled ventilation limits air supply-based CO_2 setpoint during occupied hours to save energy. However, this energy-saving is at the cost of reduced ventilation, and the same is not recommended during the pandemic period. Hence, demand control ventilation should be turned off to improve ventilation rates (Afshari et al., 2021; Eykelbosh, 2021), or the CO_2 concentration setpoint should be lowered enough to maintain adequate indoor ventilation if demand control ventilation is

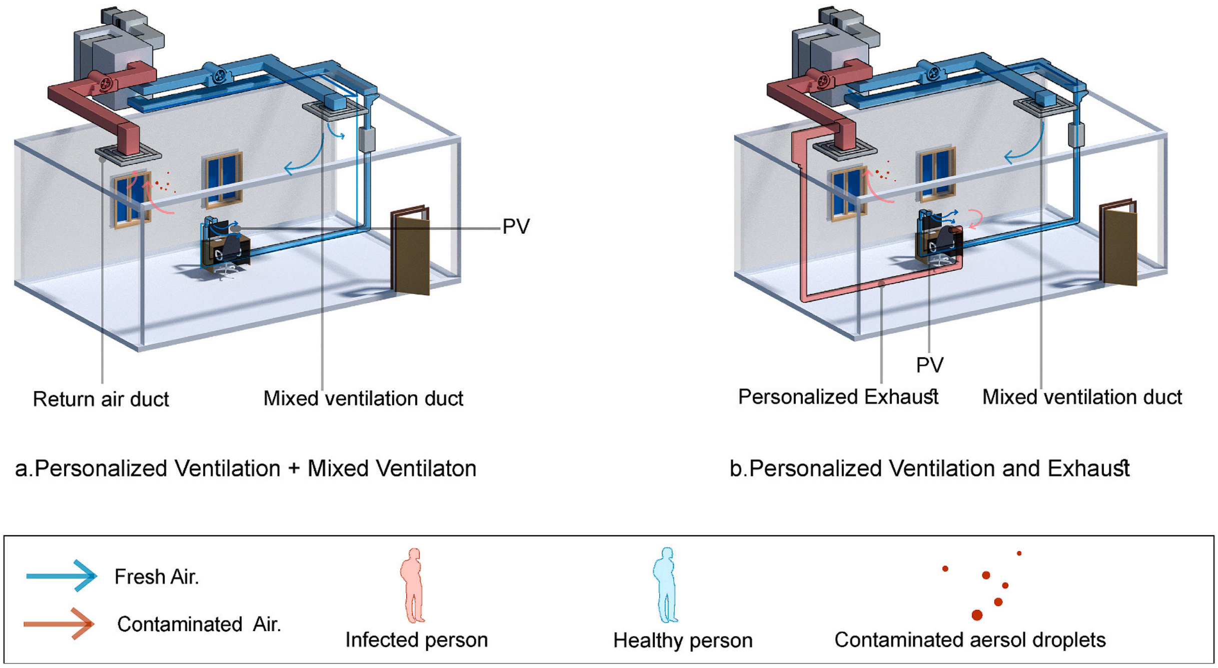


Fig. 3. Personalized ventilation strategies to minimize the SARS-CoV-2 transmission risk.

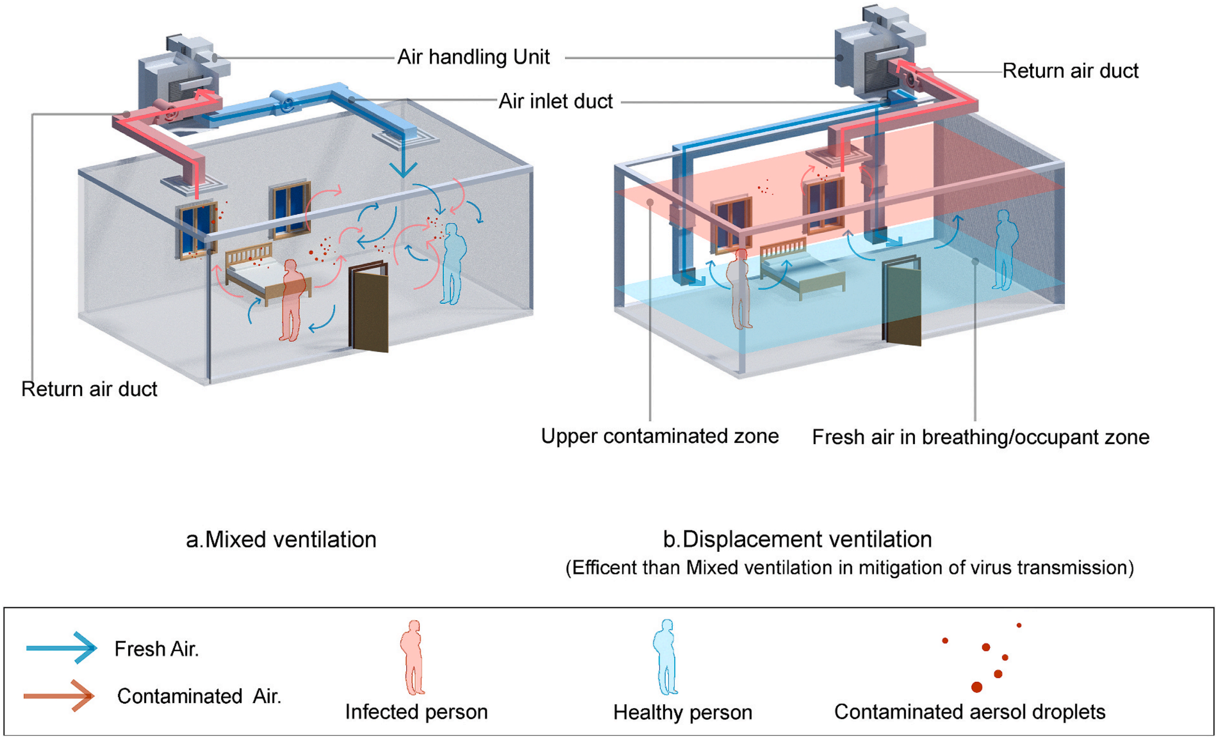


Fig. 4. Mixed and Displacement ventilation strategies.

used to reduce the virus's transmission risk (REHVA, 2020b).

To conclude, high-intensity fresh air ventilation avoiding recirculation of contaminated air must be used in order to minimize the spread of infectious diseases through the air. This effectively and swiftly removes the virus particles and keeps indoor aerosol concentrations as low as possible. Both the natural and mechanical ventilation strategies have the potential to reduce airborne transmission if designed and operated efficiently. Hence, existing international and national standards and guidelines should be revised in order to incorporate the threat of airborne infectious agents. Country, region, and context-specific space ventilation standards have to be formulated according to the various variables that is acting upon these spaces.Also, technologies and various building system components have to be optimized to maintain the energy efficiency parameters while incorporating these changes. Table A1 (in appendix A) summarizes the various ventilation strategies to improve IEQ and their reported effectiveness.

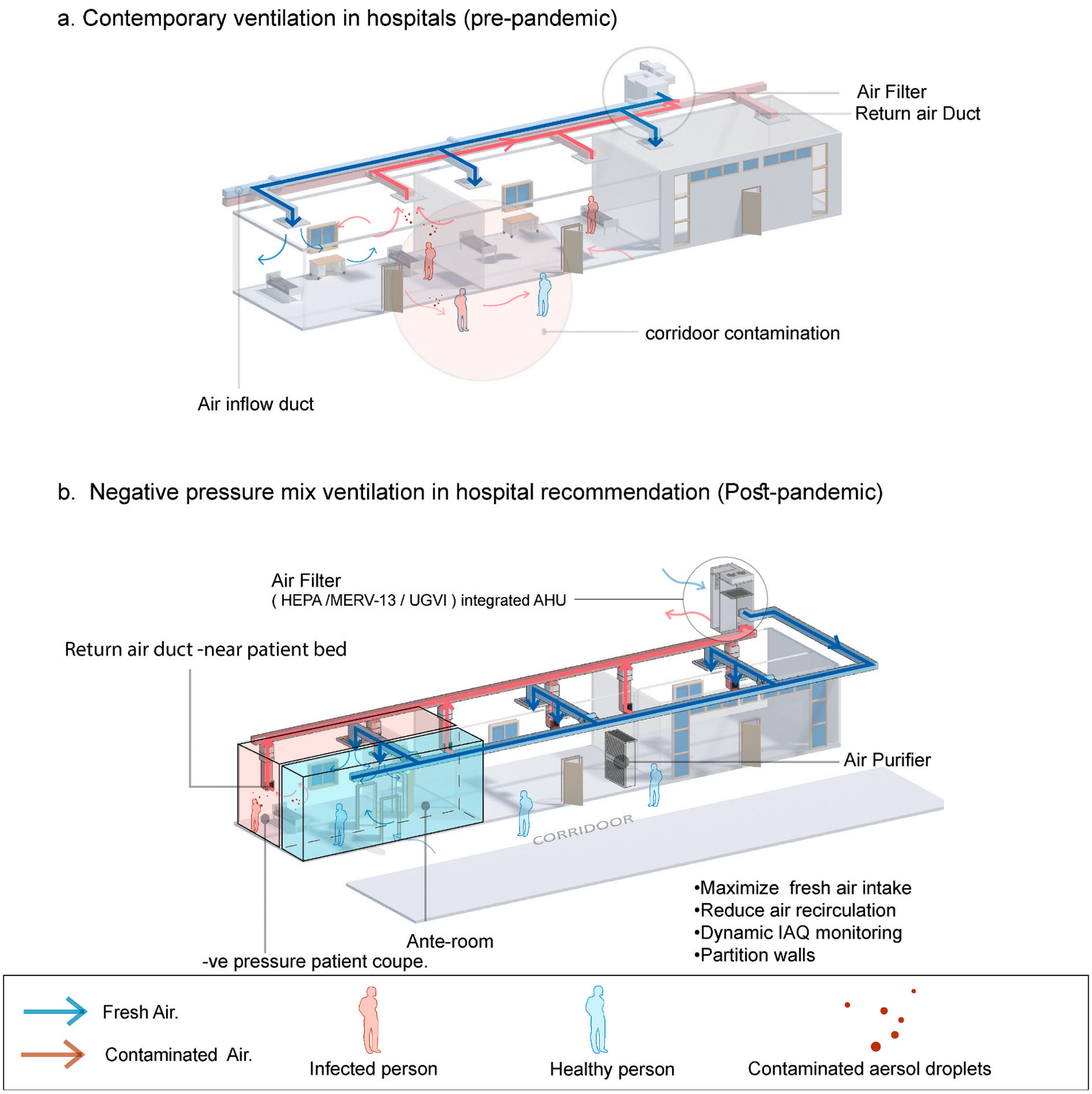


Fig. 5. Strategies to reduce virus transmission from hospital isolation rooms.

3.3. *Air filtration and purification*

Filtering or purifying the air with various filters and purifiers in indoor spaces has been found to lower the viral load in indoor spaces hence minimizing the chances of virus transmission (Elias and Bar-Yam, 2020). Air filters remove PM through several mechanisms, which include interception, impaction, inertial collision, diffusion, gravitational effect, electrostatic attraction, etc. (Hayashi et al., 2020; Xu and Zhou, 2014). Natural ventilation faces critical challenges mostly in urban areas for various reasons, such as outdoor air pollution. The intake air can be filtered using air filters to remove the contaminants and then can be supplied into the indoor spaces in such cases (ASHRAE, 2020c; Azimi and Stephens, 2013; Elsaid and Ahmed, 2021; Fermo et al., 2021; Lowther et al., 2020; Nwanaji-enwerem et al., 2020; REHVA, 2020a). Various researchers indicated that air filtration or purification systems could be provided in the ducts of air conditioning systems (retrofitting), inside the room, and for the occupant zones to functionally minimize the risk of the virus transmission through aerosols (Mousavi et al., 2021; Noorimotlagh et al., 2021; Shen et al., 2021).

International agencies such as ASHRAE (2020c); REHVA (2020b) have recommended various measures to curb airborne infectious aerosol exposure. The measures include the application of mechanical air filters, MERV and HEPA filters, Electronic Air Cleaners, Gas-Phase Air cleaners, Ultraviolet disinfection devices, etc., in places with high outdoor pollution, such as metropolitan cities, where natural ventilation is problematic and infeasible. Incoming outdoor air can be screened with High-Efficiency Particulate Air (HEPA) filters to remove infectious agents and contaminants (Kumar and Morawska, 2019; Nazarenko, 2021). HEPA filters effectively reduce bio-aerosols since they remove at least 99.95% of the particles with a diameter of 0.3 μm and larger fractions while only causing low-pressure drops (Blocken et al., 2020; Lowther et al., 2020). All-day use of HEPA filters has been found effective in reducing the $PM_{2.5}$ concentrations (31%–72% reduction) in indoor spaces, and all-day use of air filters can result in an 8–37% reduction in mortality associated with indoor air pollution (Liao et al., 2019). In indoor spaces such as operating rooms (ORs), airborne infection isolation rooms (AIIRs), and Protective Environments (PE), the coupling of HEPA filtration with HVAC air recirculation has been found to be very effective. These systems purify the air by removing (through filtering) and diluting (by recirculation) impurities from the room at the same time (Mousavi et al., 2021). The capital cost of the HEPA filter is low, but it has high operational and energy costs. A reduction in efficiency was reported with a 200–250 nm particle size range when HEPA filter-based air purifiers were tested in a laboratory setting in China, and this is critical as the particles with these size ranges are present in megacities and can penetrate the building envelope and remain suspended in the air (Lowther et al., 2020) and can act as a virus carrier.

Electrostatic precipitators (ESPs) are air filtering devices that use a small industrial fan to move the air through the filter. The electrically charged solid and liquid particles in the air are collected on a grounded plate within the device. ESP has a lower pressure drop when compared to other mechanical air filtering devices with comparable efficiencies and hence can be used as an alternative to HEPA filters (Afshari et al., 2020). ESP claims a reduction efficiency of 34.1% for $PM_{2.5}$, which is impressive as they have lower energy cost compared to the HEPA filters. The indoor air can be cleaned using ESP filters multiple times to yield better efficiency (Blocken et al., 2020; Vervoort et al., 2021). Another alternative is the electrostatic enhanced pleated filter (EEPF), which produces great filtration efficiency while consuming less energy at the same time. EEPF filter was found to have a contaminant removal efficacy of more than 98% and uses 70% less energy than a HEPA filter (Feng and Cao, 2019).

Azimi et al. (2021) investigated the effect of recirculating HVAC particle filters on the regulation of size-resolved infectious aerosols. Recirculating HVAC filtration, particularly using MERV 13–16 filters, was anticipated to produce the highest risk reductions at low operating costs than equal levels of fresh air ventilation from outside. Medium efficiency filters (MERV 7–11) are cheap but found to be less efficient in minimizing the transmission risk in indoor spaces (Azimi et al., 2021). MERV 7 as primary filters, along with the use of MERV 14 as secondary filters, was found to be efficient in removing 98% of airborne particles in the diameter range of 0.3–1.0μm , hence minimizing the infection risk of COVID-19 (Elsaid and Ahmed, 2021). The infectious droplet nuclei filtration efficiency of HVAC filters is shown in Fig. 6.

A study by Cooper et al. (2021) in the United Kingdom reported that $PM_{2.5}$ concentrations in indoor spaces were reduced by a mean of 45% over 90-min usage of Home Air Purifiers (HAP). This reduction is critical as PM is a potential carrier for viruses. The study also revealed a link between PM concentration and fan speed. The higher the fan speeds of HAP, the lower the concentration of $PM_{2.5}$ in indoor spaces and hence the reduced risk of virus transmission (Cooper et al., 2021).

The HYLA-EST device, a commercial air purifier based on a water-bath filtration system that forces air through without the need for any other form of filter, was put to the test by (Fermo et al., 2021). The results showed that the HYLA-EST device successfully reduces airborne particle concentrations and VOC levels. In the experiment conducted in a residential setting, PM_{10} and $PM_{2.5}$ levels were reduced by approximately 90% and 80%, respectively. In addition, using the HYLA device as an air purifier resulted in a reduction of roughly 40% in VOC concentrations of the order of hundreds of ppb to more than 1 ppm. Therefore, it can be concluded that the HYLA-EST device could effectively control the infection risk through airborne transmission by improving IAQ. Strategies to improve IAQ through various purification/filtration strategies are depicted in Fig. 7.

Mobile air purifiers were tested in classrooms and have been reported as a realistic and feasible measure that can be easily introduced during an ongoing pandemic particularly when there are no fixed ventilation systems, and natural ventilation is not feasible (Curtius et al., 2021). The experimental study was conducted by Curtius et al. (2021) using commercially available mobile air purifiers equipped with HEPA filters with 99.97% efficiency for particle absorption in the/size range of 0.1–0.3 μm.Occupant staying for 2 hours in a confined room with a highly infectious person, the Philips model 2887/10 commercial air purifier with a total air exchange rate of 5.7 h^{-1} decreases the inhaled infectious dose by a factor of 6. The filters from the purifiers should be considered medical waste and should be collected, disinfected, and disposed of carefully to avoid secondary infection (Zhao et al., 2020).

Air filtration/purification is an efficient way of reducing the airborne transmission of viruses in indoor spaces, where providing adequate fresh air ventilation is challenging. The cost, pressure drop, life-time and increase in energy consumption are the deciding factors when selecting a filtration medium. Optimization of these factors and context-specific selection of the filtration/purification devices according to the contaminant type and size in indoor spaces will enhance the health of the occupants. Cost-benefit analysis should be performed to obtain a holistic picture of the filter performance while selecting an appropriate filter medium. Table A2 (in appendix A) summarizes the various air filtration strategies to improve IEQ and their reported effectiveness.

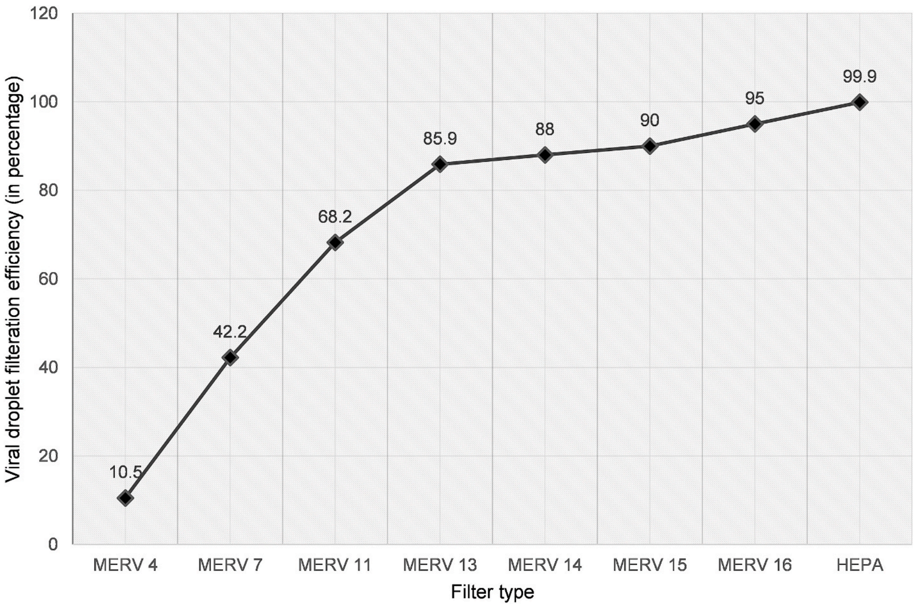


Fig. 6. Infectious droplet nuclei filtration efficiency of HVAC filters, Adapted from (Azimi and Stephens, 2013).

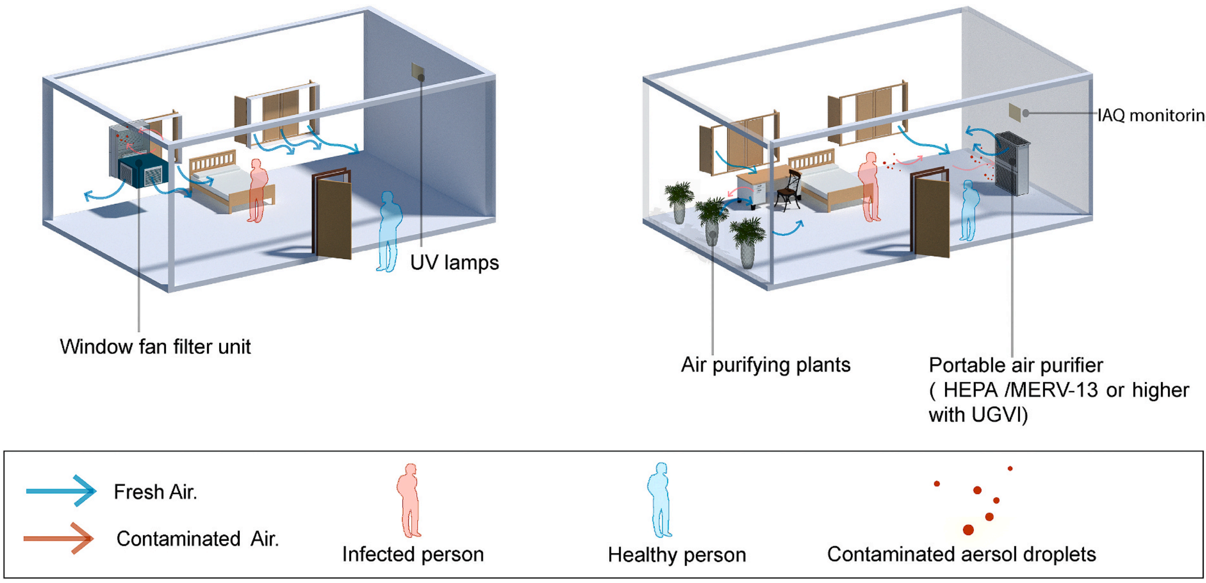


Fig. 7. Purification/filtration strategies to reduce indoor airborne transmission.

3.4. *Other approaches for enhancing IAQ*

Multiple parameters define the IAQ of a space. A robust and holistic system is much needed to identify and monitor these parameters dynamically in indoor spaces to effectively maintain the IAQ, thereby improving the health and well-being of the individuals living inside that space.

Raspberry Pi-based low-cost air quality sensor module was used by Zhang et al. (2021) to propose an IAQ monitoring system to monitor these parameters effectively. The comprehensive custom-made module can measure temperature, relative humidity, $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3, CO_2, and TVOCs in the indoor air. Real-time IAQ monitoring systems in indoor spaces will help in understanding the risk hours and hence will alarm the occupants to take necessary precautions against the transmission. A review study on the role of relative humidity in virus transmission pointed out that, that the probability of airborne spread of SARS-CoV-2 is higher in dry indoor settings ($RH< 40\%$) than in humid conditions ($RH > 90\%$) (Ahlawat et al., 2020) and maintaining relative humidity levels between 50% and 60% could reduce the long-term presence of coronavirus (Jin et al., 2021). Raj et al. (2020) recommended air purification and humidity control check to be made a pre-requisite in all indoor spaces with clean outdoor air supply, thereby decreasing the viral transmission due to rapid respiratory droplet drying. Similarly, Stabile et al. (2021) proposed a unique CO_2 concentration-based feedback control technique for continuously monitoring and adjusting the airing procedure to reduce the possibility of transmission risk inside the classrooms. The author accessed the required air exchange rates for mechanical and naturally ventilated schools in order to minimize the airborne spread of the virus (Stabile et al., 2021). Management of IAQ using an IoT-based indoor garden was evaluated by Kim et al. (2020). An IoT-based IAQ monitoring system was used to collect real-time data on $PM_{2.5}$, CO_2, temperature, and humidity in the study. The investigation of indoor pollutants after the installation of indoor gardens indicated that the installation of plants reduced some of the PM and CO_2 concentrations, which contributed to IAQ improvement and thus lessened the risk of virus transmission.

The intake fraction, which is described as the part of air mass exhaled by the sick individual and subsequently inhaled by the healthy individual, is used to estimate the risk of cross-infection through the air (Bennett et al., 2002). Melikov et al. (2020) inferred that a moderate increase in room volume (in the examined classroom, the volume was increased by raising the ceiling height) reduced the incidence of airborne infection. It was reported that when the room volume is increased by 17% approximately, the intake fraction reduces by 2.8%.

The International Commission on Illumination classifies the UV spectrum into three bands based on their wavelength. UV-C wavelengths range from 200 to 280 nm, UV-B wavelengths range from 280 to 320 nm, and UV-A wavelengths range from 320 to 400 nm (Maverakis et al., 2008). UV-C is the most effective way to kill viruses and is the most common way to disinfect air and surfaces. UV-C can be utilized to limit SARS-CoV-2 viral transmission by inactivating the virus in the air and on surfaces. UV-C radiation is used in germicidal ultraviolet radiation (GUV) and Ultraviolet Germicidal Irradiation (UVGI). Although UV radiation is detrimental to germs and viruses, it is also likely to be hazardous to human skin and eyes as well (Houser, 2020; Raeiszadeh and Adeli, 2020). Integration of UVGI in HVAC systems has been depicted in Fig. 8. The World Health Organization, the ASHRAE, REHVA, and various other studies recommend using UVGI to combat airborne infections such as COVID-19 (ASHRAE, 2020c; Azuma et al., 2020; Kenichi Azuma et al., 2020; Megahed and Ghoneim, 2021; Melikov et al., 2020; Morawska et al., 2020; REHVA, 2020a; Shen et al., 2021).

Sodiq et al. (2021) proposed a novel concept of air circulation through localizing infectious disease to the infected person(s) alone through PV technique, UVGI technique, along with a nonporous air filter in indoor settings(such as airplanes, trains, metros, etc.) to decrease the risk of the viral transmission (Sodiq et al., 2021). The typical VAV-based HVAC system enhances cross-contamination in indoor spaces by recirculating air streams that may contain infectious particles. On the other hand, the Dedicated Outdoor Air System (DOAS), when combined with radiant heating and cooling, substantially lowers the cross-contamination by reducing the path between respiratory particles and return grilles and by adopting a laminar airflow pattern. The conventional approach causes nearly 1.7 times more particles to stay in the room than compared to the DOAS systems (Williams and Rivera, 2021).

Botanical biofilters are activated systems that allow air movement through the plant growth substrate to increase the rate at which the indoor atmospheric environment is exposed to the plant-substrate system components that are active in air pollutant removal (Irga et al., 2017). The system demonstrated removal efficacies of $53.35 \pm 9.73\%$ for TSP, $53.51 \pm 15.99\%$ for PM_{10}, and $48.21 \pm 14.71\%$ for $PM_{2.5}$ at its highest efficient airflow rate. Furthermore, the system's ability to remove VOCs and CO_2 as well as control temperature and humidity places it ahead of many non-biological systems as a simple IAQ improvement system.

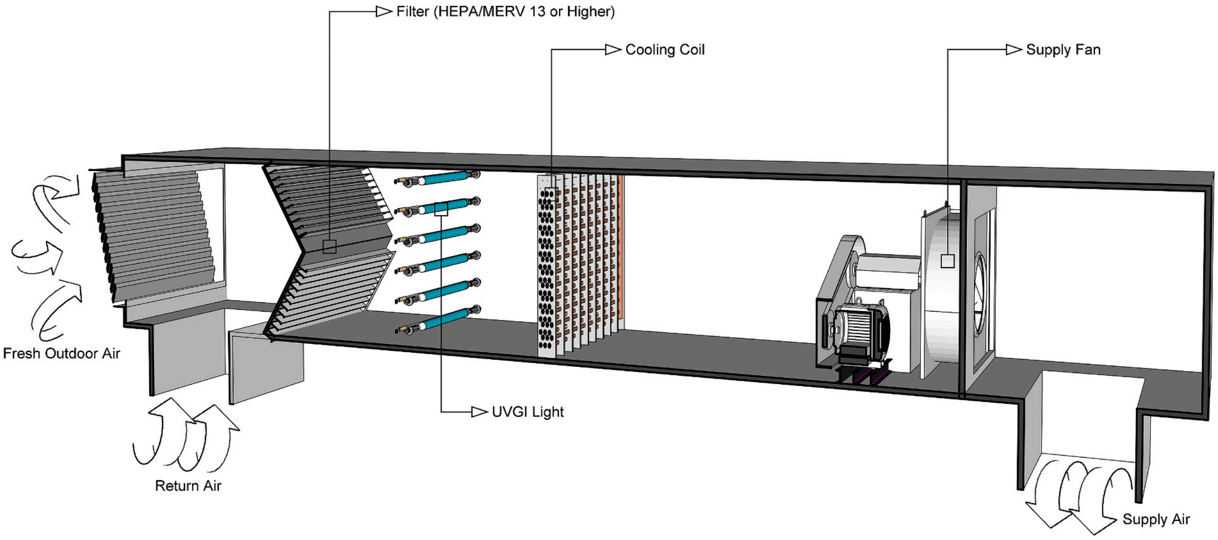


Fig. 8. UVGI and Filter integration in HVAC systems.

Overall, adopting effective ventilation strategies which dilute the indoor contaminants and regulate the airflow patterns in indoor spaces such that the interception of occupants with bioaerosols will be minimal was found to be effective in curbing the transmission. Various ventilation strategies have to be adopted according to the indoor and outdoor context. Air filtration and purification/disinfection using various techniques were found to be effective in reducing the viral load in the air. Air purifiers with disinfection features such as UV will be more effective in combating infectious agents effectively. Recirculating HVAC systems in buildings must incorporate efficient air filtration techniques to curb the infectious agent transmission in indoor air.

In the pre-pandemic era, achieving appropriate thermal comfort in buildings was prioritized over a good IEQ. Regular HVAC systems work by the principle of controlling the fresh air delivery tominimize heating/cooling load of the building and hence result in recirculation of air in indoor spaces. A new concern has arisen due to the spread of SARS-CoV-2, which has necessitated increased IEQ and prioritized ventilation measures to control the disease spread. In this regard, "emergency" ventilation protocols were employed as per the revised guidelines of various international agencies, which have resulted in positive outcomes in terms of IAQ but not in terms of Indoor Environmental Quality IEQ and energy consumption. Several IAQ enhancement techniques (ventilation, air purification/filtration, etc.) can be adopted at various scales, ranging from the entire building to a single room or a space, to personal microenvironments and the breathing zone, with varying performances, but these measures shouldn't increase the building energy usage. Energy efficiency and IAQ must not be mutually exclusive but rather complementary to each other. Efforts should be put forward to ensure that energy efficiency and IEQ interventions are also carried out with IAQ improvement strategies to tackle the current challenges of climate change, global warming, and the ongoing COVID-19 pandemic.

4. Key observations

IAQ improvement strategies can be mainly grouped into three; source control, Ventilation improvement strategies, and Air filtration/purification strategies. The role of fresh air ventilation and air filtration/purification in minimizing the spread of infectious agents has been discussed extensively in the recent literature. The summary of the review has been discussed below.

- A positive correlation between air contaminants such as $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, etc., and incidence rate, mortality rate, and infection risk of the virus has been confirmed by various studies and thus makes the air quality of the environment/built space a critical parameter to be looked upon
- Indoor Environmental Quality parameters, for instance, temperature, humidity also have an influence on the spread of the virus in indoor spaces
- Various other factors, including living conditions, climate, weather, individual health, culture, etc., influence the incidence and spread of infectious agents
- Increasing the supply of fresh outdoor air (through natural, mechanical, or hybrid ventilation) to dilute the air contaminants and avoiding recirculation of indoor contaminated air in indoor spaces can minimize the spread of infectious agents
- Air filtration, using air filters such as MERV 13, HEPA or higher, or an air purifier with an efficient air filtering system can minimize the transmission of infectious agents
- MERV 7 as primary filters, along with the use of MERV 14 as secondary filters, was found to be efficient in removing 98% of airborne particles in the diameter range of 0.3–1.0 μm
- PM2.5 and NO2 has been reported with a higher association with COVID-19 when compared to PM10.
- Special consideration to improve IAQ should be undertaken in policy making and health management especially in areas of high outdoor and indoor pollution, such as urban centres, slums, industrial areas, and low-income settlements.
- Monitoring and controlling the air humidity to prevent pollution diffusion was found to reduce transmission risk
- It is recommended to set the zone temperature at the higher end of the comfort zone, or even an elevated zone setpoint temperature is preferred. However, in the case of elevated zone setpoint temperature, thermal distress should be compensated with elevated air movement.
- In the case of demand-controlled HVAC systems, the CO_2 setpoint should be significantly lowered to maintain significantly higher ventilation (25 cfm per person), and the ventilation should be ON 24/7 irrespective of the occupant's presence/absence.
- Displacement ventilation should be preferred more than a mixed ventilation system, as it reduces the mixing of contaminated air and provides more fresh air in the occupant's breathing zone

- Directional ventilation (airflow direction from fresh zone to contaminated zone) and high air exchange rates between indoors and outdoor could be efficient in minimizing airborne SARS-CoV-2 in indoor spaces
- Ceiling or table fans could be operated in a way that it should not mix the contaminated air with incoming fresh air in hospital/hostel/hotel isolation rooms
- Use UVGI for sterilizing the air/surface. This kind of UV germicidal filter/treatment should be incorporated with HVAC systems and other possible points for the inactivation of viruses in buildings
- Personalized Ventilation is the most preferred system as it directly provides fresh air in the breathing zone

5. Future research directions

The current standards, techniques, and systems focus on ventilation systems that concentrate primarily on thermal comfort parameters. In addition, variable air volume (VAV) based HVAC systems are supposed to control the ratio of fresh outdoor air and recirculated indoor air to maintain the required ventilation and energy efficiency. However, for maximum possible energy efficiency, VAV systems should supply only the ASHRAE 62.1 specified minimum required ventilation which may not be sufficient to reduce the spread of the SARS-CoV-2 virus in confined spaces (Anand et al., 2022). Therefore, theongoing pandemic and threat of future airborne diseases reiterate the need for a novel ventilation strategy/system for built spaces to improve indoor environmental quality (IEQ) without compromising thermal comfort and energy efficiency parameters. Also, studies need to explore and assess feasible IEQ improvement retrofit strategies and their cost-based analysis for various building typologies. Although many studies have been done for offices, schools, and other public spaces, there is a scarcity of studies that assesses multiple strategies to improve IAQ in mechanically ventilated residential spaces (for example: for split air-conditioning systems).

Further studies and developments are required in several areas including, but not limited to;

- Empirical analysis of viral loads and their settling patterns, along with the efficacy of the various measures mentioned in the review, are scarce
- In the past, researchers investigated strategies/technologies which use the application of machine learning, deep learning, and artificial intelligence with IoT-based strategies (smart systems) for improving the IAQ of built spaces. However, the implementation/validation of the same in real buildings is not sufficiently explored.
- There is limited research to conclude the effect of partition walls, temporary screens, and other partition strategies in mitigating the virus spread and on the best material, size, and orientation of the partition walls and their combination with other IAQ improvement strategies
- Studies addressing IAQ and IEQ improvement retrofitting strategies to curb viral transmission and their cost-based analysis are limited
- Risk prediction models which predict the transmission risk in indoor spaces have to be improved and has to be explored more
- Existing guidelines and standards can be further strengthened to improve IAQ/IEQ and optimize energy consumption
- There is a need for novel and holistic technology/building systems which address the ventilation, thermal comfort, and filtration/purification in the built environment
- Studies that empirically establish the influence of parameters such as weather, socio-demographic characteristics, etc., with airborne transmission are limited
- Gender, age-specific, and subgroup analyses studies and association with viral disease spread rates and mortality rates are limited
- More indepth research on the ventilation rates for various building and indoor space typologies.
- There iare limited studies that investigates the energy expenditure with respect to the risk reduction capability of various IAQ improvement strategies

6. Conclusion

Airborne viruses stays infectious in the air for hours, and pollutants such as particulate matter (PM_{10}, $PM_{2.5}$), NO_2, SO_2, CO, O_3, CO_2, TVOC, can enhance the incidence, spread rapidity, and mortality rate of COVID -19 disease. Other environmental parameters such as temperature and humidity were found to have a notable influence on indoor viral transmissions. Thus, maintaining adequate IEQ levels is vital in minimizing the spread of the SARS-CoV-2 virus. However, most of the existing air conditioning and mechanical ventilation systems have limits in maintaining thermal comfort, IEQ, and energy balance at the same time. So, there is a need for a novel ventilation strategy/system for the built spaces to improve the IAQ without compromising thermal comfort and energy efficiency standards. This review paper acts as a guide for post-pandemic building operation, which explores a set of strategies/methods to improve the IAQ of built spaces and thereby minimize the transmission of infectious agents. The identified strategies are context-specific; the application and efficiency of each of them vary according to the circumstances and environmental conditions. Professionals such as architects and civil engineers should select, integrate and implement various sustainable strategies that can enhance IEQ to protect individuals against indoor airborne infectious agents.

Credit author statement

Ajith N Nair: Writing – original draft, Data curation, Methodology, Formal analysis, Visualization; **Prashant Anand:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition; **Abraham George:** Writing – review & editing, Supervision, Funding acquisition; Nilabhra Mondal: Visualization, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Ventilation strategies to improve IEQ and their reported effectiveness.

Reference	Year	Ventilation and associated strategies	Context	Key findings	Notes
(Amoatey et al., 2020; ASHRAE, 2020b; Hayashi et al., 2020; Nembhard et al., 2020; REHVA, 2020a; Santos et al., 2020)	2020	Various fresh air intake ventilation measures	All spaces	• High-intensity fresh air ventilation has been found effective in reducing the viral transmission risk	• Increasing the fresh air ventilation rates using mechanical ventilation results in an increase in energy consumption.
(Blocken et al., 2020; Perazzo et al., 2021; Rajesh and Bhagat, 2020)	2020,2021	Displacement ventilation	Isolation rooms, Hospitals, public buildings, sports centers, small office	• Reduction of cross-contamination and transmission is dependent on the dominant airflow pattern. • Displacement ventilation performs better than normal mixed ventilation in minimizing COVID-19 airborne transmission	Mixed ventilation mixes the contaminated air with the fresh air in the breathing zone thus increases risk of transmission
Li et al. (2021)	2021	Ceiling fan	Experimental setup/ test room	• Employing ceiling fans minimized the cross-infection risk in air-conditioned rooms. • Ceiling fan operation reduced the exposed individual's breathing zone concentrations by more than 20% through increased dispersion of the aerosols. • The increase in fan speed also decreased the average contamination concentration	• The study assumed steady-state transmission and hence didn't consider transient flows. • Tracer gas was used for the study that cannot represent real situations' complex dynamics.
(Li et al., 2013; Shen et al., 2021)	2013,2021	Personalized Ventilation (PV)	All indoor spaces	• The usage of personal ventilation in indoor spaces demonstrated the efficiency of 67% in reducing the infection risk. • Doesn't mix the clean air with the contaminated air	The potential of personalized ventilation systems in COVID-19 pandemic management is huge and under-explored.
Ying et al. (2020)	2020	Adaptive wall-based attachment ventilation	Airborne infection isolation room	• 15–17% reduction in the average contaminant concentration when compared to a ceiling or upper sidewall air supply	
(Afshari et al., 2021; CDC, 2021; Eykelbosh, 2021)	2021	Demand Control Ventilation (DCV)	All spaces	Demand control ventilation based on temperature and occupancy should be turned off	• CO2 concentration setpoint should be lowered enough to maintain adequate indoor ventilation if demand control ventilation is used

Table A2
Various air filtration/Purification strategies to improve IEQ and their reported effectiveness.

Reference	Year	Air Filter/ Purifier	Objective	Context	Efficiency	Notes
(Feng and Cao, 2019)	2019	Electrostatic enhanced pleated air filters (EEPF)	Development of electrostatic enhanced pleated air filters (EEPF).	Experimental setup	Compared to HEPA, ideal EEPF exhibited equivalent filtration effectiveness (>98%) and consumed 70% less energy.	• It improves fabric filter performance without introducing pressure drop by utilizing an external electric field. • The results reveal that duct velocity, applied voltage, and filter type all have an effect on EEPF filtration efficiency.
Lowther et al. (2020)	2020	HEPA Air purifiers *	To assess the effectiveness of HEPA purifiers in eliminating fine and ultrafine particles (UFP).		AP's effectively removed UFPs, removal effectiveness was lowered in the 200 nm–250nm size range.	• Particles in the size range (200–250 nm) present in substantial concentrations in megacities and can successfully penetrate the shells of buildings and remain suspended in the air and pose a risk to human health.
(Afshari et al., 2020; Vervoort et al., 2021)	2020	Electrostatic precipitators	The efficacy of existing ESPs in eliminating pollutants.	Naturally ventilated school courtyard	34.1% reduction in $PM_{2.5}$ concentrations.	
(Azimi and Stephens, 2013)	2013	Multiple Air Filters	Assessing the effect of recirculating HVAC particle filters on the containment of	Hypothetical office space.	• MERV 13–16 filters produced the highest risk reductions at low cost • Medium efficiency filters (MERV 7–11) are cheap but appear to be	The advantage of HEPA over MERV13-16 is very little considering 1.6–2.3 times the cost of operation

(continued on next page)

Table A2 (*continued*)

Reference	Year	Air Filter/ Purifier	Objective	Context	Efficiency	Notes
			size-resolved infectious aerosols		less successful in decreasing infectious disease risks.	
(Curtius et al., 2021) (Cooper et al., 2021)	2021	Mobile air purifiers	• 4 HEPA filter air purifiers were tested for efficiency and practicability • Effect of a commercially available home air purifier on PM2.5 concentrations and perceived IAQ	High school classroom	• Air purifiers quickly, efficiently, and uniformly minimized the concentration of aerosols • 90% reduction in aerosol concentration in less than 30 min (ACH 5.5 h^{-1}). • 45% $PM_{2.5}$ concentrations reduced in bedrooms over 90 min of HAP use.	• Air purifiers with HEPA filters and a high CADR of roughly $1000 m^3/h$ or above must be used. • Uniform mixing and high air exchange rates can be achieved by combining multiple small purifier units.
Fermo et al., (2021)	2021	Commercial air purifier device, HYLA-EST device	HYLA-EST device's ability to minimize aerosol concentration, PM and VOC	4m × 4m × 2.5 m ($40m^3$) apartment room	• 16.8 (90% reduction) and 7.25 times (80% reduction) reduction of PM_{10} and $PM_{2.5}$ concentrations were reported, respectively, corresponding to a reduction of about 90% and 80%. VOC concentrations were also reduced by more than 50%.	• The equipment under test is based on a water-bath filtration mechanism

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