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A critical review of heating, ventilation, and air conditioning (HVAC) systems within the context of a global SARS-CoV-2 epidemic

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ABSTRACT

The Coronavirus disease (COVID-19) has spread over the world, resulting in more than 225 million patients, and 4.7 million deaths in September 2021. It also caused panic and terror, halted numerous activities, and resulted in the world economy deteriorates. It altered human behavior and compelled people to alter their lifestyles to avoid infection. Air conditioning systems are one of the most important sectors that must be considered because of the pandemic SARS-CoV-2 all over the world. Air is used as a heat transfer medium in heating, ventilation, and air conditioning (HVAC) systems. The air contains a variety of pollutants, viruses, and bacteria, all of which have an impact on and destroy human life. Significantly in summer, people spend more time in air conditioners which results in lower levels of vitamin D and melatonin which may affect the functioning of their immune system and are susceptible to receiving SARS-CoV-2 from other individuals. As an important component of air conditioning and ventilation systems, the air filter plays a significant role. As a result, researchers must work harder to improve its design to prevent the ultra-small particles loaded with COVID-19. This paper contributes to the design of existing HVAC systems in terms of their suitability and impact on the spread of the hybrid SARS-CoV-2 epidemic, as well as efforts to obtain a highly efficient air filter to remove super-sized particles for protection against epidemic infection. In addition, important guideline recommendations have been extracted to limit the spread of the SARS-CoV-2 throughout the world and to get the highest quality indoor air in air-conditioned places.

Contents

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Abbreviations

AHU	Air handling unit
A/C	Air conditioning
ASHRAE	American society of heating, refrigeration, and air conditioning engineers
CAR	Chinese association of refrigeration
CDC	Center of disease control and prevention
CHVAC	China heating, ventilation, and air conditioning
COVID-19	Coronavirus disease 2019
CRAA	China refrigeration and air-conditioning industry association
DCV	Demand control ventilation
DOAS	Direct outdoor air supply units
ECDC	European center for disease prevention and control
EEAF	Enhanced electrostatic air filters
EEPF	Enhanced electrostatic pleated filter
ERV	Energy recovery ventilation
ERW	Energy recovery wheels
HRV	Heat recovery ventilation
HIV	Human immunodeficiency virus
HVAC	Heating, ventilation, and air conditioning
HEPA	High-efficiency particulate air
IAQ	Indoor air quality
ISA	Indian consultative society of anesthesiologists
MERV	Minimum efficiency reporting value
OSHA	Occupational safety and health administration
PEF	Peak expiratory flow
PM	Particle matter
PRRSV	Porcine reproductive and respiratory syndrome virus
PS	Population size
REHVA	Federation of European heating, ventilation, and air conditioning associations
RLT	German association of indoor ventilation technologies
SBS	Sick building syndrome
SHASE	Society of heating, air conditioning and sanitary engineering in Japan
SNAF	Silk nanofibrous air filter
TVOC	Total volatile organic compound
UVGI	Ultraviolet germicidal irradiation
WHO	World health organization

1. Introduction

The COVID-19 pandemic is regarded as one of the most catastrophic disasters to have struck the world in the last two decades, as it has infected and killed many people while also putting the global economy in a state of stagnation and limiting many activities. The World Health Organization recently declared COVID-19 a global epidemic on March 11, 2020, following its spread and outbreak in late 2019 from Wuhan, China. As a result, the World Health Organization has declared the highest level of global readiness and imposed challenges and restrictions to prevent the spread of COVID-19 infection. The sources and reasons for the COVID-19 virus's spread varied, and the definite reasons for transmitting and spreading the virus have yet to be identified. The rapid spread of the Coronavirus has resulted in the suspension of many industrial, commercial, and agricultural activities, as well as many investment activities, causing the global economy to deteriorate. Fig. 1 offers the distribution of confirmed cases of COVID-19 globally as of week 35-2021.

There are currently numerous trials underway for treatment, drug, or vaccine to halt the spread of COVID-19 as a result, it is possible to follow preventive measures such as social distancing, quarantine, and hand washing, particularly in outdoor environments where the virus is present. The most important guidelines demonstrated that atmospheric aerosol is made up of dispersed solid or liquid particles suspended in the air in a relatively closed environment. According to World Health Organization statistics, 4.6 million people die each year from diseases caused by poor air quality (Cohen et al., 2017). As a result, poor air quality contributes to an increase in the number of deaths each year (European Environment Agency). Particles in the form of industrial dust particles, dust particles, car emission particles, bacteria, microorganisms (viruses), and other suspended pollutants are present in the air. The aerosol is dispersed infected droplets via infected patients and becomes bio-aerosols, which act as an epidemic vector (Adhikari et al., 2019).

Although the particles in a bioaerosol range in size from 0.3 to 100 µm, the respirable size fraction of 1–10 µm is of primary concern (Tindale et al., 2020). However, the aerosol can travel hundreds of meters or more, allowing viruses to be carried and transmitted (Kulkarni et al., 2016). The prevalence of COVID-19 on September 08, 2021, is depicted in Fig. 2 (data collected by the European Center for Disease Control and Prevention) (Elza et al., 2020; Ali and Alharbi, 2020; Lidia and Junji, 2020a; Damia, 2020). Coronavirus particles have a spherical shape with an average diameter of approximately 120–160 µm and a surface with an average diameter of 20 µm.

The Coronavirus (COVID-19) particles have club or petal-shaped surface projections (peplomers or spikes). A schematic outline of COVID-19 like particle production is shown in Fig. 3.

Fig. 4 depicts the size of coronavirus in comparison to others (Changotra et al., 2021). According to research (Elza et al., 2020), SARS-CoV-2 can survive in the air for hours and varies depending on air temperature and humidity, as well as on surfaces for several days, with the average lifespan of coronavirus as aerosol particles being around an hour. SARS-CoV-2 can survive for up to 72 h on plastic and stainless steel, 24 h on cardboard, and up to 4 h on copper, according to laboratory testing (Elza et al., 2020).

Estimates show that the sequence interval for COVID-19 is 4–6 days, which is 95% shorter than the average incubation period of the epidemic virus and confirms that secondary transmission may occur before the onset of the disease and its symptoms (Nishiura et al., 2020).

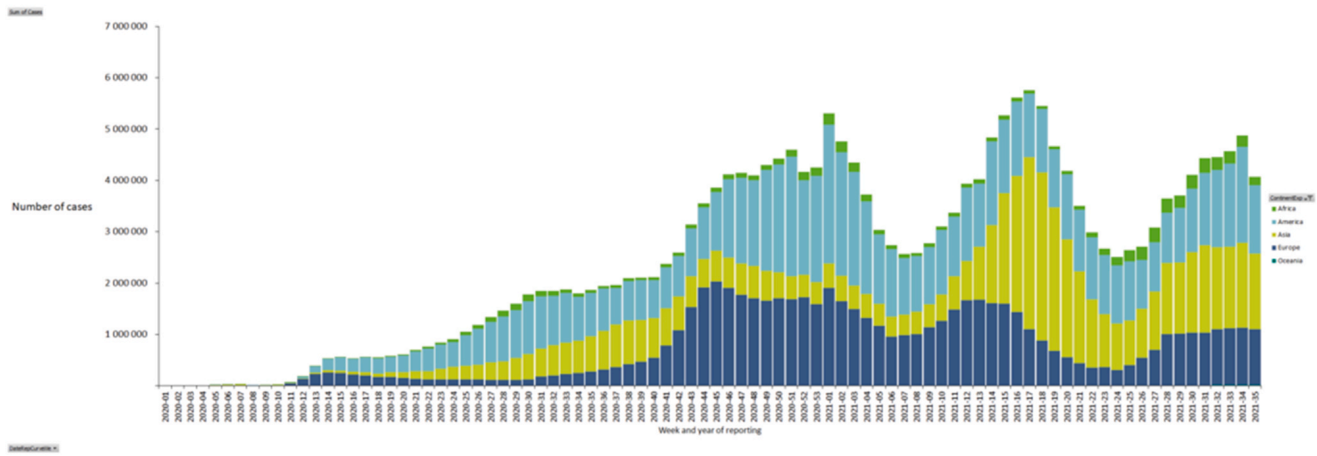


Fig. 1. Distribution of confirmed cases of COVID-19 globally.

The design of a heating, ventilation, and air conditioning (HVAC) system is critical to achieving optimal air quality and comfort. This is referred to as air quality, and it is necessary to achieve a balance between thermal comfort and air quality in healthcare facilities to improve IAQ. However, the process of transporting outside air through air conditioning systems and treating it with fine filters is not always 100% efficient. As a result, there is a chance that some microscopic particles will escape into the treated air and infect the population with the COVID-19 viruses. This necessitates reviewing the cycle and path of these devices, as well as designing their components to ensure virus-free air. Air conditioning systems contain critical components that may aid in virus transmission and must be updated, such as air handling units, filters, transmission channels, and fans. This paper identifies and discusses the current situation to identify the factors that influence indoor air quality and assess its effects in light of the Corona global pandemic (COVID-19). Furthermore, the study includes an assessment of the current state of the air conditioning devices, as well as determining future requirements and expectations, as well as the challenges that must be corrected and their compatibility with the emerging pandemic. The

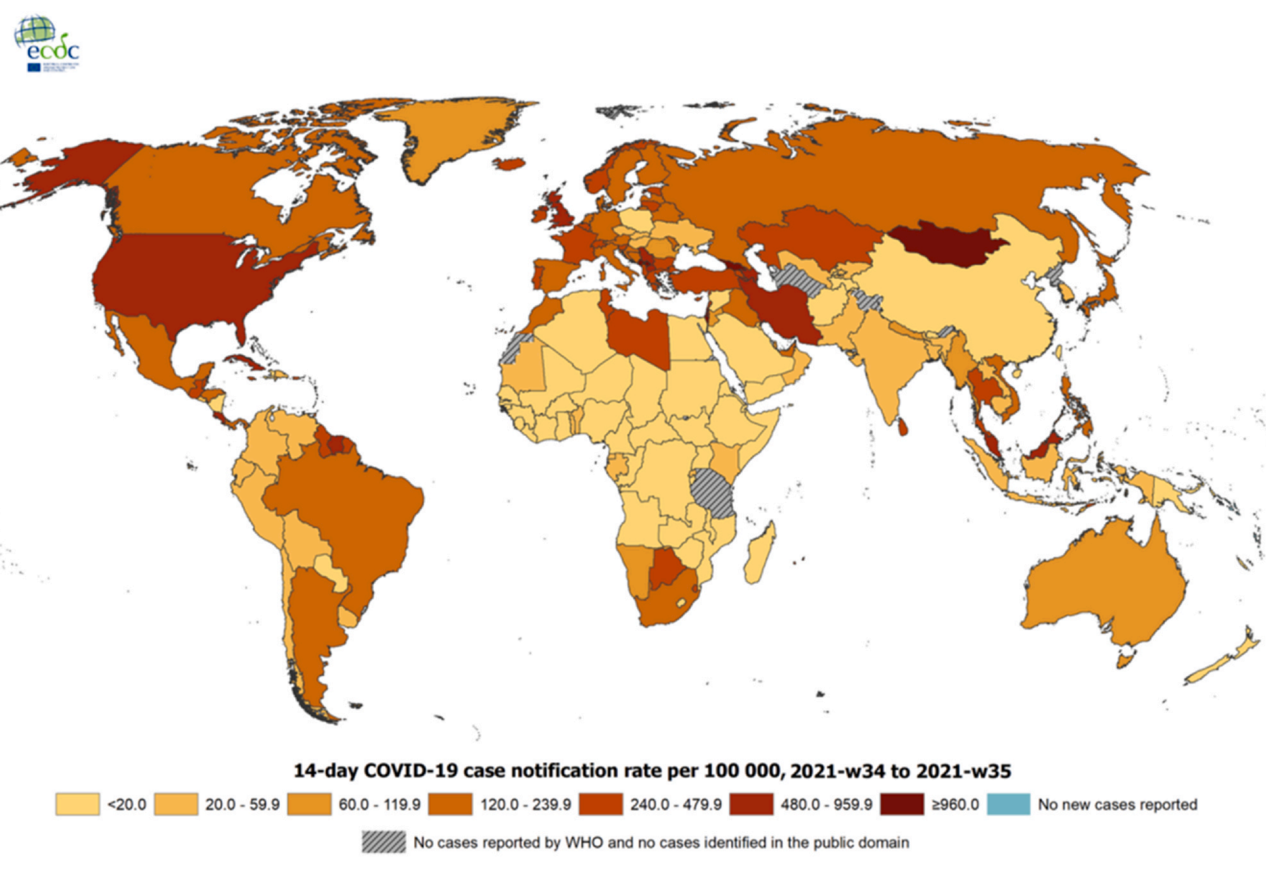


Fig. 2. Prevalence of SARS-CoV-2 on September 08, 2021 (European CDC) (Elza et al., 2020; Ali and Alharbi, 2020; Lidia and Junji, 2020a; Damia, 2020).

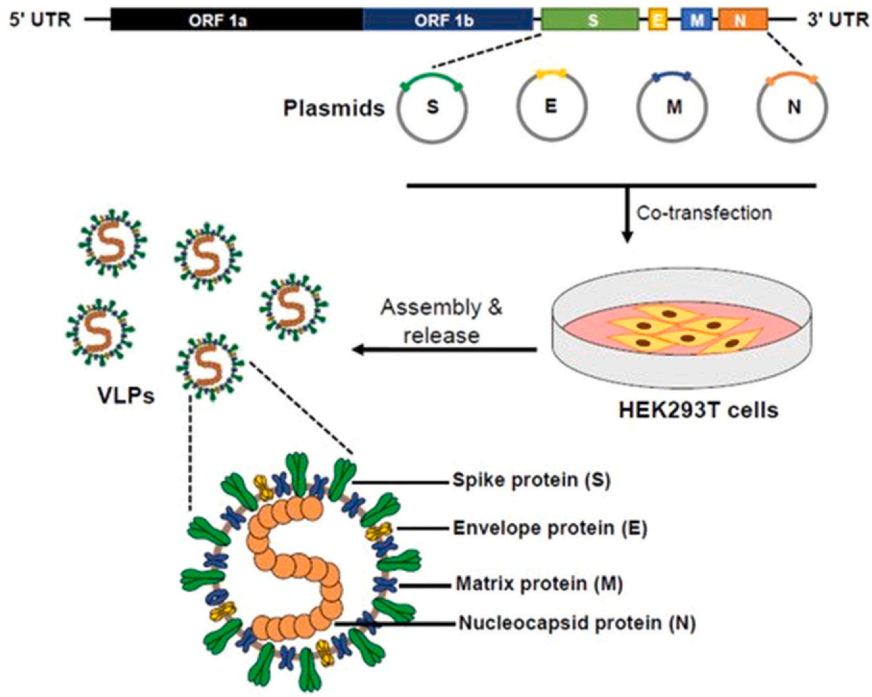


Fig. 3. Sketch outline of COVID-19 like particle production (Kumar et al., 2021).

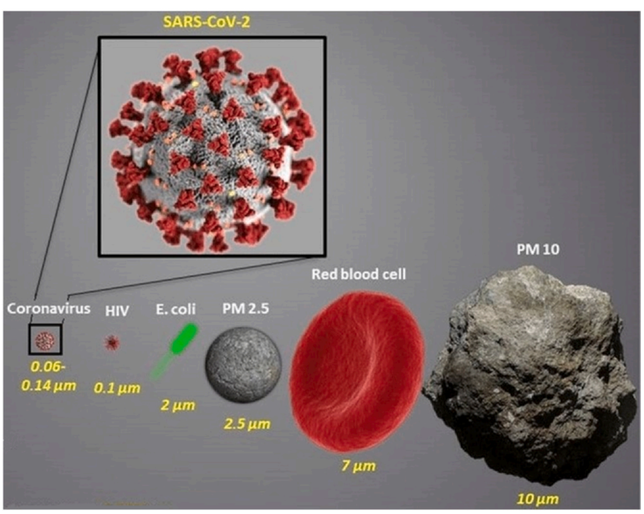
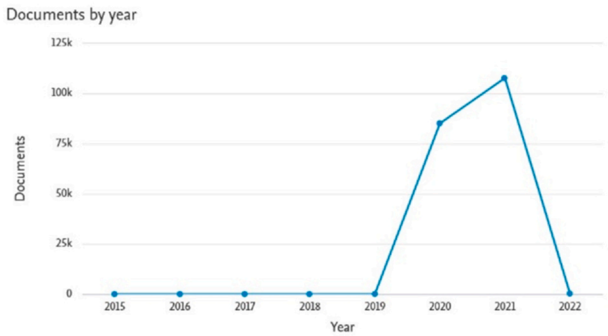


Fig. 4. Size of SARS-CoV-2 in comparison to others (Changotra et al., 2021).

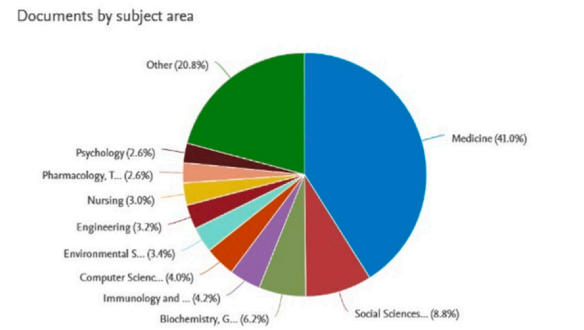
importance of various types of air conditioners is evident in many applications (Elsaid, 2020a), particularly in hospitals. On the other hand, given the spread of the coronavirus's global pandemic, it is critical to study the subject from multiple perspectives. Furthermore, the current study is related to the investigation by reviewing previous literature to assess the impact of important elements that group factors as variables with the prevalence and death rate of the global coronavirus epidemic and its relationship to air conditioners and air filters. These factors include the effect of air pollution on the prevalence of people infected with the coronavirus epidemic, the effect of airborne particles as a vector for infection with COVID-19. The effect of medium-temperature and humidity climatic conditions on the prevalence of those affected by the global epidemic is also investigated. For the first time, the study examines the mechanisms and current air-conditioning systems, as well as their relationship to the global pandemic prevalence rate. It proposes methods for correcting their positions to limit pandemic spread and focuses on the quality of air filters that are suitable for limiting the pandemic spread in isolation rooms, hospitals, and other applications.

2. Review methodology

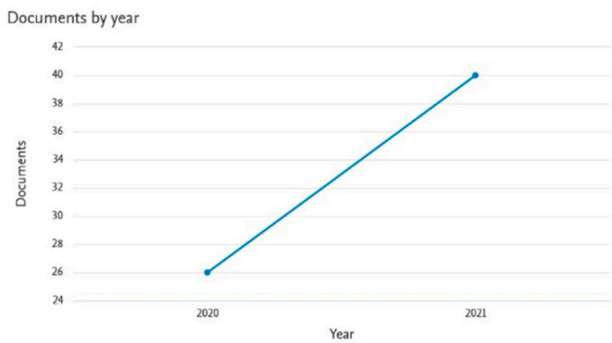
The review methodology for the current research work is based on the use of the interfaces of the most famous search engines by Elsevier and SCOPUS research service tools. In the beginning, the SCOPUS search service is used for articles using the search word "COVID-19" during the period from 2015 to 2022 CE, which showed that the research that concerned the study of the COVID-19 epidemic began incrementally since 2019 until it reached 90,000 articles during 2020 and in 2021 reached to 110,000 articles as illustrated in Fig. 5a. There is a steady increase in related research, which Fig. 5b depicts that most of these research articles are directed to the medical academic side by approximately 41%, while the environmental and engineering side with rates of 3.4% and 3.2%, respectively such as the subject of the present research. This statistic didn't specify the actual number of research articles that were covered the current research work topic, and that is why the word "COVID-19 + HVAC" was used on the same interface as SCOPUS. The results of the research announced that with the query with the specified keyword of "COVID-19 + HVAC", there were 26 research works in 2020 that dealt with the relationship of COVID-19 to HVAC systems, while during the year 2021 a few research articles boosted and reached up to 40 research papers as displayed in Fig. 5c. With the allocation of the distribution ratios of these numbers with the subject area using a keyword of "COVID-19 + HVAC", it turns out that the most percentages are directed to environmental research articles by 23.3% and the engineering research articles by 21.7%, as shown by the announced statistic in Fig. 5d. Moreover, by utilizing the Elsevier



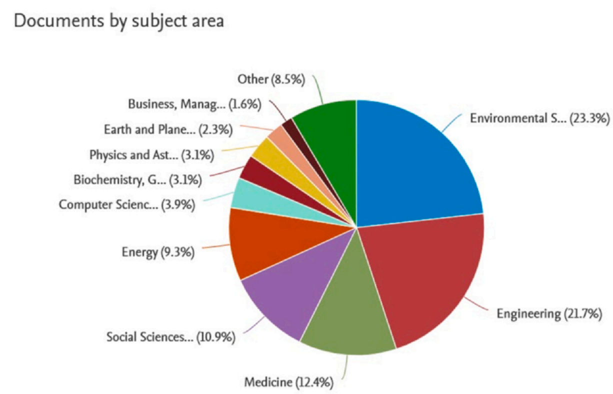
(a) SCOPUS tool search results of number of documents by year using a keyword of "COVID-19".



(b) SCOPUS tool search results of documents by subject area using a keyword of "COVID-19".



(c) SCOPUS tool search results of number of documents by year using a keyword of "COVID-19-HVAC".



(d) SCOPUS tool search results of documents by subject area using a keyword of "COVID-19-HVAC".

(e) Keyphrases search tool of Elsevier on most related topic.

Fig. 5. Review methods by search tools on SCOPUS and Elsevier interface. (a) SCOPUS tool search results of number of documents by year using a keyword of "COVID-19". (b) SCOPUS tool search results of documents by subject area using a keyword of "COVID-19". (c) SCOPUS tool search results of number of documents by year using a keyword of "COVID-19-HVAC". (d) SCOPUS tool search results of documents by subject area using a keyword of "COVID-19-HVAC". (e) Keyphrases search tool of Elsevier on most related topic.

search service interface, for the top 50 most relevant keyphrases, based on 38 relevant publications as manifested in Fig. 5e. The different search service interfaces present as manifested in Fig. 5 that there is a research gap and a search opacity to guide and confront the global COVID-19 epidemic which is threatening humanity especially with HVAC systems.

Accordingly, the relationship between COVID-19 and HVAC systems should be determined well. The scientists should publish in

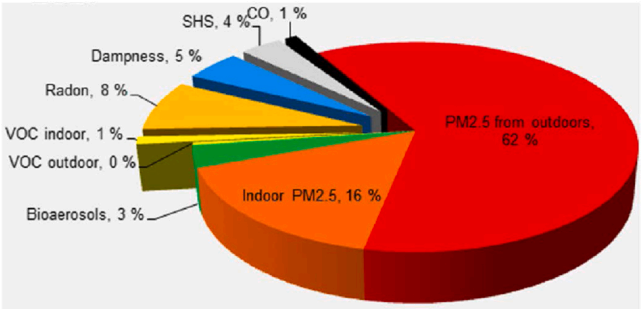


Fig. 6. Burden of disease due to indoor pollution (Asikainen et al., 2016).

this region where there is an academic lack of information provided to reach the best solutions to limit and eliminate the spread of the global COVID-19 epidemic. The current research deals in detail with air pollutants, ventilation, temperature and humidity and their impact on the spread of the COVID-19, through world and recommendations to limit the spread of COVID-19.

3. Air pollution and its relationship to COVID-19

3.1. Sources of indoor air pollution

Individuals spend their time for a long time in their homes, schools, workplaces, and workshop. This certainly works to increase the concentration of pollutants by accumulating pollutants generated inside buildings throughout the day.

Since indoor air pollution is a mixture of untreated outdoor air with indoor sources, there is some overlap between the health effects of indoor and outdoor air pollution. However, because of the unique indoor pollution sources combined with the significant amount of time spent indoors, there is a separate burden of disease as depicted in Fig. 6 attributable to indoor air pollution sources, which is estimated to be over 700,000 years of healthy life lost within the European Union (Asikainen et al., 2016). This burden is exacerbated in low-resource settings (e.g., low- and middle-income countries), where higher absolute levels of exposure and poorer health infrastructure compound the effect.

Fig. 7 shows a schematic for the different types of pollutants that may be generated inside buildings. These pollutants may have caused a variety of health problems in varying degrees as well as help in the spreading of COVID-19.

3.2. Air pollution and its impact on the spread of COVID-19

There is growing concern that air pollution is contributing to the COVID-19 pandemic (Ali and Islam, 2020; Comunian et al., 2020). Air pollution is considered one of the millennium's most pressing issues, with some early research indicating a link between air pollution and virus spread. As a result, determining the role of atmospheric particles in virus spread, disease, and death is critical. Covid-19 can be transmitted via air, and atmospheric particulate matter (PM) can create an environment conducive to virus transmission over greater

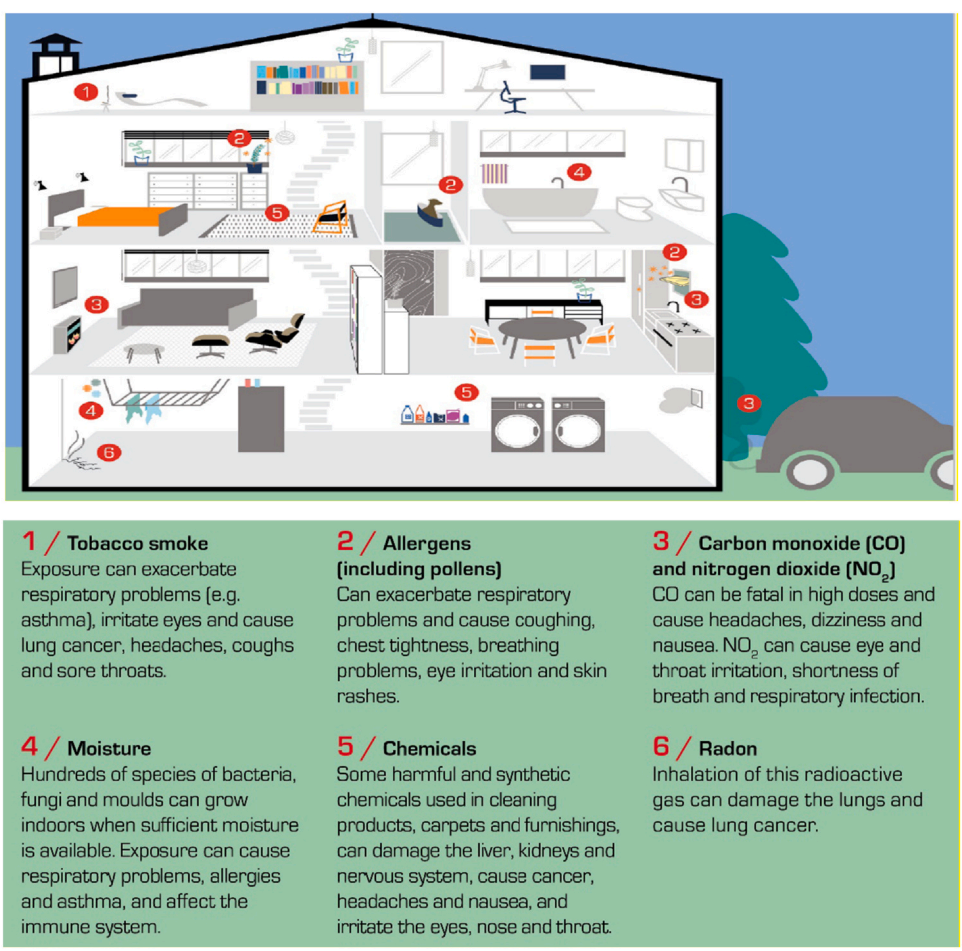


Fig. 7. A schematic of the different types of the pollutants generated inside buildings (Asikainen et al., 2016).

distances than those considered for close contact (Mostafa et al., 2021; Mele et al., 2021).

COVID-19 spreads through airborne particles and droplets. Infected people with COVID can expel particles and droplets of respiratory fluid containing the SARS CoV-2 virus into the air when they breathe normally, talk, sing, exercise, cough, or sneeze. Droplets, or aerosol particles, range in size from visible to microscopic. Droplets are divided into two types: those larger than 5–10 µm in diameter and known as respiratory droplets, and those smaller than 5 µm in diameter and known as aerosols, which stay airborne for an extended period (Bhagat et al. 2020). These droplets transport the virus and spread infection. Indoors, very fine droplets and particles will continue to spread through the air and can build up (Bhagat et al., 2020). COVID-19 can be transmitted by inhaling the virus from more than one and a half meters. Particles from an infected person can spread throughout a room or to an indoor location. Particles can also remain in the air after a person leaves a room, and in some cases can remain airborne for hours. Spread can also occur through contact with contaminated surfaces, though this route is now thought to be less likely. The data available so far indicate that indoor transmission of the virus far outstrips outdoor transmission, possibly due to longer exposure times and the decreased turbulence levels (and therefore dispersion) found indoors. The data obtained to date reveal that indoor transmission of the virus far outweighs outdoor transmission, probably due to the longer exposure times and lower levels of disturbance present indoors. An aerosol is a multiphase system composed of the atmosphere with suspended solid and liquid particles, which can carry toxic and harmful substances, especially liquid ingredients (Cao et al., 2021). Cao et al. (2021) have been researching aerosol transmission as a SARS-CoV-2 transmission pathway, as well as aerosol pollution reduction because of the COVID-19 lockdown. Human-exhaled aerosol transmission is a direct spread of SARS-CoV-2, whereas ambient aerosol transmission is an indirect spread of the virus in which the aerosol acts as a carrier. One approach is that ambient aerosols act as virus vectors indirectly; the second approach is that ambient aerosols can stimulate the expression of SARS-CoV-2 receptor and protease and increase the binding site of SARS-CoV-2, thus increasing the morbidity and mortality of COVID-19. The association between aerosol and COVID-19 can be categories as manifested in Fig. 8. The first is that SARS-CoV-2 spreads via aerosol, and the second is that aerosol pollution decreased during COVID-19 lockdown (Cao et al., 2021).

Finally, lockdown indicated many benefits that were positively reflected in reduced air pollution. It is expressed as NOx emission reductions ranging from 20% to 77% and reductions ranging from 16% to 60% in various cities. Emissions of carbon dioxide have also been reduced by 5–10%. Also, it was found that the global level of particulate matter has decreased by 9–200%, and the decrease in CO

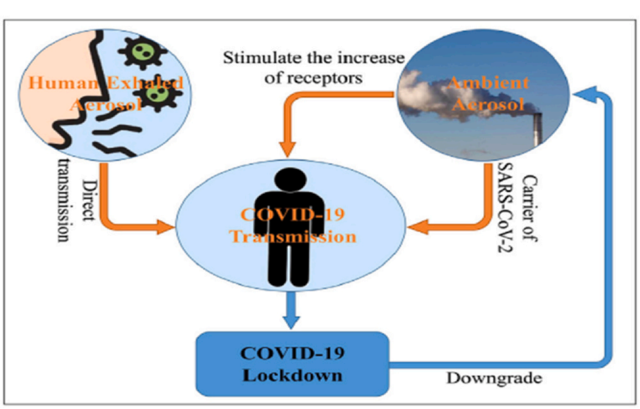


Fig. 8. The relationship between aerosol and SARS-CoV-2 (Cao et al., 2021).

levels followed a like tendency, with the reduction level being between 30% and 60% due to the reduction in the use of fossil fuels (Mousazadeh et al., 2021; Granella et al., 2021; Urrutia-Pereiraa et al., 2020; Ghosh and Ghosh, 2020; Sannigrahi et al., 2021).

4. The role of HVAC systems in the spread of COVID-19

In light of the wave of the spread of the COVID-19 epidemic around the world, starting from its source in Wuhan, China, which quickly dispersed to the whole world due to the lack of full awareness of the characteristics of the COVID-19 epidemic, and therefore the lack of safe preparedness from countries, especially developing countries, and accordingly, an epidemic spread at an accelerating rate between countries, during which the World Health Organization (WHO) announced the lifting of the world's highest state of readiness (Musselwhite et al., 2021). The lack of information and the many errors were the cause of the rapid and turbulent increase in the spread of the epidemic among humans and the increase in the number of deaths (Dargahi et al., 2021). Due to the lack of understanding of the world population of what is happening and the lack of guidance by deliberate scientific decisions, the state of terror from the officials in the countries led to the complete closure as the only solution to the slow rate of the spread of the COVID-19 epidemic, such as China, Italy, USA, KSA, United Kingdom, France, Poland, India, Jordan, Germany, Israel, Canada, Brazil, Belgium, etc (Malekshoar et al., 2021). The characteristics of the COVID-19, due to its survival for hours and days, threaten humanity from the continuity of the transmission of the epidemic. The following Fig. 9 shows the hours of the spread of the COVID-19 epidemic for different materials (Fathizadeh et al., 2020).

Many researchers differed, and some questioned the possibility of the spread of the deadly COVID-19 epidemic through different HVAC systems, but it was due to the lack of information and the lack of a definitive answer to doubt (Morawska et al., 2020; Tang et al., 2021), which motivated the research team to complete the current research work to cover this research gap. In the next part, a review of previous studies was conducted to answer the questions that come to the minds of many, do the different HVAC systems in their current situation contribute to the spread of the COVID-19 epidemic? If so, what are the HVAC modifications required for reducing the rate of spread of the COVID-19 epidemic globally? Francesco Chirico et al. (2020) introduced a review study to evaluate the SARS-CoV-2 risk with the use of air conditioning systems. Sufficient evidence of the airborne transmission of SARS-CoV-2 in previous Asian outbreaks, that considered in the guidelines released by organizations and international agencies for controlling the spread of COVID-19 in indoor environments. The main conclusion of the review suggested that great variability in the viral load in patients, makes it necessary to adapt the safety of the HVAC systems to the specific control needs.

4.1. Do current HVAC systems achieve the requirement to reduce the spreading of COVID-19?

In this section, we introduce and discuss a frequently asked question scientists are trying to respond univocally. A frequently asked question, scientists are trying to answer unequivocally. Relying on what has been proven about the survival of the small droplets suspended in the air for hours, the possibility of transmission of infection is possible, whether in an open place, or even closed area, especially with the movement of air circulation from one room to another in the event of the presence of injured, until this moment the World Health Organization has not cut its opinion on command. Therefore, this topic has two directions, the first is that any virus is affected by multiple factors, including: temperature, air humidity, and air pollution. As from the previous paragraph, it was extracted that the infection is transmitted through droplets, or surfaces

Fig. 9. Approximate periods of survival of the COVID-19 on different surfaces (Fathizadeh et al., 2020).

contaminated with it in the air, and the air transmits it to healthy individuals, the COVID-19 is transmitted through contaminated people or surfaces. Moreover, if any person is in a group, in front of a post office, or in a queue, and the temperature is high, and this person sneezes, and the spray spreads to those around him, infection by COVID-19 will occur, and if this happens in a closed place, such as a supermarket, infection is also possible. It is certainly possible that the SARS-CoV-2 virus is airborne like its closely related predecessor, SARS-CoV-1. This is supported by several retrospective studies revealing the transmission pathway of SARS-CoV-1 in Prince of Wales Hospital, Hong Kong (Li et al., 2005). It is therefore of concern that it exacerbates the transmission of SARS-CoV-2 in the summer months and continues for a long time. This situation is particularly relevant for warmer countries such as those in Southeast Asia and the Middle East and North Africa (MENA) region. Notably, in the summer, (1) people spend more time indoors in air conditioners which results in lower levels of vitamin D and melatonin, which may affect the functioning of their immune system, (2) and when they are close to other people, it can increase chances of spreading new pathogens such as SARS-CoV-2 to other individuals (Siddiqui and Khan, 2020). As for the other part of the question, there is an urgent need to determine the prevalence of SARS-CoV-2 in air conditioning systems in public schools, hospitals, shopping malls, mosques, public places, etc. If we know and understand the dimensions of the problem and its causes, we will have the opportunity to enhance our ability to rationally develop therapeutic and diagnostic interventions, and preventive measures, as well as to improve existing air conditioning systems with preventive measures to limit the spread of the epidemic. All HVAC systems rely on the use of air as a medium for heat exchange between them and the place to be conditioned, and therefore air is considered a carrier medium for microbes, pollutants, and viruses (Souza et al., 2020). All sites and inhabited places with their occupants that are not air-conditioned cause heat stress that leads to feelings of discomfort and a sense of difficulty coexisting in this climate and this may affect the degree of their activity, health, and immunity, and thus reduce resistance to infection with the COVID-19 and similar viruses. Opinions differ on whether air as a heat exchange medium between HVAC systems and the air-conditioned place is a vector of the deadly epidemic of the COVID-19. The HVAC systems work to create the climatic conditions that make the occupants of the air-conditioned place feel thermal comfort (ASHRAE). HVAC systems create suitable conditions according to the type of application by controlling air temperature, air velocity, air humidity, air distribution, and air purity (Mouchtouri et al., 2020a). The Indian Consultative Society of Anesthesiologists (ICSA) announced that infection with the COVID-19 is transmitted from an infected patient to a healthy person through the ambient air and recommend the application of strict measures to isolate those infected with the epidemic COVID-19 (Global Burden of Disease Collaborative Network, 2018). Lee (2020) estimated the minimum respiratory particle size that could include SARS-CoV-2 to be about 4.7 μm. The official reports of the World Health Organization (WHO) announced that virions through airborne transmission in droplet nuclei with a particle size of < 5 μm can be present for long periods of time, with travel distances > 1 m (WHO, 2020a). Accordingly, the transmission of particles < 5 μm through the airborne leads to a certain possibility of the spread of COVID-19 through the air for several hours (Cook, 2020; Brosseau, 2020; Eikenberry et al., 2020). The World Health Organization has recently suggested that airborne transmission of SARS-CoV-2 can occur in special conditions such as "cardiopulmonary resuscitation (CPR), intubation, bronchoscopy, open suctioning, positive pressure ventilation, high flow nasal cannula (HFNC), and manual ventilation prior before intubation," which in these cases may create an aerosol (Zhu et al., 2020; Friedlander, 2020; Li et al., 2020). Cokia (Gralton et al., 2011) highlighted some of the geo-environmental determinants at the level of 55 Italian provinces to identify the causes of the accelerated spread of COVID-19 that raised the level of infection and mortality while proposing a strategy to deal with the epidemiological threats of viral infection. The results of extensive statistical studies showed that the wide spread of COVID-19 in northern Italy is related to the air carrying the virus. In addition, cities where air pollution increases with a viral infection, have a very high risk of 300% for transmission of infection from patients with a viral infection to a healthy person. They attributed the reasons for the mutation of COVID-19 during airborne transmission and transmission to humans, causing a viral infection through contaminated droplets and increasing the speed of transmission from an infected patient to another healthy person. The research suggested that the viral infection of COVID-19 occurs a complex interaction between air pollution and meteorological conditions, the biological characteristics of the viral infection, and the health level of people (habits, immune system, age, gender. etc.). Cornelius et al. (Centers for Disease Control and Prevention) codified an important note in tracking the spread of the epidemic through a note by a medical team escorting a Boeing 737, regional jet, Learjet 35, and air-conditioned. The plane is boarding an evacuation of American citizens from the source of the epidemic in Wuhan, China, to secure their exit from the source of the COVID-19 epidemic. After conducting a comprehensive examination of all American passengers and separating those who tested positive for the virus into healthy and non-positive individuals, all the plane's occupants are now very safe. Within a short period and through continuous follow-up throughout the flight, it was found that American citizens on board the flight had been infected despite the procedures for separation and strict quarantine. During which, it was announced that the air was a carrier of the virus and that the epidemic had spread to healthy individuals through the air conditioning ducts that transmitted the virus between members of the plane. Malhotra et al. (2020) confirmed that one of the ways of transmission of COVID-19 from infected individuals is due to aerosol droplets in the air as a heat transfer medium by people with COVID-19. The US Centers for Disease Control and Prevention (CDC) (Liew et al., 2020) also recommended separating isolation rooms for patients infected with respiratory viruses from airborne infections who are undergoing treatment procedures. Therefore, they recommended that the isolation rooms for the injured should be of negative pressure to prevent microorganisms from escaping through the corridors, and thus ease the spread and transmission of infection among everyone. When SARS spread in Hong Kong (Brian et al., 2020) and Singapore (Tan et al., 2020) and spread quickly with the same frequency as the COVID-19, United Christian Hospital shifted the roles of isolating people with COVID-19 in the hospital from positive air pressure to negative pressure for patients with a viral infection, thus reducing the number of patients infected with SARS. Exhaust air fans are also attached to high-efficiency micro air filters with windows. Indeed, the experiment succeeded in reducing the spread of the airborne epidemic and using high-efficiency particulate air filters to remove 99% of fine air matter because the air change rate is approximately 25 times per hour (Phoon et al., 2019). Delikhoon et al. (2021) reviewed the related articles to exactly evaluate the SARS-CoV-2 transmission and the effects of negative pressure ventilation, air conditioning system, and related protection approaches of this virus. The predicted results through the whole review manifested that the airborne transmission of COVID-19 can be bounded indoors with sufficient ventilation through occupied rooms, by routine disinfection of toilets, using negative pressure, using face masks, and maintaining social distancing. V. Antony Aroul Raj et al. (2020) explored, through statistical studies of available data for several regions and cities in India, that the rates of infection with the COVID-19 increase in frequency and accelerate the spread of the virus in cold and dry conditions as seen in Fig. 10.

Li et al. (2007) studied the relationship between ventilation techniques and bioaerosol. Adequate ventilation rates from outside fresh air for hospital buildings have been recommended to regulate

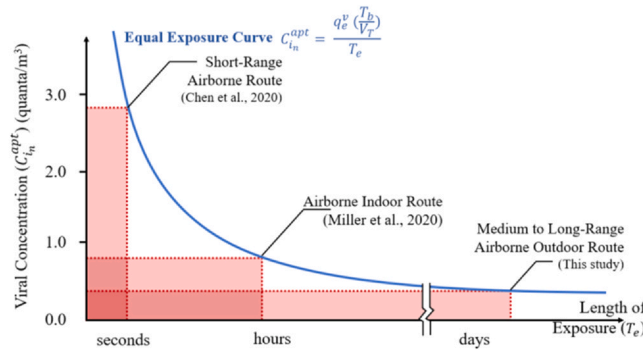
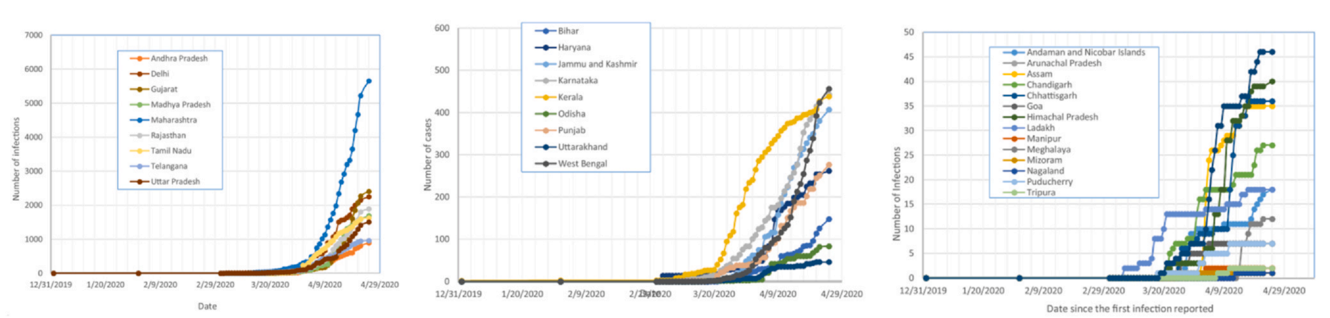


Fig. 11. Patterns of COVID-19 transmission (Huang et al., 2021).

bioaerosol levels to a considerable degree (Li et al., 2007). Many hospitals have conventional ventilation systems that move air from patient areas to remaining circulatory areas. Jagriti Saini et al. (2021) contributed to define the relationship between the COVID-19 pandemic, public health, and indoor air quality. The authors recommended that the must be monitored indoor air quality through trusted systems for hospitals, schools, offices, and homes for enhanced health, well-being and limit the COVID-19 transmission. The following research article by Huang et al. (2021) described the possibility of airborne transmission of COVID-19 in the outdoor air between neighboring apartments in densely populated cities in Hong Kong using CFD and ATOR simulation software. The purpose of this paper was to identify airborne pathogens, natural decay, outdoor dispersal, apartment entry, and inhalation exposure of susceptible persons in adjacent apartments. The results indicated that the COVID-19 epidemic could recede if the quantitative emission rate from the primary patient was less than 30 q/hr. Fan-assistant natural ventilation increased the risk of contracting the deadly COVID-19 epidemic. The airborne transmission of COVID-19 via the outdoor route could be a significant risk for residents in high-density cities. The viral exposure, a function of viral concentration, length of exposure, and pulmonary ventilation rate are expressed by equation in Fig. 11. The constant one quantum exposure is shown in the rectangular hyperbola curve. Exposure to a low viral concentration for a long period of time, in the order of days such as it, may occur in a high-density residential neighborhood, can equate a short exposure to a high viral concentration as it was reported in studies on short-range airborne route (Chen et al., 2020) and airborne indoor route transmission (Miller et al., 2020).

Several attempts to research reviews of many studies to specifically determine the rate of airborne transmission of the COVID-19 and its spread behaviors between communities (Borges et al., 2021; Rahmani et al., 2020; Aghalari et al., 2021). Several scientific research works were reached 25 research papers to reveal the extent



(a) High rate of spread. (b) Medium rate of spread. (c) Low rate of spread.

Fig. 10. Frequency rates of COVID-19 spreading of Indian states (Antony Aroul Raj et al., 2020). (a) High rate of spread. (b) Medium rate of spread. (c) Low rate of spread.

Table 1
Summarized report about infected cases and sampling data (Rodríguez et al., 2021).

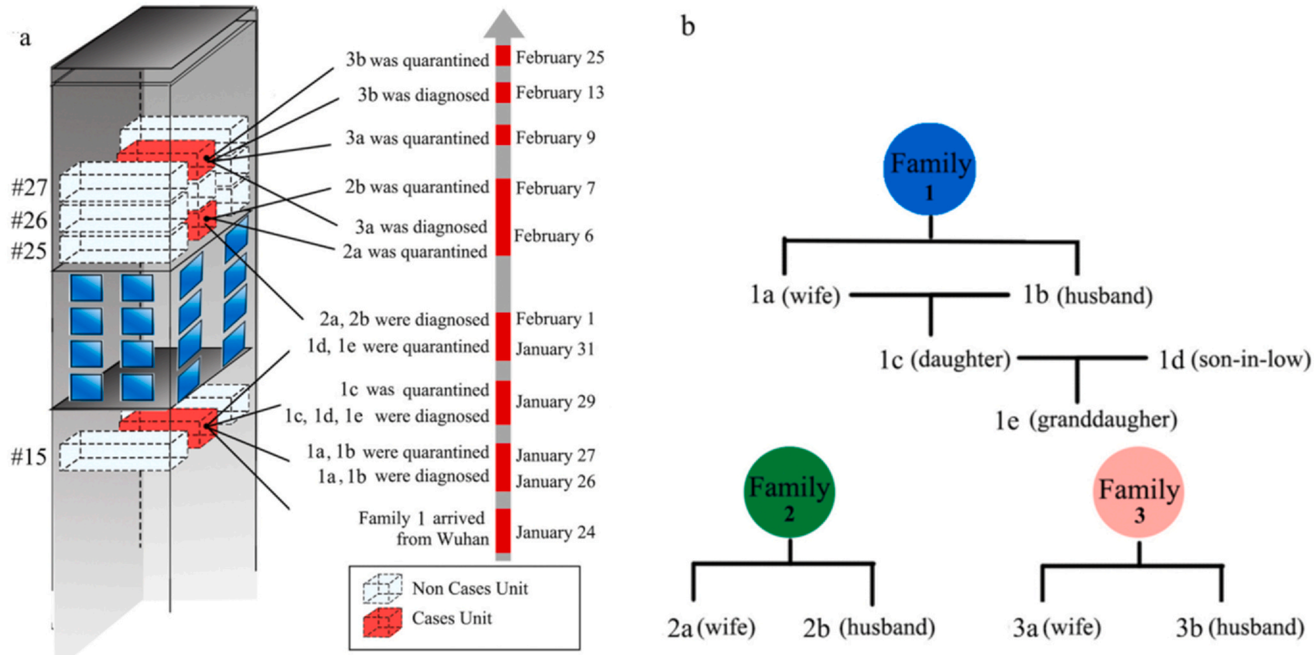
Room	Age	Air sampling	Surface sampling	Symptoms in sampling day	Severity of the illness[a]	Diagnosis by PCR test	Days[b]	Use of PAC	Room size (m^2)	T (°C)	R.H. (%)	$PM_{2.5}$[c] (µg/m³)	PM_{10}[c] (µg/m³)
A	28	Yes	No	Headache, fatigue, loss of smell and taste	Severe	Yes	5	Yes	15	21	60	5	6
B	21	Yes	Yes	Sore throat, fatigue	Mild	Yes	3	Yes	16	23	48	5	5
C	60	Yes	No	No symptoms	Mild	Yes	5	Yes	60	22	50	6	7
D	54	Yes	No	Cough, fever, fatigue	Very severe	Yes	2	Yes	13	22	47	5	6
E	35	Yes	No	Cough, fever, fatigue	Mild	Yes	3	Yes	27	22	58	6	6
F	75	Yes	Yes	Control = No symptoms		No		No	22	23	44	6	7
G	44	Yes	Yes	Control = No symptoms		No		No	17	21	48	5	5
H	46	Yes	No	Fever, fatigue	Mild	Yes	5	Yes	22				
I	48	Yes	No	Headache, fatigue, loss of smell and taste	Mild	Yes	47	Yes	16				

[a] Medical diagnostic.
[b] Number of days since the date of clinical diagnosis to the sampling date.
[c] PM concentrations after the PAC usage.

of the possibility of the SARS-CoV-2 being present in the air of indoor environments from a group of different samples to analyze the viruses stuck in them. The results of these research papers showed that 15 research papers reported the positive results of the COVID-19 in the air, while in the number of 10 research papers, results represented a negative effect of the COVID-19 in the air (Borges et al., 2021). While through other review research works (Rahmani et al., 2020) which totally agreed and assured that SARS-CoV 2 was present in some air samples that were collected from patient's rooms in hospitals. This result warrants its airborne transmission potential. In addition, they advised in their research works to reduce the transmission of SARS-CoV-2 and cut the airborne transmission pathway of SARS-CoV-2 in hospitals (Aghalari et al., 2021). Another attempt by María Rodríguez et al. (2021) assessed the extent of contamination of surfaces and air through the indoor environment with the COVID-19 due to home isolation of patients infected with the COVID-19 epidemic by collecting 29 different samples inside 9 homes in Spain. Numerous air samples were accumulated by using an air collector. For sampling, the collector was positioned 1.5 m above the floor and 2 m far from the room occupant, who was not wearing a mask, to recover the ambient aerosols instead of the direct emitted drops. During sampling, only one person was in the room whose dimensions are detailed in Table 1. The objective was to specify the efficiency of PAC with a HEPA filter to reduce the spread of the COVID-19.

The results showed that before using the PAC with the HEPA filter, 75% of the samples were positive results, and the COVID-19 was found through the air, while after using the PAC with the HEPA filter, it predicted that the effectiveness of the PAC with the HEPA filter was 80% in preventing the spread of the COVID-19, and therefore the recommendation to use it in places with insufficient ventilation. A critical review of the evidence on air contamination with COVID-19 in hospital settings and the factors associated with contamination, including viral load and particle size was established by Gabriel Birgand et al. (2020). After a significant review of 24 research articles combined with evidence, the surrounding area of COVID-19 patients was contaminated with a live viable virus by repeatedly sampling at different intervals and distances. High viral loads found in toilets and bathrooms, staff areas, and public hallways suggest that these areas should be carefully considered. Guozhen Lin et al. (2021) observed the reasons for the transmission of COVID-19 through 9 cases of Coronavirus patients within one community in Guangzhou. All the investigated cases were lived in three vertically aligned units at the same building distributing the same piping system as depicted in Fig. 12.

The predicted results of airflow detection and simulation experiment manifested that the flushing of toilets was increased the speed of airflow in the pipes and transmitted the airflow between apartments which carried the COVID-19 epidemic and easily transferred through cases. The COVID-19 epidemic spreads through multiple zones of buildings through air conditioning systems, especially central ones, due to air ducts distributed for conditioned and returned air around the entire building zones. The exchange of heat between these places and the circulation of air through them leads to an increase in the risk of spread the COVID-19 epidemic, especially if there are centrally air-conditioned zones with traces of COVID-19. A group of scientists conducted a research investigation that found traces of COVID-19 in centrally conditioned hospital air ducts (Pung et al., 2021). These results highlighted that the infection of the Coronavirus spreads more quickly through central air conditioning systems. The results of the analysis of swabs of rooms for Coronavirus patients at the Singapore National Center for Infectious Diseases (SNCID) indicated that the COVID-19 epidemic may be more contagious than previously thought due to central air ducts connected via rooms of patients infected with the COVID-19 epidemic (Ong et al., 2020). Through more careful investigations, it was



(a) Quarantine date for the studied cases. (b) The relationship between the studied cases.

Fig. 12. Details of the nine under investigation cases (Lin et al., 2021). (a) Quarantine date for the studied cases. (b) The relationship between the studied cases.

found that a patient with mild symptoms was found, and after his clinical examination, it was found that the patient contained traces of the Coronavirus. It was clear from the research observations that the airborne droplets carried traces of infectious and the air carried the viruses through the duct layout of air conditioning systems which were deposited after some time on the internal surfaces of the air ducts by the air-conditioned as a vector medium for the epidemic. The global epidemic of Coronavirus also spread in an air-conditioned restaurant in Guangzhou, China, through three groups of families during the severe partial closure period in China period from January 26 to February 10, 2020. The results showed that the virus transmission through airborne droplets by air conditioning systems of air distribution outlets was a central cause of transmission Infection to the three families is via centrally conditioned air. Moreover, 1% of the COVID-19 epidemic patients did not show any suspicious symptoms of infection, while only one patient had a fever (Lu et al., 2020a; Chan et al., 2020). Fig. 13 shows a schematic diagram of China restaurant table arrangement and A/C airflow directions.

Another study by Yuguo Li et al. (2021) numerically analyzed the results by investigating a research paper by Jianyun Lu et al. (2020a) of an outbreak involving three non-associated families in the conditioned restaurant in Guangzhou, China, and assessed the possibility of aerosol transmission of SARS-CoV-2 and characterize the associated environmental conditions. An epidemiological data was obtained from a camera system of video record and a patron seating arrangement from the restaurant and measured the dispersion of a warm tracer gas as a surrogate for exhaled droplets from the suspected index patient. Computer simulations were performed to simulate the spread of fine exhaled droplets and compared the in-room location of subsequently infected cases and the spread of the simulated virus-laden aerosol tracer. The ventilation rate was

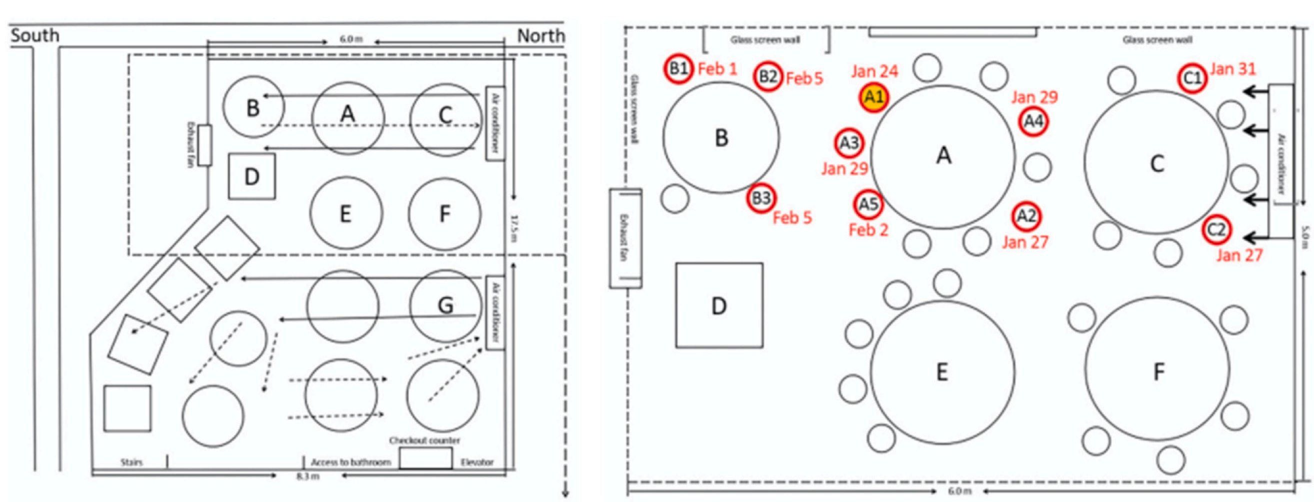


Fig. 13. Plan of the restaurant tables and A/C arrangements (Lu et al., 2020a; Chan et al., 2020).

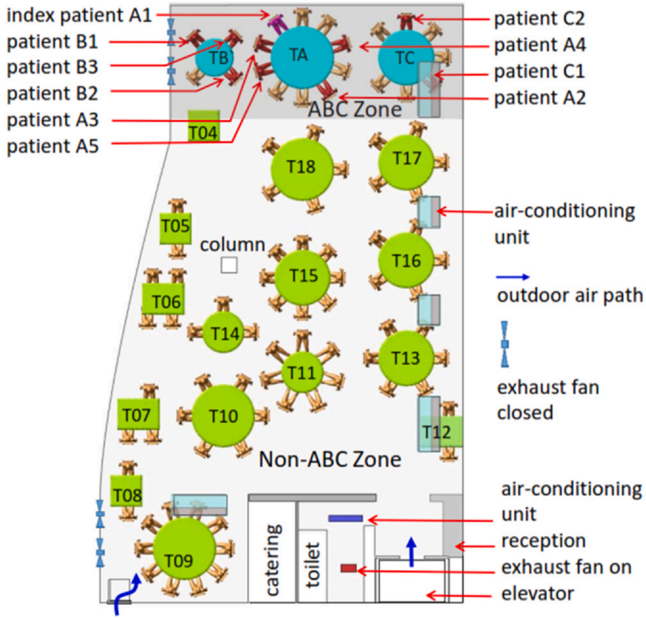


Fig. 14. COVID-19 infection with a distribution of conditioned air inside a restaurant (Li et al., 2021).

measured using the tracer decay method. Fig. 14 shows the distribution of conditioned air for three families inside a restaurant and the probability of corona infection.

Through the numerical analysis, it was found that there were 10 cases of SARS-CoV-2 infection among the three families, A, B, and C, while the ventilation rate was 0.75–1.04 L/S.P. It was found through the numerical analysis of the results that the aerosol transmission of SARS-CoV-2 due to poor ventilation leads to the rapid spread of COVID-19 in the community as illustrated in Fig. 15.

Varvara A. Mouchtouri et al. (2020b) collected samples from different places in a nursing home and three wards in isolation hospitals during the ongoing outbreak of the COVID-19 epidemic. Samples were tested by real-time reverse transcriptase-polymerase

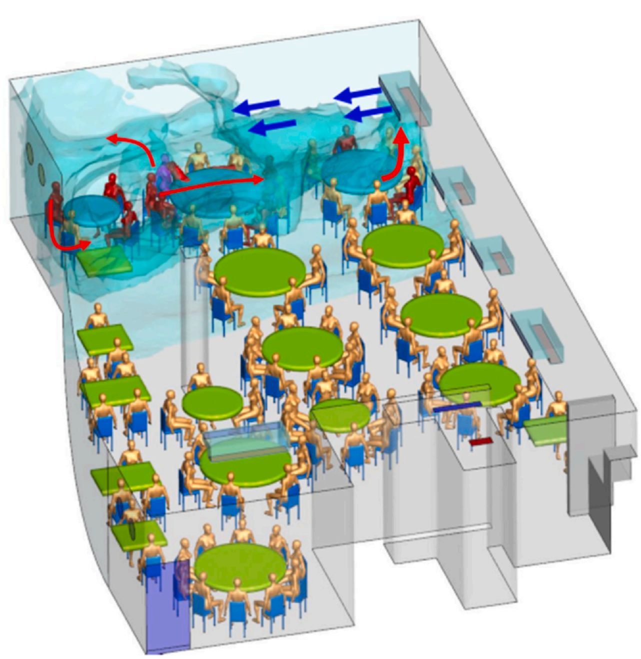


Fig. 15. Simulation of A/C arrangements inside a restaurant and droplets dispersion by a patient (Li et al., 2021).

chain reaction. The results showed that SARS-CoV-2 positive swabs samples taken from the surfaces of food preparation and service areas, hospital isolation wards, duct screen, air conditioning filter, wastewater treatment unit, and air samples during investigations conducted in response to the COVID-19 outbreak cases on board the ferry for a nursing home, isolation facility, and COVID-19 hospital wards. Luca Borro et al. (2021) numerically simulated the HVAC systems in the transmission of the contagion of cough at the "Bambino Gesù" Vatican State Children's Hospital through the waiting room and a hospital recovery room as manifested in Fig. 16.

An infection indicator parameter (η) was expressed to estimate the amount of contaminated air inhaled by each person as illustrated in Fig. 17.

The CFD results of the waiting room show that HVAC airflow remarkably improves infected droplets diffusion in the whole indoor environment within 25 s from the cough event, despite the observed dilution of saliva particles containing the virus. At the same time also, their number is reduced due to removal through the HVAC system or deposition on the surfaces.

4.2. Modifications of HVAC systems in the event of a COVID-19 pandemic

4.2.1. A recently crucial investigations with recommendations to face COVID-19

The research paper by Ashraf Mimi Elsaid and M. Salem Ahmed (2021) presented the different classifications of air conditioning systems with the modifications needed to face the COVID-19 super spreading. The next section explores the important attempts of the recent publications related to the modifications of HVAC systems through Sars-CoV-2. Moreover, Societies of HVAC with recommendations under several aspects to face the pandemic Coronavirus are discussed too.

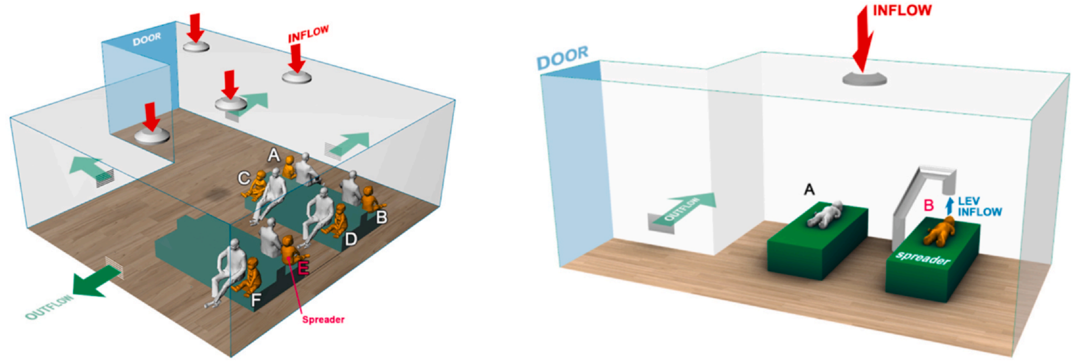
Wenxin Li et al. (2021) experimentally investigated the transmission properties of aerosols in a room using an outdoor air system coupled with ceiling fans. The use of tracer gas was simulated as the cores of exhaled droplets from an infectious person, and a respiration thermal dwarf was used as a seated exposed person without an epidemic. A thermal breathing manikin was located at 1.5 m opposite the tracer gas source whilst an aerosol sampling probe was fixed at 5 mm below the tip of the nose to measure the SF_6 concentration at the breathing zone as illustrated in the next Fig. 18.

The effect of air supply rates, ceiling fan speeds, source positions, and breathing patterns of an exposed person on aerosol transmission was studied. The results showed that increasing the air change per hour from 4.5 to 5.6 and 7.5 reduced the average concentrations at the sampling points by 18% and 38%, respectively. Ceiling fans generated local air movement and mixed air within the space, and a higher operating speed contributed to a concentration distribution and reduced focus rate by 20% with better aerosol dispersion. Ceiling fans show the potential to reduce the risk of cross-infection in air-conditioned spaces.

Another research work by Ahmed Sodiq et al. (2021) was reviewed the indoor spread of infectious diseases by the conditions of the HVAC systems. The available reports have demonstrated that the COVID-19, with an average aerodynamic diameter up to 80–120 nm, is viable as an aerosol in the indoor atmosphere for more than 3 h, and its spread may be assisted by the HVAC systems as manifested in Fig. 19.

The review conclusion explored that the innovative air circulation concept supported using UVGI in combination with nanoporous air filter to combat the spread of SARS-CoV-2 and other harmful microbes in enclosed spaces as cleared in Fig. 20.

Yonghong Jia et al. (2021) analyzed the mechanism and potential health risk of respiratory virus transmission in air-conditioned rooms and propose a method to study the risk of virus transmission



(a) Case-1, emergency waiting room with 6 pairs of men and children. (b) Case-2, a hospital recovery room with two beds of two pediatric patients

Fig. 16. Cases distribution through an emergency waiting and a hospital recovery rooms (Borro et al., 2021). (a) Case-1, emergency waiting room with 6 pairs of men and children. (b) Case-2, a hospital recovery room with two beds of two pediatric patients.

in central air conditioning systems by investigating the data from medical experiments. Several parameters were investigated as the decay characteristics of indoor pathogen droplets, effects of air temperature, and relative humidity on the virus survival in the air or on surfaces as manifested in Fig. 21.

The important findings prove that the indoor temperature and humidity were controlled in the range of 20–25 °C and 40–70% by central air conditioning during the epidemic period, which not only benefits the health and comfort of residents, but also weakens the vitality of the virus as seen in the next Fig. 22 (a) and (b).

The larger the droplet size, the longer the viruses survive. Since the filter efficiency of the air conditioning filter increases with the increase in particle size, increasing the number of air changes of the circulating air volume can accelerate the removal of potential pathogen particles as the presented data in Fig. 23. Therefore, the scientific operation of centralized air conditioning systems during the epidemic period has more advantages than disadvantages.

Han Liu et al. (2021) numerically simulated by using CFD of indoor airflow and the associated aerosol transport in a restaurant setting-induced infection of COVID-19 caused by asymptomatic individuals as seen in Fig. 24.

The numerical results from simulations shown that a remarkable link between regions of high aerosol exposure index and the reported infection patterns in the restaurant, providing strong support

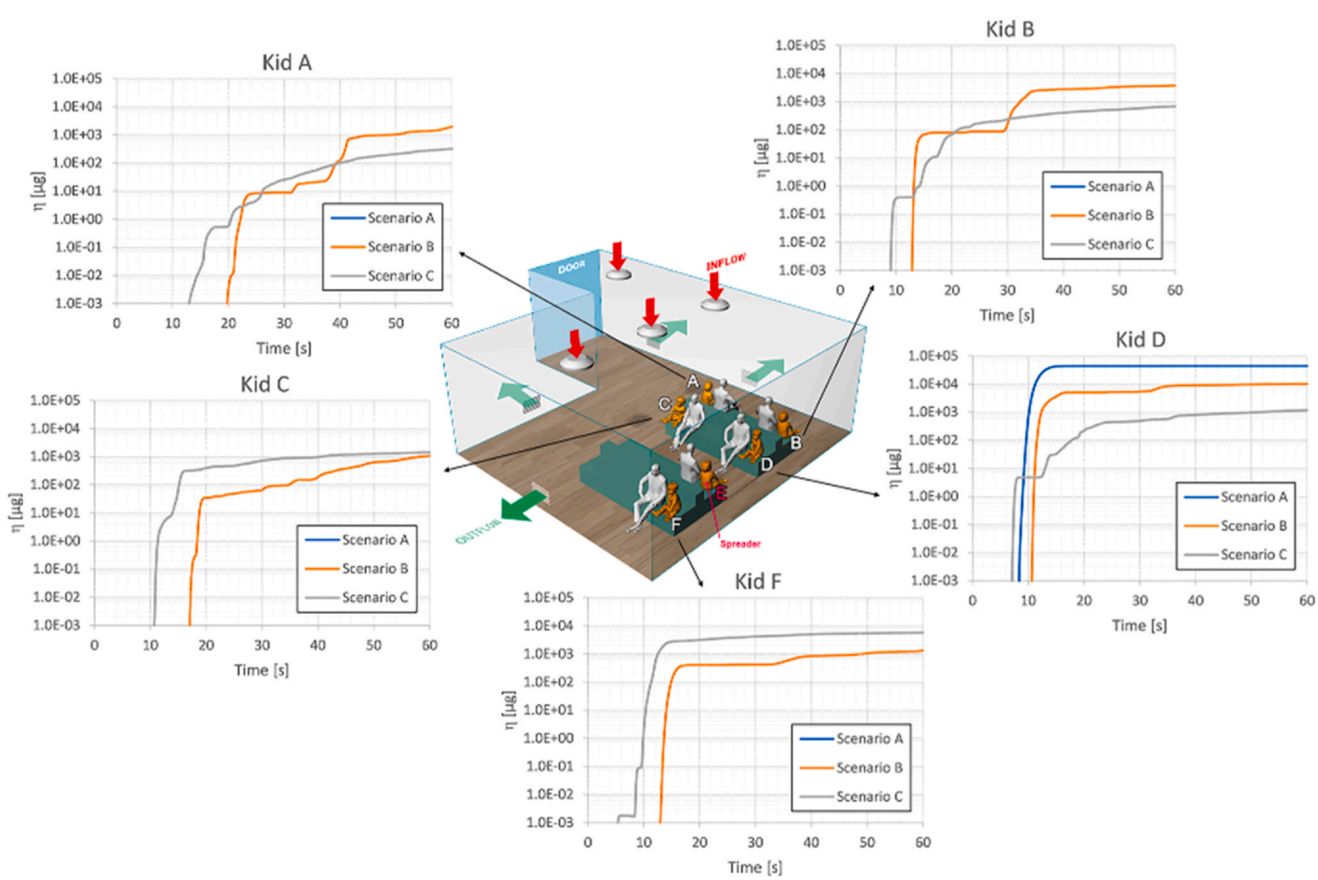


Fig. 17. Temporal evolution of infection indicator parameter inside kids waiting room (Borro et al., 2021).

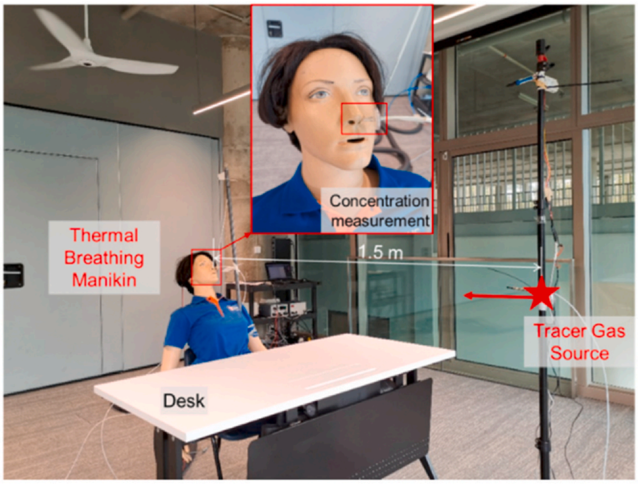


Fig. 18. A manikin position with tracer gas source and aerosol sampling probe (Li et al., 2021).

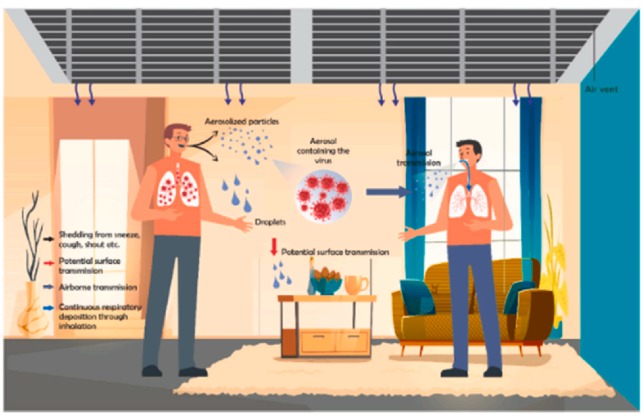


Fig. 19. Sketch of the SARS-CoV-2 transmission criteria through indoor environment (Sodiq et al., 2021).

to the airborne transmission occurring in this widely reported incident. Moreover, the returning aerosols from air conditioning/ventilation systems due to the limited filtration efficiency can also cause aerosol exposure of individuals adjacent to or facing the ventilation outlets as 30% to the total infection risk in some ventilation and thermal settings. A. Hammond et al. (2021) investigated the available all markets air filters to reduce the incidence of respiratory infections and/or remove bacteria and viruses from indoor air especially COVID-19. The predicted results explored that higher numbers of viable bacteria in the HEPA filter were remarked than in floor dust samples. Moreover, HEPA filtration combined with ultraviolet light reduced bacterial load in the air by 41% (sampling time not reported). Neither paper investigated the effects of viruses. There is an important absence of evidence regarding the effectiveness of a potentially cost-efficient intervention for indoor transmission of respiratory infections by SARS-CoV2. To prevent the diffusion of the global epidemic COVID-19 in restaurants, the researchers recommended that temperatures should be monitored and not reduced to an extent that would accelerate the spread of the coronavirus whilst the distance between tables should increase and ventilation should be improved as much as possible (Lu et al., 2020b). It is standard practice for buildings and transportations to use recycled air through air-conditioning systems. Hence, it is recommended that any ventilation or air conditioning system that operates with the recycling mode now operate on full outdoor air (Wong et al., 2020). In general, the main parameters of indoor

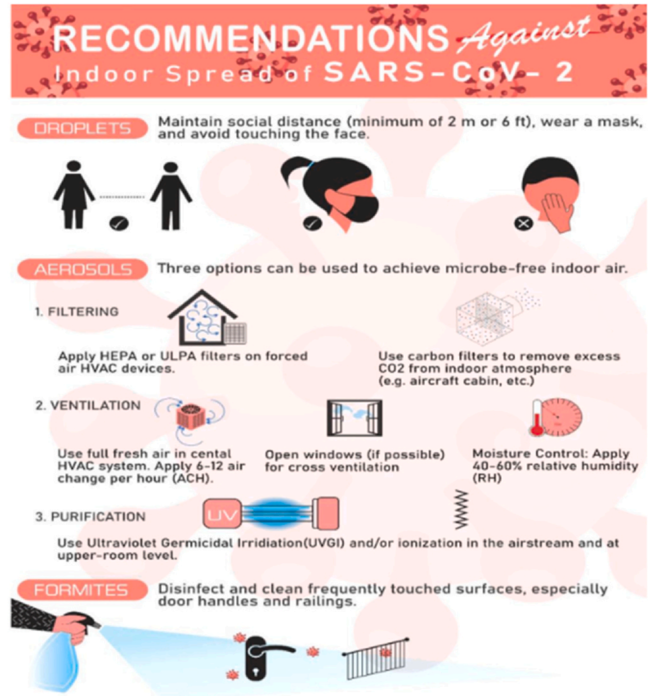


Fig. 20. Improvement actions against indoor air droplets spread of COVID-19 (Sodiq et al., 2021).

comfort/health are: temperature, humidity, air purity, and air velocity. For temperature to be adjusted, ASHRAE and CDC recommend a range of 20–24 °C in winter and 24–27 °C in summer (ANSI/ASHRAE). Air conditioning improves air quality using various techniques (Gomaa et al., 2012); the most used being external ventilation and filtration. It is important that there is no feeling of local cooling of the body due to the movement of air caused by air conditioning in the occupied space. The ASHRAE research guidelines indicate that the maximum airspeed in the occupied space is 20 m/s by the room's heating, ventilation, and air conditioning system (Elsaid, 2020b; ANSI/ASHRAE). The following are important considerations for air distribution that must be considered (Lipinski et al., 2020a):

- The ideal distribution of the renewed air exit position is achieved through a position that ensures good airflow, but it does not blow air directly into the occupied area and guarantee that the air can transport and spread before reaching the inhabited area.
- Consider the amount of airflow with the cooling capacity of the unit (around 5.7–11.3 cubic meter/ton in North America). In addition, the cooling capacity in relation to the air-conditioned space should not be large or small, i.e., calculated correctly.
- Regular distribution of temperatures and control of the rate of airflow and airspeed (no more than 20 m/s in the building), which avoids the risk of transporting virus-carrying particles from one part of the room to another.

4.2.2. Recommendations of HVAC associations over the world to face COVID-19

4.2.2.1. Precautionary measures according to ASHRAE recommendations. After extensive studies of the set of necessary countermeasures to prevent the continued spread of the epidemic through air conditioning proposed by ASHRAE, ASHRAE issued guidelines in two statements issued on April 20, 2020 (ASHRAE, 2020a), opposing WHO advice not to operate residential or commercial HVAC systems to clarify the following elements.

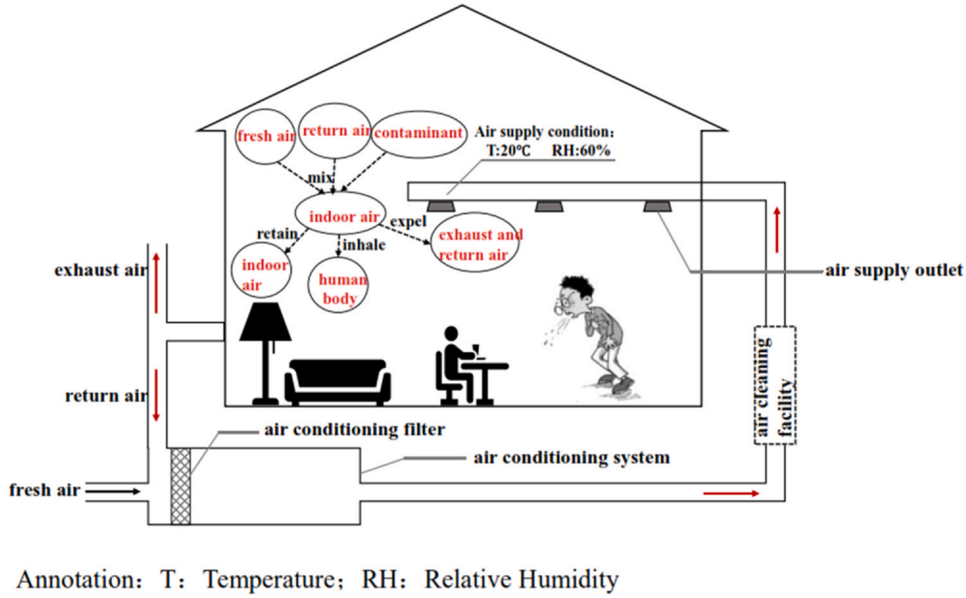


Fig. 21. Sketch of indoor transmission of COVID-19 with A/C operation regulations (Jia et al., 2021).

A. Statement 1: relates to air transmission of SARS CoV-2/COVID-19. Studies show that transmission of SARS-CoV-2 by inhalation is a sufficient possibility; Therefore, exposure to the virus through the air must be controlled. With the proper operation of HVAC systems, exposure to airborne coronavirus can be mitigated.
B. Statement 2: relates to HVAC operating systems in a manner that minimizes exposure to SARS-CoV-2. Ventilation and filtration can reduce the concentration of virus in the air, and thus can reduce the risk of transmission of covid viral infection through the air. Moreover, it is essential that people do not experience heat stress in an unconditioned place by disrupting the HVAC system. Appropriate HVAC air filters help reduce the transmission of viruses.

Guidelines for construction operations during the COVID-19 pandemic were published in the ASHRAE Journal on March 24, 2020. Furthermore, ASHRAE updated the "ASHRAE Position Document on Infectious Aerosols" on April 14, 2020. On May 7, 2020, ASHRAE was released whereby it provides ASHRAE COVID-19 Building/Reopening Readiness Guidance to mitigate potential health risks while re-opening closed buildings during the COVID-19 pandemic (ASHRAE, 2020b). ASHRAE's guidance on construction during the COVID-19 pandemic argues that HVAC systems play a secondary role in the transmission of infectious diseases, and that SARS-CoV-2 viruses primarily spread. Through the air carrying of coronavirus droplets and contact in non-medical premises, maintaining a social distance (1–2 m), frequent cleaning and disinfection of surfaces, hand washing, and other frequent hygiene strategies are far more important than strategies related to the HVAC system. It was also recommended that measures should be taken with HVAC systems as follows (Schoen, 2020):

1. Open the outdoor air dampers to 100% outdoor air if possible, with DCV disabled.

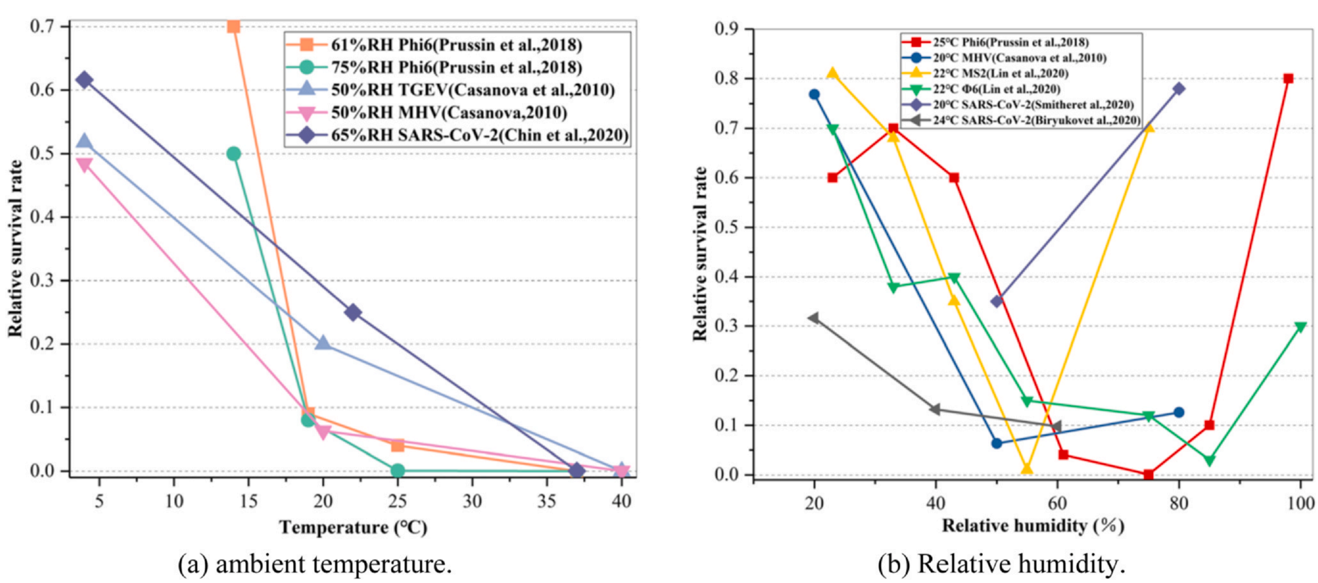


Fig. 22. Effects of temperature and relative humidity on survival of viruses on surfaces (Jia et al., 2021). (a) Ambient temperature. (b) Relative humidity.

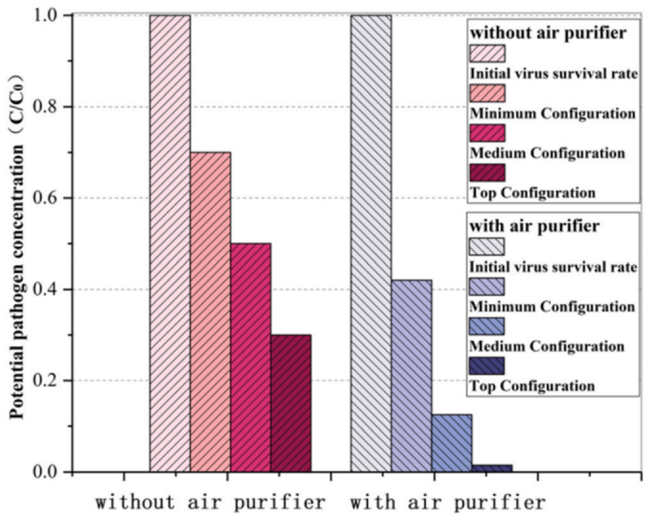


Fig. 23. Potential pathogen concentration under different configurations of A/C systems (Jia et al., 2021).

2. Upgrade central air filters to MERV-13 as much as possible (filtration efficiency 90% for particles from 3.0 to 10.0 μm), making sure to close filter edges to reduce viral overrun. According to ASHRAE 52.2, droplets less than 5 μm in diameter (droplet cores or aerosols) can be suspended in the air over long distances and time because they pose a high risk to aid the transmission of SARS-CoV-2 (WHO, 2020b). MERV-13 air cleaner can effectively reduce the transmission of infectious aerosols.
3. Keep the system running 24 h a day during the entire week (7/24).
4. Use portable room air cleaners with HEPA filters which can reduce the risks of COVID-19 transmission.
5. The necessity of using ultraviolet germicidal lamps (UVGI), especially in some high-risk places that are densely populated by citizens. ASHRAE Position Document on Infectious Aerosols (ASHRAE, 2020c).
6. For healthcare facilities, there are standards in ventilation design to mitigate the transmission of infectious diseases through the air (ASHRAE, FGI). For other building types, general ventilation and air quality requirements are provided by ASHRAE in ANSI/ASHRAE Standards 62.1-2019, ANSI/ASHRAE Standards 62.2-2019, and ANSI/ASHRAE/ASHE Standard 170-2017.
7. The strategies recommended by the ASHRAE position document mainly include aeration, dilution and extraction, compression, airflow distribution and optimization, mechanical filtration, UVGI, and moisture control.

- The use of natural ventilation can reduce the risk of infectious aerosols.
- Pressure differences between zones in the building should be controlled so that air flows from safe areas to unsafe areas.
- Use areas to public areas, such as from anterooms to airborne infection isolation rooms.
- The UV-C (ultraviolet with wavelengths from 200 to 280 nm) provides the best effect, with 265 nm to kill the virus through air.
- Operate HVAC related devices including exhaust fan and outside air damper to provide flushing 2 h before and post occupancies.

The US Centers for Disease Control and Prevention (CDC) and ASHRAE agree that ultraviolet radiation reduces the risk of transmission of the coronavirus (CDC, 2009). It is also recommended that 100% fresh air should be supplied with HEPA or UVGI filters installed in the passenger's breathing area.

4.2.2.2. Precautionary measures according to REHVA recommendations. On April 3, 2020, REHVA updated the basic guidelines necessary to limit the spread of COVID-19 including the mechanism of virus transmission, the mechanism of operation of multiple ventilation equipment, the shelf life of the virus in different temperature and humidity environments, and the operation of heat recovery equipment, with 14 practical measures to operate the services Buildings (REHVA, 2020).

It is important and necessary that the heating, ventilation, and air conditioning system does not operate as usual during the outbreak of the COVID-19 epidemic, and therefore it is recommended to implement a set of precautionary measures and measures to prevent the spread of the epidemic. The REHVA Recommendation can be summarized in the following aspects.

1. Safe ventilation of spaces and areas with outdoor air is considered to mitigate airborne transmission of SARS-CoV-2 in buildings. REHVA recommends providing as much outdoor air reasonably as possible.
2. Ensure that each person receives fresh air by maintaining or increasing social distancing (minimum physical distance of 2–3 m between people).

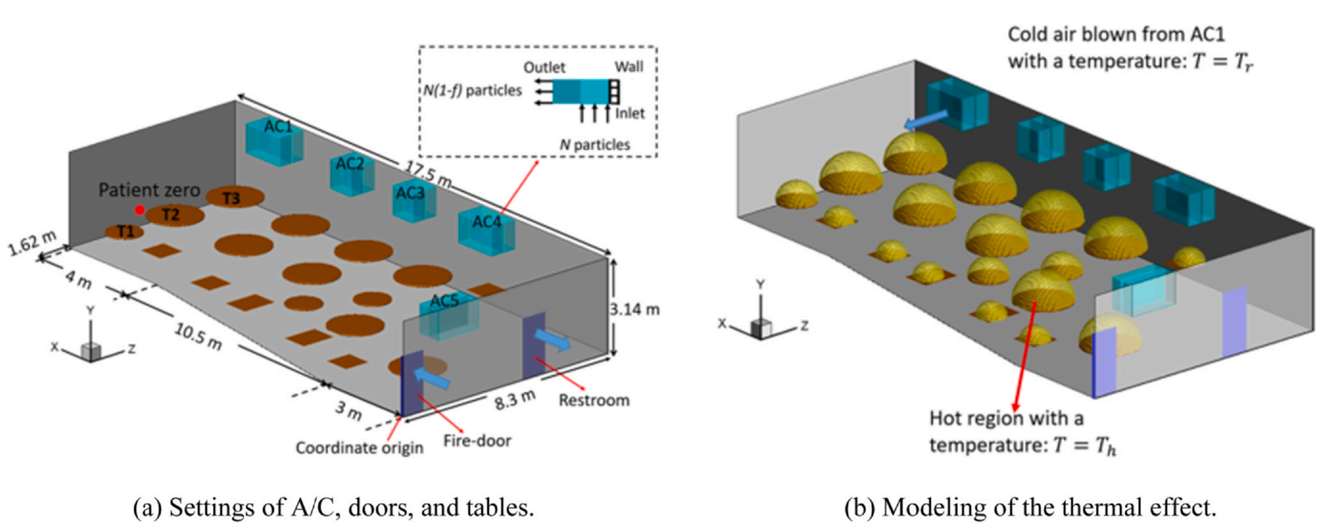


Fig. 24. Simulation setup techniques (Liu et al., 2021). (a) Settings of A/C, doors, and tables. (b) Modeling of the thermal effect.

Table 2
Comparison of the different strategies of the most important specialized associations in countries (Guo et al., 2021).

Parameter	ASHRAE association	REHVA association	SHASE association	Related associations of China
Outdoor air	1. Increase the amount of outdoor air. 2. Open outdoor air dampers, as high as 100% if possible.	1. Supply as much outdoor air as reasonably possible. Switch the terminal devices to 100% outdoor air if possible. 2. Open windows regularly.	1. Supply as much outdoor air as reasonably possible. Switch the terminal devices to 100% outdoor air if possible. 2. Open windows regularly.	1. Supply as much outdoor air as reasonably possible. Switch the terminal devices to 100% outdoor air if possible. 2. The ratio of outdoor air should be greater than 40%.
Operation of HVAC systems	1. Operate HVAC related devices to provide flushing 2 h before and post occupancies. 2. Keep the system on for 24 h a day, 7 days a week if possible. 3. Disable DCV.	1. Run ventilation at the nominal speed for at least 2 h before occupancies and at a lower speed 2 h after occupancies. 2. Run toilet ventilation system for 24 h a day, 7 days a week. 3. In DCV systems, change the CO_2 setpoint to 400 ppm.	1. Increase the running time of HVAC equipment, running it continuously for 24 h if possible. 2. Run the exhaust system in toilets continuously. 3. Lower the CO_2 setpoint.	1. Increase the air supply temperature in heating mode and decrease the temperature in cooling mode.
Temperature and humidity setpoint	1. Control the temperature and humidity are beneficial. But the temperature and relative humidity setpoint should be considered on a case-by-case basis.	1. There is no need to adjust the temperature and humidity setpoint.	1. The temperature should be controlled between 17 and 28 °C, and the relative humidity should be controlled between 40% and 70%.	Have not mentioned.
Pressure differential	1. The air should flow from safe areas to unsafe areas, from personal use areas to public areas.	1. Ensure the negative pressure in the toilets.	1. Ensure the negative pressure in the toilets.	1. A slight positive pressure should be maintained in the kitchen. 2. Keep negative pressure in toilets.
Filters equipped in the HVAC system	1. Improve the level of the central air filter as much as possible, at least to the grade of MERV-13.	1. Filters should be replaced and maintained as usual.	1. For a system with 100% outdoor air, the filter can be operated as usual. 2. For return air operation, check the differential pressure of the filter more often and replace the filter sooner than usual.	1. Maintain filters as usual.
Air cleaning	1. HEPA filters and UVGI are recommended.	1. It is recommended to locate the air-cleaning device close to the breathing zone. 2. Special UV cleaning equipment installed for the supply air or room air treatment are also effective.	1. Air cleaners are effective as auxiliary devices. 2. Ventilation is more effective than air cleaners.	1. Indoor air cleaners should be operated. 2. UV devices should not be installed in the HVAC system.
Heat recovery equipment	1. Check the status of heat recovery wheels in the systems for leakage.	1. If heat exchangers with leakage below 5%, operate with increasing amount of outdoor air ventilation.	1. For the static total heat exchanger, operate in heat exchange mode.	1. Indirect heat exchangers and other heat exchangers can operate as usual.
Other recommendations	1. Create the strategic plan prior to opening a building.	1. Close the lid when flushing toilets. 2. Avoid dried-out water seals.	1. Close the lid when flushing toilets. 2. Check water seals regularly.	1. Check water seals regularly. 2. Keep the uplift ventilation pipe.

3. Open windows regularly for 15 min, even in buildings with mechanical ventilation, especially a room previously occupied by others.
4. It is recommended to operate the ventilation at the nominal speed for at least two hours before the time of occupancy of the building.
5. In DCV control systems, it is proposed to change the CO_2 setpoint to 400 ppm, which will ensure that the ventilation system operates at the nominal speed.
6. Continuing to operate the ventilation systems at night and during weekends at a lower speed.
7. In the buildings where the epidemic has spread, it is necessary to evacuate, and it is not recommended to turn off the ventilation system and turn it on at a lower speed.
8. For the toilet aeration system, it is recommended to keep working 24 h a day, 7 days a week, to avoid the fecal-oral route.
9. For operating terminal devices of central A/C systems (air handling units) it is recommended to use 100% outdoor air.
10. SARS-CoV-2 through studies is very stable for 14 days at 4 °C, stable for 1 day at 37 °C and stable for 30 min at 56 °C (Chin et al., 2020). This means that relatively high temperatures that do not affect the feeling of thermal comfort are working to reduce the rate of spread of the epidemic as much as possible.
11. With relative humidity, according to research studies during the range (40–60%), the nasal chambers and mucous membranes of humans are less sensitive to infection (Salah et al., 1988) and therefore it is recommended to maintain relative humidity inside air-conditioned places between 50% and 60%.
12. REHVA recommended relocating the air-cleaning device close to the breathing zone. Special UV cleaning equipment installed for the supply of air or room air treatment is also effective.
13. The leakage rate of properly operating rotary heat exchangers within the range of 1–2%.

4.2.2.3. Precautionary measures according to SHASE recommendations. The SHASE's recommendations regarding the operation of air-conditioning equipment and other facilities as SARS-CoV-2 infectious disease control are as follows:

1. Open the outside window regularly to increase the outside air to replace 95% of the indoor air when the outside air is three times the volume of the room.
2. Maintaining external ventilation continuously for homes and small buildings.
3. For central air conditioning, it is recommended to increase the opening of the external air damper and exhaust air damper to 100% if possible.
4. It is recommended to lower the CO_2 setpoint. It is also recommended to increase the running time of air-conditioning equipment, running it continuously for 24 h. if possible.
5. The exhaust system of the toilet should be kept running continuously.
6. Ensure negative pressure in the toilet, the toilet window should be kept closed.
7. Ensure ventilation rate of (30 m^3/h/p), the temperature should be controlled between 17 and 28 °C, and the relative humidity should be controlled between 40% and 70%.

4.2.2.4. Precautionary measures according to China associations recommendations. During the spread of the COVID-19 pandemic, many research institutions and associations specialized in air conditioning in China as CRAA, CHVAC, and CAR associations announced a set of recommendations for the use of air conditioning during the COVID-19 pandemic, as follows:

1. Install energy-saving, bi-directional ventilation fans to meet the ventilation need for rooms without external windows.
2. For the central ventilation system and the central exhaust system, it is recommended to keep the doors open or to install blinds on the doors.
3. Install a mechanical exhaust fan to ensure that the total exhaust volume of the central exhaust system is not less than 70% of the outside air volume.
4. When the ventilation is insufficient, the exhaust system should be cycled and add a portable room air cleaner with a HEPA filter.
5. Mechanical ventilation and air conditioning systems must be turned on in advance and closed later.
6. The kitchen pressure should be slightly higher than that in the other areas. To maintain the positive pressure in the kitchen, the pressurized ventilation system should be turned on while the kitchen exhaust fume fan runs.
7. The exhaust systems of the toilets, sewage rooms, etc., are recommended to operate continuously to maintain negative pressure (The Architectural Society of China, 2020).

In the next research study by Mingyue Guo et al. (2021) compared different organizations and societies strategies as depicted through the following Table 2.

5. The role of ventilation systems in the spread of COVID-19

Deficient indoor ventilation has been linked to an increase in the transmission of respiratory infections such as influenza, tuberculosis, and rhinovirus infection (Centre for Evidence-Based Medicine (CEBM); Zheng et al., 2021; European Federation of Trade Unions in the Food Agriculture and Tourism (EFFAT); Hamner et al., 2020; Lednicky et al., 2020; Santarpia et al.).

While the role of ventilation in preventing SARS-CoV-2 transmission is unknown at this time, it is believed to be largely transmitted by large respiratory droplets; however, several articles indicate that aerosols played a role in the COVID-19 outbreak (Knibbs et al., 2011). Two studies (European Centre for Disease Prevention and Control, 2020; Qian et al., 2020) strongly imply that aerosol transmission may occur in enclosed spaces (short-lived aerosols) where many people live for long periods of time. It is now well established that COVID-19 transmission occurs most frequently in enclosed spaces. Ventilation systems that have been modified to reflect the new situation play a critical role in reducing the spread of the SARS-CoV-2 pandemic through various modifications.

5.1. Ventilation systems improvement methods in the event of a COVID-19 pandemic

5.1.1. Importance of ventilations through COVID-19 pandemic

As people spend 80–90% of their time in confined spaces, dilution of pollutants within the space should be the first consideration to reduce exposure risks and maintaining a healthy environment. One such engineering control technique for maintaining IAQ is ventilation. Ventilation is considered an effective engineering control because it dilutes air contaminants in confined spaces through indoor-outdoor air exchange (Lidia and Junji, 2020b; Nembhard and Burton, 2020). Ventilation can be provided either naturally using windows, louvers, vents, or mechanically through an HVAC system. An adequate ventilation rate is necessary for reducing the infection risk in confined spaces such as offices, residential areas, public buildings like malls, restaurants, museums, and public vehicles. A high ventilation rate does not give assurance of eliminating the viral load, but it can dilute the contaminants that reduce the viral concentration to a great extent. The ventilation rate of 288 m^3/h/p is suggested by WHO for healthcare settings which can be achieved either by natural or mechanical ventilation. But the dependence of natural ventilation on climatic factors makes it less viable, also this is not possible in offices as most of the glass façade buildings have fixed glazing and

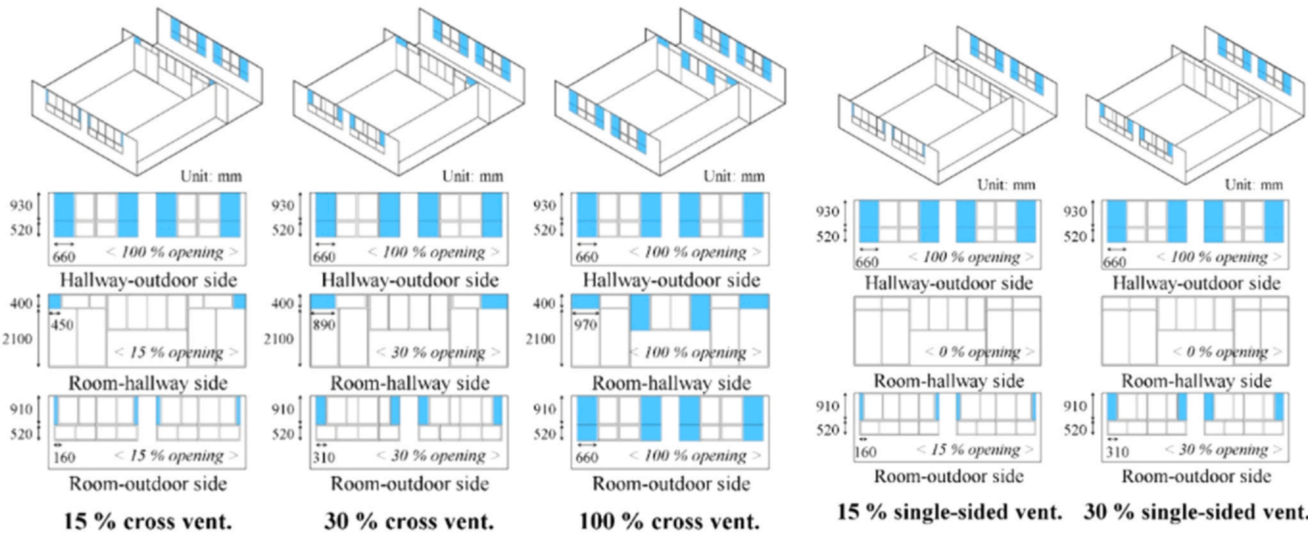


Fig. 25. Window opening conditions (blue shading indicates open windows (Park et al., 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hence, it is preferable to install a mechanical system. HVAC is primarily used for controlling the probability of increasing infections. But if the system is not implemented properly, it can worsen the situation and can itself become the source of transmission or outspread of virus-laden aerosols as already noticed in past SARS epidemics. Generally, the HVAC system recirculates the air as bringing fresh air will consume more energy, so the recirculation can also be a source of an increased rate of infection. According to ASHRAE, REHVA guidelines, recirculation of air should be prohibited in the indoor environment in the current situation especially for centralized conditioning systems (V. & A/C. The Federation of European Heating (REHVA), 2020). The HVAC system can also deter the situation if low temperature and relative humidity are maintained. Some studies suggested maintaining negative pressure and high relative humidity in intensive care units of hospitals using adequate mechanical ventilation rate as the SARS-CoV-2 virus was detected majorly in ICU. The study has shown that high temperature and relative humidity can reduce the infection risk as these conditions can make the virus less active. Analogous to this, studied the impact of the dry environment on infection risk indoors considering different climatic conditions. It stated that when surrounding air has lower relative humidity and temperature, naturally or in conditioned space, than the body temperature, the droplet size gets reduced due to combined mass and heat transfer. The reduced droplet cannot be filtered out by the respiratory tract as the mucus membrane also dries up. But in hot and humid conditions, the mucus membrane will be wet which humidifies and dilutes droplet nuclei, thus making the virus less active. The required ventilation rate for diluting the contaminants can be reduced by maintaining a physical distance. If occupancy density reduces to 25% for the first 30 min in the office, ventilation rate drops by more than 4/5, and by 40% in the public bus (Sun et al., 2020). ASHRAE also suggested increasing the outdoor air ventilation by lowering the population in buildings. It is also recommended that the system must be run at maximum outside airflow for 2 h before and after the building is occupied. So, it can be concluded that we must find a middle ground for appropriate mechanical ventilation rates where high temperature and relative humidity can be maintained without negotiating with thermal comfort. Ventilation is the process of changing the air inside buildings to remove airborne undesirable substances. There are two ventilation techniques, one is natural ventilation through windows and doors, and the other is forced ventilation in which acting with ventilators or wind tunnels. Ventilating systems are preferably incorporated with a filter to prevent unwanted fine particles. With good airflow or ventilation, small particles reduce and disperse more quickly, as they do when you open windows to air out a smoky room (The National Health Commission of the People's Republic of China). Although aerosols can contribute to the spread of COVID-19, most infections are always related to close contact with infected people, whether the infected person is symptomatic (The National Health Commission of the People's Republic of China). To date, there is no evidence that the COVID-19 virus can be transmitted in air over long distances or via air ducts (The National Health Commission of the People's Republic of China).

There is currently no evidence that air purifiers alone are effectively helping to reduce the spread of COVID-19 transmission. Portable air cleaners or air purifiers may be useful as a supplement to HVAC ventilation or if there is no outdoor air exchange (The National Health Commission of the People's Republic of China). Check that the exhaust air from the air purifier does not blow directly onto a person. Based on window opening rates, locations, and weather conditions, field measurements were made to estimate the natural ventilation performance of a school building (Toronto Public health, 2021). This research suggested a window opening region that can be used in real-world situations to reduce viral air infection. The tracer gas decay method was used to compute ventilation rates, and the Wells-Riley equation was used to quantify infection risk. The Wells–Riley equation is given by (Azuma et al., 2020):

$$P_I = \frac{C}{S} = 1 - e^{-(Iqpt/Q)} \tag{1}$$

Where:

P_I = The probability of infection (–).
C = The number of susceptible individuals to become infected (–).
S = The number of susceptible individuals (–).
I = The number of infectious individuals (–).
p = The pulmonary ventilation rate of a person (m^3/h).
q = The generation rate of infectious quanta (h^{-1}).
t = The exposure time (h).
Q = The room ventilation rate with clean air (m^3/h).

The average ventilation rates under cross-ventilation conditions were 6.51 h^{-1} for 15% window opening and 11.20 h^{-1} for 30% window opening. The ventilation rates for single-sided ventilation were reduced to roughly 30% of those for cross-ventilation instances. In all

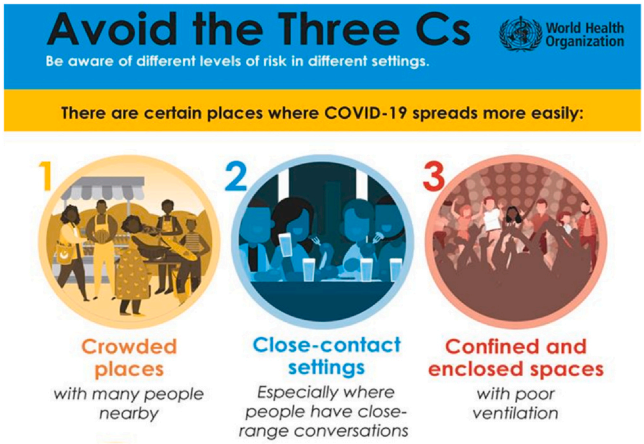


Fig. 26. The three C's with poor ventilation (Fadaei, 2021).

conditions, the risk of infection is less than 1% when a mask is worn and more than 15% of the windows are open with cross-ventilation. If the exposure time is less than 1 h, infection likelihood can be minimized to less than 1% using single-sided ventilation and a mask. The infection rate exceeds 1% in all cases where the exposure time exceeds 2 h, regardless of whether a mask is worn. In addition, power consumption increased by 10.2% when the air conditioner was operated with a 15% window opening ratio (Toronto Public health, 2021). Fig. 25 shows a schematic diagram of window opening conditions in which cross-ventilation means open opening both room-outdoor side and the room-hall wayside windows, while single side ventilation means that the windows on the room outdoor side are opened.

Indoor air management will not stop the spread of COVID-19 on its own, but it can reduce the number of people infected when people also wear a face mask; stay at least 6 feet away from others who are not household members; practice good hand hygiene; clean and disinfect frequently touched surfaces and take any other steps to control and stop infection. According to studies and research, improving the ventilation process and the devices that perform the ventilation process reduces corona infection significantly by working to improve and develop them to suit the new situation of the corona pandemic (Fadaei, 2021). Proper ventilation can probably prevent COVID-19 expansion, and when combined with particle filtration and air disinfection, it is even more effective (Fadaei, 2021). The findings indicate that the six basic COVID-19 control strategies are as follows: hand hygiene, social distancing, screening, and case finding, isolation and separating, decontamination and disinfection, and effective ventilation (Fadaei, 2021). Many situations increase the risk of Coronavirus spread. People stay close to each other for extended periods of time, which increases the risk of transmission. Indoors, particularly in poorly ventilated areas, are more hazardous than outdoors. Activities where more particles are expelled from the mouth, such as singing or breathing heavily during exercise, also increase the risk of transmission. Therefore, WHO (World Health Organization) advices avoiding the three Cs stated previously, Fig. 26. The three C's are a useful way to think about this.

They describe settings where transmission of the COVID-19 virus spreads more easily:

- Crowded places.
- Close-contact settings, especially where people have conversations very near each other.
- Confined and enclosed spaces with poor ventilation.

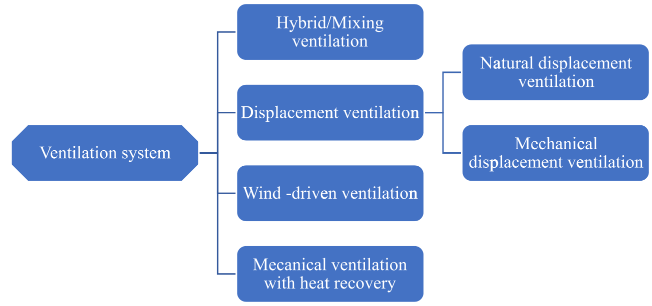


Fig. 27. A schematic plan of ventilation systems (Cao et al., 2021; Lipinski et al., 2020b).

The risk of COVID-19 spreading is especially high in places where these "3Cs" overlap.

5.1.2. Type of ventilation systems

There are numerous ventilation systems available that can help to reduce the spread of Coronavirus while also providing thermal comfort. Research articles and textbooks differed in one classification of ventilation, while the classification mostly agrees that it is either natural ventilation or mechanical ventilation, both of which fall into sub-categories. While in many of the studies that were analyzed, it was found that ventilation has comprehensive and multiple sub-categories classifications. The following diagram in Fig. 27 shows the different types of ventilation systems (Cao et al., 2021; Lipinski et al., 2020b).

5.1.2.1. Hybrid/Mixing ventilation systems. Hybrid/Mixing ventilation systems (HVS) (Cao et al., 2021; Lipinski et al., 2020b) are systems that provide a comfortable indoor environment by utilizing both natural ventilation and mechanical systems, but by utilizing different features of the systems at various times of the day or season of the year. They are two-position ventilation systems that combine mechanical and natural forces. The basic idea is to maintain a comfortable indoor environment by switching between these modes to avoid the cost, energy penalty, and environmental impact of year-round air conditioning. The operating mode changes with the seasons and throughout the day, so that the current situation reflects the external environment and always makes the best of the available conditions. The hybrid ventilation system differs from traditional ventilation systems in that HVS is a smart system with a control system that can shift between natural and mechanical modes automatically to reduce energy consumption as seen in Fig. 28.

5.1.2.2. Displacement ventilation systems. The hoods in the displacement ventilation system are located at the top of the space because the system is designed to keep occupants in the cool low area. The aim of displacement ventilation is to less mixing within the lower occupied zone, allowing heat and contaminants to lift to the top of the space and be separated into the upper-level vents.

5.1.2.2.1. Natural displacement ventilation. Warm buoyant air causes stack-driven natural ventilation, which makes air rise towards the ceiling and exit through an upper level opening as shown in Fig. 29.

5.1.2.2.2. Mechanical displacement ventilation. Natural ventilation is replaced by mechanical power in the upper part of the space when buildings lack large upper-level openings.

5.1.2.3. Wind-driven ventilation systems. Wind can also drive natural ventilation in space, with different models applying for single-sided (opening on one side of a space) and cross-ventilation (openings on two sides of space).

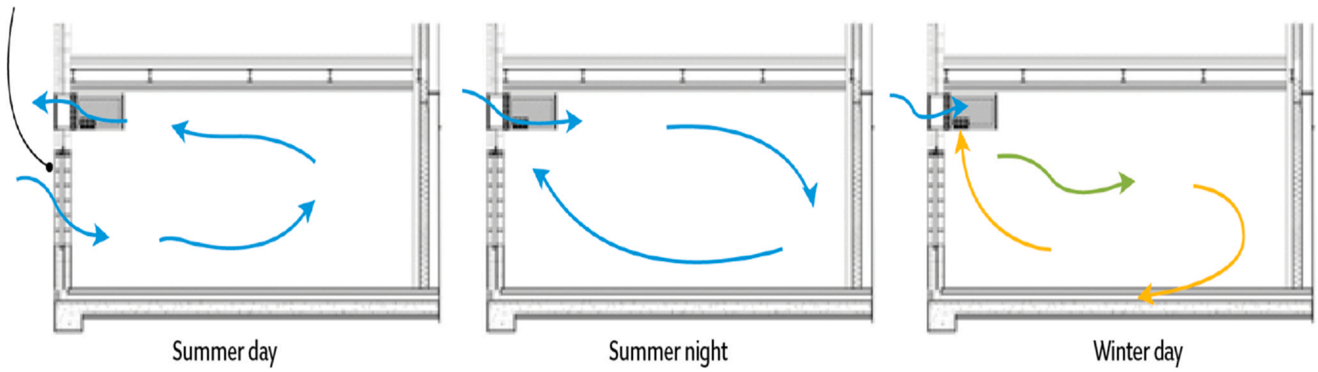


Fig. 28. Example of operating modes for single-sided hybrid ventilation system.
Source: Monodraught.

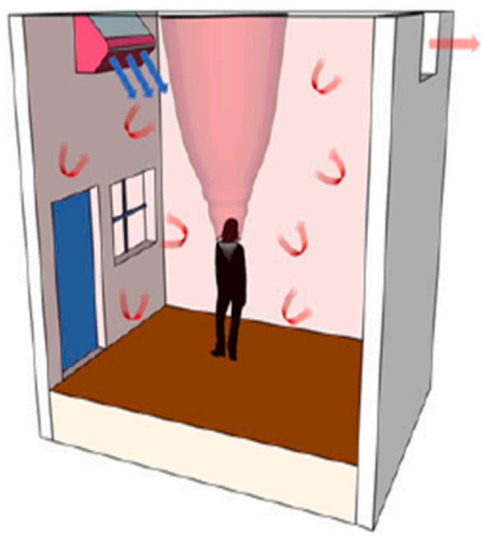


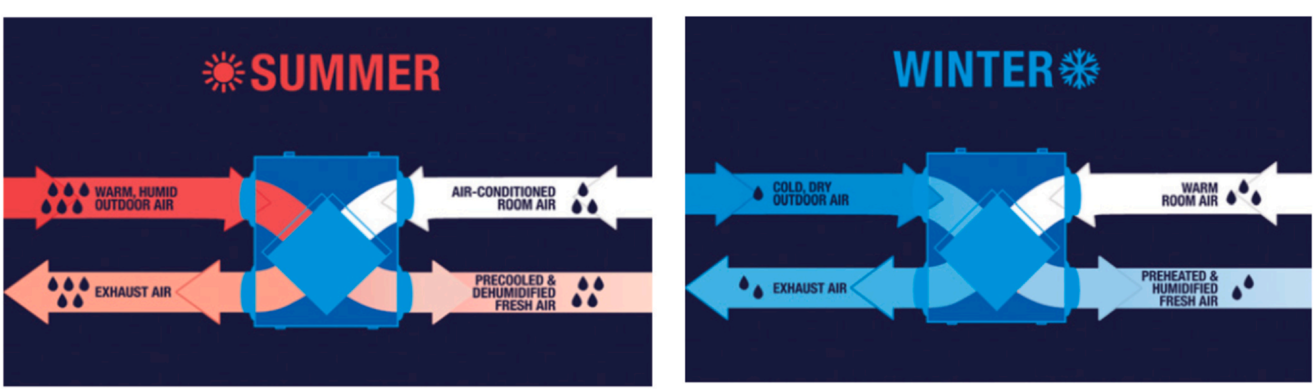
Fig. 29. Schematic showing displacement ventilation.

5.1.2.4. Mechanical ventilation with heat recovery systems. In the case of novel coronaviruses, the ventilation process could be improved by incorporating heat recovery ventilation (HRV) or energy recovery ventilation (ERV) (Agopian, 2020; Peng et al., 2015; Lian and Feng, 2016; www.nyc.gov/RetrofitAccel, 2021), allowing the IAQ to be optimized. These systems allow us to adjust and control the state of the indoor air supply directly in the case of ventilation or as a component of an energy recovery air conditioning system, thereby ensuring IAQ. An energy recovery ventilator (ERV) is a system that makes use of energy recovery technology, such as a stationary plate or a rotary wheel. This process makes use of balanced air flows to recover the total energy that would otherwise be expended, which is made up of heat (sensible energy) and moisture (potential energy) (Agopian, 2020).

In the summer, the total energy from the exit cool indoor air pre-cools and dehumidifies the warm and moist outside air as seen in Fig. 30a. In the winter, the total energy from the warm indoor air outside pre-heats and humidifies the cool, dry outdoor air as shown in Fig. 30b. As a result, less HVAC energy is required, allowing HVAC equipment to be scaled back. Pollutants are expelled, and clean outdoor air is brought inside to improve indoor air quality (IAQ) and energy efficiency as depicted in Fig. 30. As a result, ERVs are the ideal solution for high-level ventilation and energy savings.

Fig. 31 depicts the ventilation rate results based on window opening rates and ventilation strategy.

Fig. 32 depicts the infection probability as a function of exposure time and ventilation rate. When wearing a mask, the required ventilation rates to keep the infection probability below 1% should be around 1.06, 2.12, 4.24, and 6.40 h^{-1} for exposure times of 0.5, 1, 2, and 3 h. If a mask is not worn respectively, the required ventilation rate should be around 4.24, 8.51, 17.02, and 25.59 h^{-1} for exposure times of 0.5, 1, 2, and 3 h, respectively.



(a) In summer, the warm, humid outside air is precooled and dehumidified by the outgoing cool interior air.

(b) In winter, the cold, dry outside air is preheated and humidified by the outgoing warm interior air.

Fig. 30. Energy recovery ventilation renew air ERVs in both warm and cool seasons (Agopian, 2020). (a) In summer, the warm, humid outside air is precooled and dehumidified by the outgoing cool interior air. (b) In winter, the cold, dry outside air is preheated and humidified by the outgoing warm interior air.

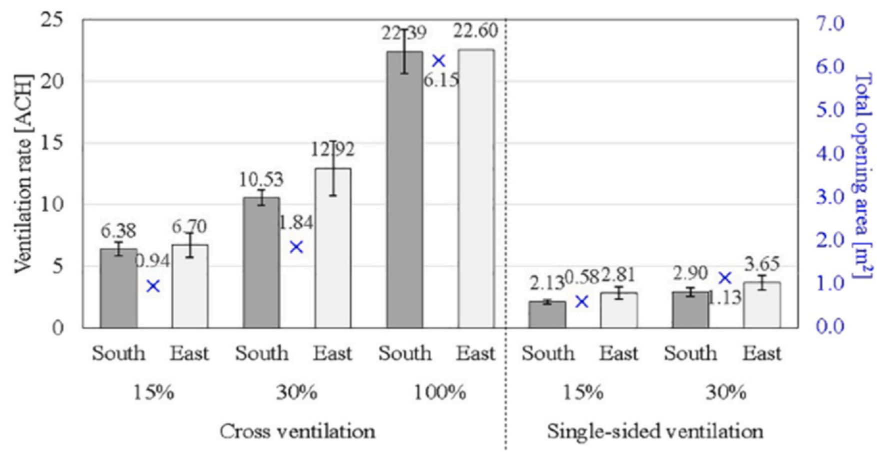


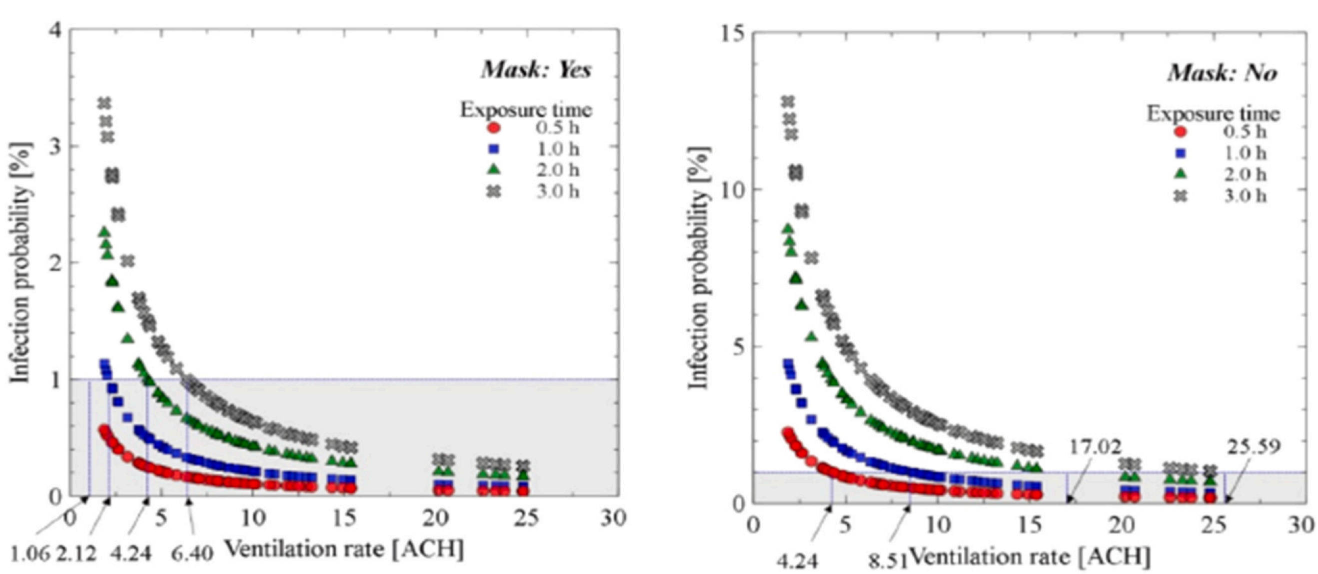
Fig. 31. Ventilation rate according to window opening method (Park et al., 2021).

Adrian Covaci (2020) issued a group of several important instructions for reducing the risk of spreading Coronavirus, including the following:

1. To inform and emphasize to building managers, hospital administrators, and infection control teams that engineering controls are effective in controlling and reducing the risks of airborne infection, and SARS-CoV-2 has the potential and is likely to be causing some infections through this route.
2. Increase existing ventilation rates (outdoor air change rate) and ventilation effectiveness using existing systems.
3. To prevent any recirculation of air within the ventilation system, as merely providing fresh (outdoor) air.
4. To supplement existing ventilation with portable air cleaners (equipped with mechanical filtration systems to capture airborne microdroplets), where there is known air stagnation (that is not well-ventilated with the existing system), or to isolate high patient exhaled airborne viral loads (e.g., on COVID-19 cohort patient bays or wards).
5. To avoid overcrowding, for example, students sitting at every other desk in school classrooms, or customers sitting at every other table in restaurants, or every other seat in public transportation, cinemas, etc. (For more clarification see Fig. 33) (Covaci, 2020).

The following study by Nehul Agarwal et al. (2021) presented an ontology graph that temporally correlates with residents' comfort during COVID-19 in a confined space with effect on parameters, as well as possible and available preventive measures as depicted in Fig. 34.

The ontology chart depicts a look at the well-established IAQ optimization measures that take influencing factors into account and can improve occupant safety in confined spaces, as well as potential future measures that could be stepped in for a sustainable indoor environment, preventing such situations in the future. IAQ can be improved using a variety of techniques, such as the planting process to create a green environment, implementing non-pharmaceutical measures, and implementing engineering controls, as shown in



(a) Infection probability with masks. (b) Infection probability without masks.

Fig. 32. Infection probability according to ventilation rate by exposure time (Park et al., 2021). (a) Infection probability with masks. (b) Infection probability without masks.

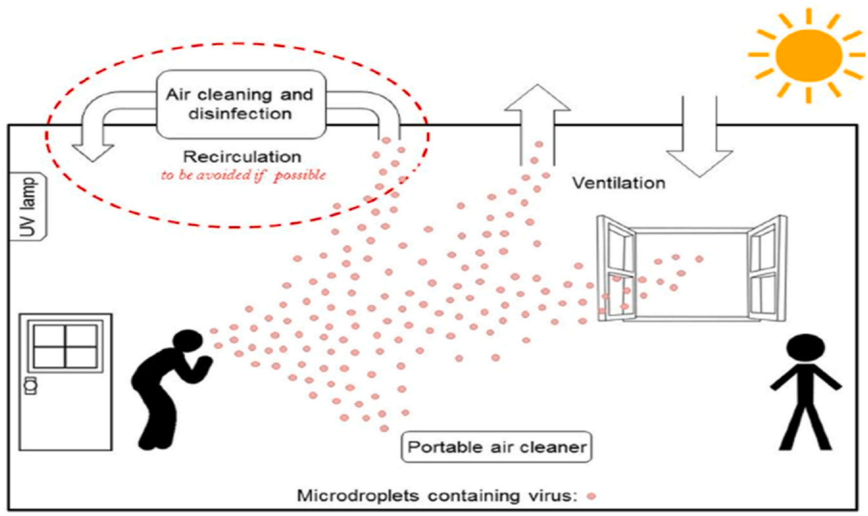


Fig. 33. Engineering level controls to reduce the environmental risks for airborne (Covaci, 2020).

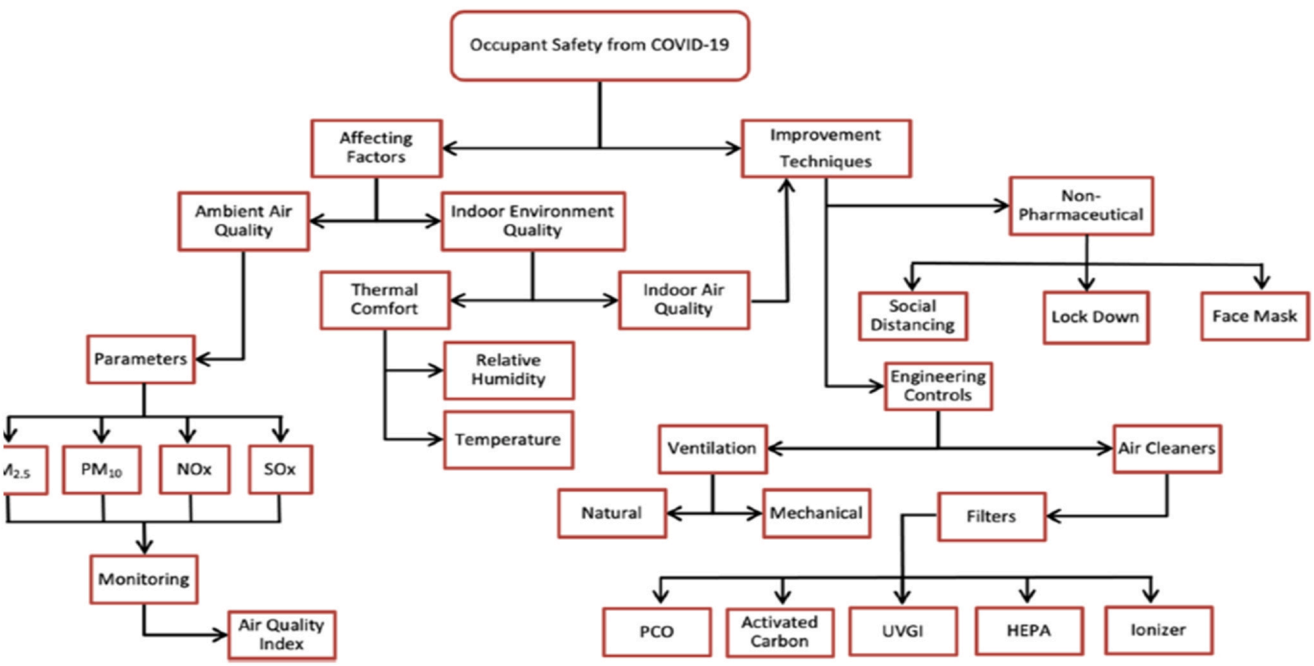


Fig. 34. The ontology chart (Agarwal et al., 2021).

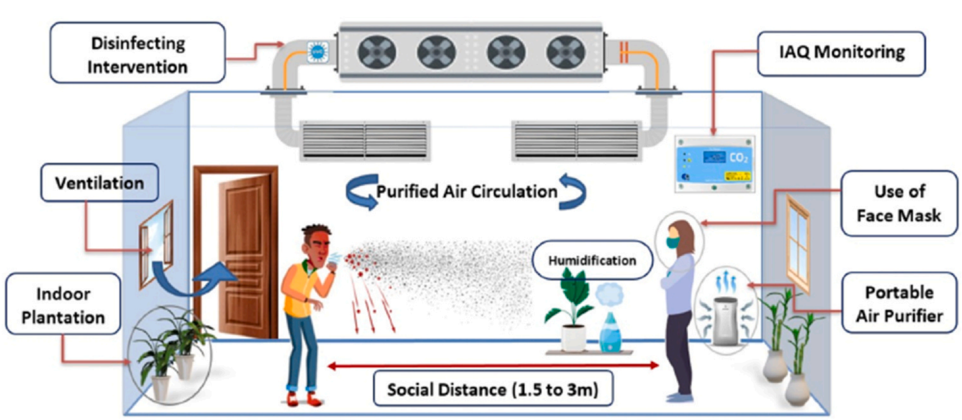


Fig. 35. IAQ improvement techniques (Agarwal et al., 2021).

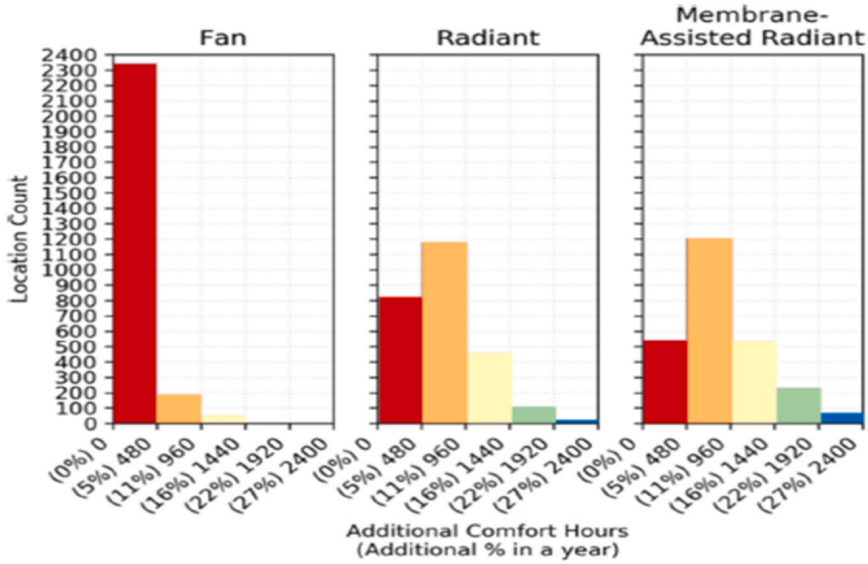


Fig. 36. Histograms of additional comfort hours and locations with different technologies (Aviv et al., 2021).

Fig. 35, which depicts all the methodologies that should be used to enhance occupant health.

Facemasks, lockdown, and social distancing are some of the methods that appear to be used to improve IAQ. So, it could be reduced the spread of COVID-19. Agarwal et al. (2021). Facemasks have become the new normal in society because they are thought to provide significant protection against SARS-CoV-2 transmission, thereby limiting disease contagion from infected individuals. Using lockdown improved the air quality in the early stages. As all transportation and industrial sectors were shut down, several countries had seen significant reductions in air and water pollution. This was one of the few positive outcomes of the strict restrictions imposed globally. Social distancing is a non-pharmaceutical method of preventing the spread of deadly viruses by keeping an appropriate distance from other people so that they do not come into physical contact. This strategy must be implemented and followed at both levels, particularly in congested areas, markets, and public gatherings. If an infected or suspected person is quarantined in the home, other housemates should keep a safe distance and protect themselves from infection (Agarwal et al., 2021). Dorit Aviv et al. (2021) proposed a system that combines a new radiant cooling technology with natural ventilation to increase fresh air delivery into buildings all year while using less energy and improving air quality. Fig. 36 summarizes the extended natural ventilation hours analysis. It can be depicted from the figure that an increase in comfort hours in three scenarios in comparison to the fan-assisted scenario, using radiant systems increases the number of locations from 200 to 1200 (5–11%) with 480–960 comfort hours. With membrane-assisted radiant panels, the number of locations with 1440–1920 comfort hours increased (16–22%) from 100 to 200, and 1920–2400 comfort hours increased (22–27%) to 70%. All of this is accomplished using open windows that allow for high ventilation rates (Aviv et al., 2021).

Preventive measures such as social distancing, lockdown or wearing masks are only effective until the authorities tighten their grip on them. Once restrictions are mitigated, a rise in COVID-19 cases can be noticed. Also, these measures do not give a permanent solution for the future. This pandemic alerts engineers to search for a better control strategy that could be most useful in preventing biological attacks. Two control strategies are recognized to help improve the health of the population and protect them from the spread of infection, namely proper ventilation, and air purification. Leung and Chan (2006) introduced and expanded on recommendations and guidelines for hospital engineers to improve indoor air quality to protect patients and health care workers from hospital-acquired infections and occupational diseases. Airborne chemical and microbiological pollutants of concern in hospitals have been identified, and major emission sources, control methods, and exposure limits have been thoroughly documented and reviewed. Appropriate engineering designs and processes were also examined, with recommendations for effective contaminant mitigation and removal. Mechanical ventilation, filtration, differential pressure control,

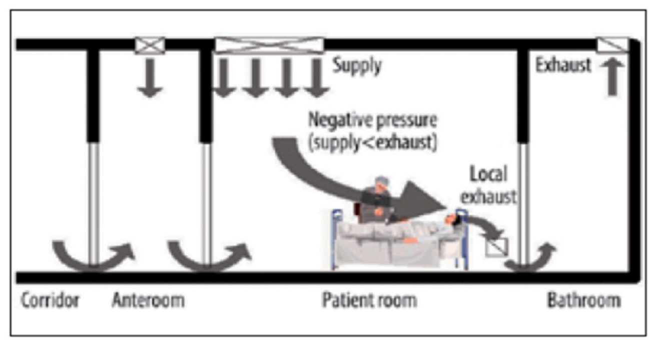


Fig. 37. Differential pressure control in infectious isolation room (Aviv et al., 2021).

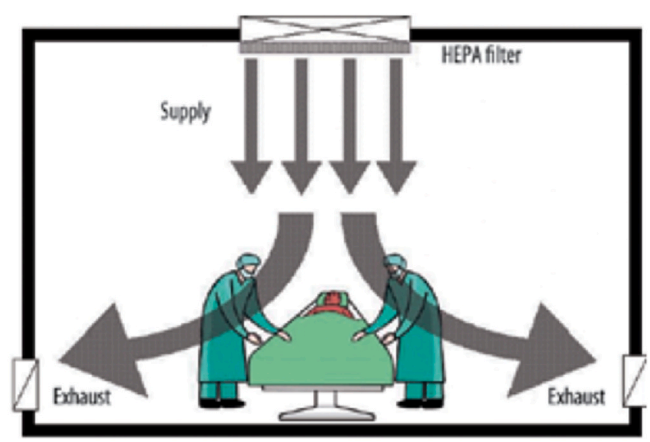


Fig. 38. Vertical unidirectional airflow in operating theater (Aviv et al., 2021).

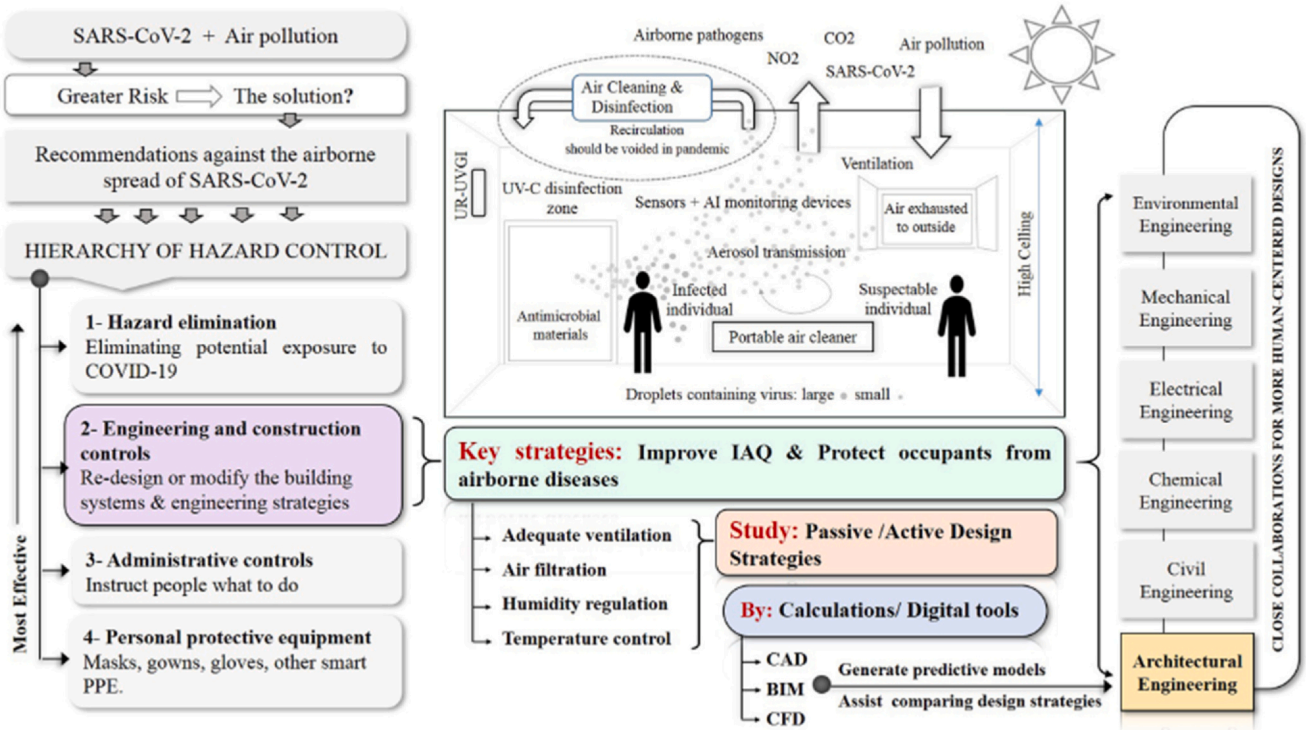


Fig. 39. Architectural and engineering roles based on the hazard control hierarchy (Megahed and Ghoneim, 2021).

directional airflow control, local exhaust ventilation, and ultraviolet irradiation were all used as control and mitigation measures (UVGI). Its applications in critical environments, such as operating rooms, isolation rooms, and other modular units, have also been considered. They discuss the airborne contaminants as well as the critical engineering mitigation measures required in various hospital facilities, such as mechanical ventilation, filtration, differential pressure control, directional airflow control, and ultraviolet germicidal irradiation (UVGI). Mechanical ventilation is essential for reducing indoor air pollutants by exhausting contaminated indoor air and bringing clean outdoor air into an air-conditioned building (ASHRAE, 1999, 2001; AIA, 2001; CDC, 1994). The recommended outdoor air change rates are based on the minimum standards for outdoor air quality. Because of the poor quality of the outdoor air, it should be treated before being drawn into the indoor environment. In critical areas such as operating rooms and delivery rooms, 100% outdoor air ventilation is required. keeping a pressure differential between two adjacent areas, such as the isolation room and corridor shown in Fig. 37, can limit air leakage in a single direction through the door undercut.

The most common unidirectional flow methods are vertical (from ceiling to floor) and horizontal (from wall to wall). Fig. 38 shows how a vertical unidirectional airflow can effectively remove contaminants dispersed by the surgical team.

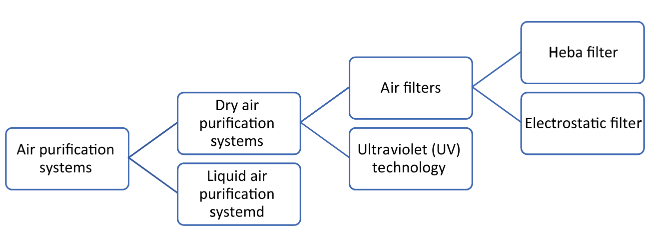


Fig. 40. Block diagram of air purification systems.

The clean air is delivered vertically from the ceiling to the surgical site. The clean air is supplied vertically from the ceiling to the surgical site, where the supply diffusers should be unidirectional. The polluted air is drawn to the sides at floor level. Significantly attempt has gone into developing engineering techniques to keep airborne pathogens out of the population or to keep them at low enough levels to not cause disease (Megahed and Ghoneim, 2021). Fig. 39 illustrates architectural and engineering controls in constructed environments based on the threat control pyramid.

5.2. Air purification systems as a practical solution accompanying the improvement ventilation process

Poor indoor air quality can have a negative impact on occupants' comfort and health. Based on the most recent Amos (2016) data, more than 5.5 million people die prematurely each year as a result of outdoor and indoor air pollution. The importance of ventilation in maintaining a clean indoor environment cannot be overstated. Ventilation systems, on the other hand, can be major sources of airborne pollutants due to insufficient system design, distribution, cross-contamination, and other factors. As a result, air filtration technology plays an important role in safeguarding human health by removing indoor air pollutants, as well as giving an alternate solution for decreasing energy consumption, operating expenses, and so achieving sustainability (Yu et al., 2021; Liu et al., 2017a). Fig. 40 shows a block diagram of air purification systems.

5.2.1. Liquid air purification systems

Washing systems are used to remove contaminants and suspended particulates from filthy air. Washing machines mostly consist of fresh air, return air, mixed air, and supply air. These systems wash the air before treating it thermally and distribute it to the places to be fed. This system is similar to that used in cooling towers where the required air is washed with a large amount of sprinkled water from top to bottom or through a system that ensures the distribution of water to all the amount of air. Chemicals and

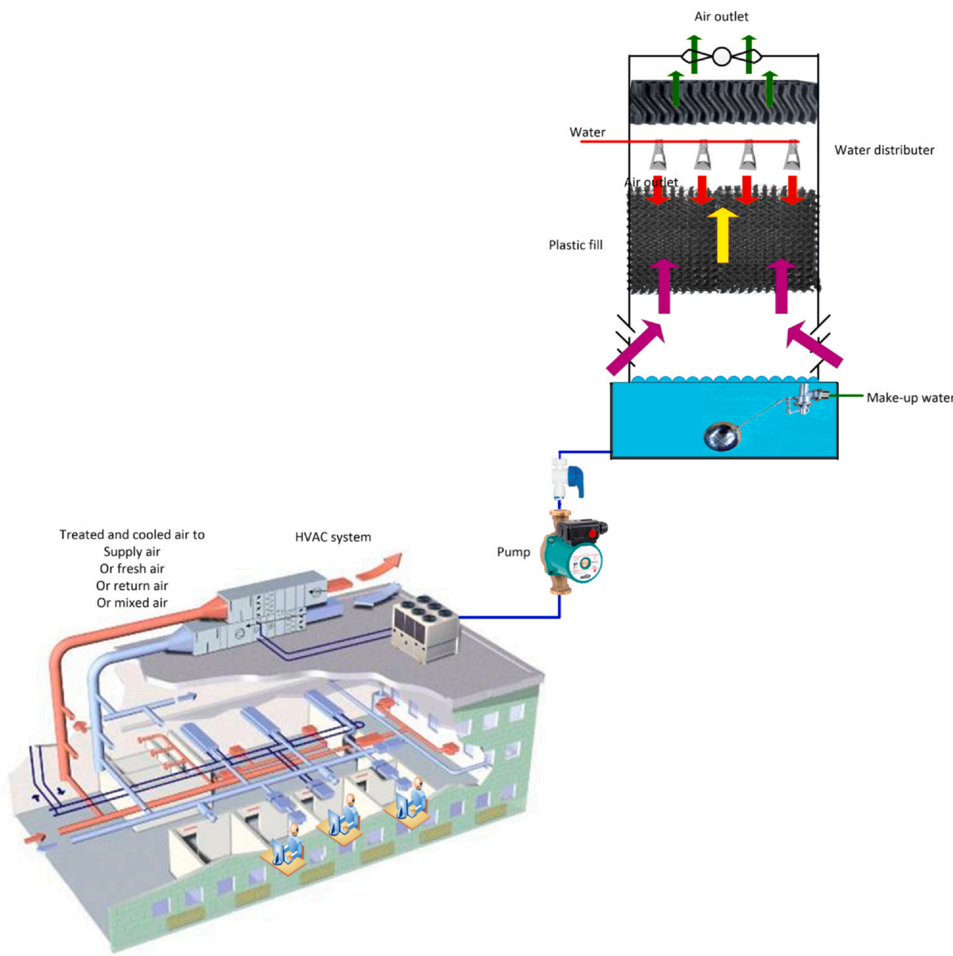


Fig. 41. A layout sketch of liquid air purification systems (Elsaid and Ahmed, 2021).

sterilizers are also added to the air used in the air conditioning process to sterilize the air. In addition, it can add other substances that change the viscosity of the water to ensure polarization or attract unwanted substances to the air to be treated. Fig. 41 shows a liquid air purification system that is treated in a cooling tower equipped with chemicals and sterilizers and then the treated air flows into the HVAC system to be cooled. Then, the cold-treated air is forced to the feeding, mixing, or return points (Ahmed and Elsaid, 2019).

5.2.2. Dry air purification systems

There are two types of air purifying technologies, active and passive. Active air purifiers release negatively charged ions into the air, causing pollutants to stick to surfaces, while passive air purification units use air filters to remove pollutants. Passive purifiers are more efficient since all the dust and particulate matter is permanently removed from the air and collected in the filters. Several different processes of varying effectiveness can be used to purify the air. As of 2005, the most common methods were high-efficiency particulate air (HEPA) filters and ultraviolet germicidal irradiation (UVGI) (Honeywell, 2017). There are two forms of air purification techniques, active and passive. Active air purifiers issue negatively charged ions into the air, causing pollutants to stick to surfaces, while passive air purifiers use air filters to remove pollutants. Passive purifiers are more efficient as dust and particulates are permanently removed from the air and collected in filters (Air Cleaning Technologies, 2005). Many various techniques of varied effectiveness can be employed to clean the air in which the most common methods were high-efficiency air (HEPA) filters and germicidal UV irradiation (UVGI). The dry air purification systems use UV technology and air filter to improve the air quality, as shown in a block diagram of Fig. 40.

5.2.2.1. Ultraviolet (UV) light to purify and sterilize the air. Ultraviolet germicidal radiation (UVGI) is a disinfection method that uses short-wavelength ultraviolet (UV-C or UV-C) rays to kill or inactivate microorganisms by destroying their nucleic acids and disrupting their DNA, rendering them unable to perform their functions cellular vitality. UVGI is used in a variety of applications, such as purifying food, air, and water (Air Cleaning Technologies, 2005).

The scientific community does not yet have a particular deactivation dosage for the COVID-19 virus (SARS-CoV-2). However, we know that utilizing direct UVC radiation at a wavelength of 254 nm, the dosage values for comparable viruses in the same SARS virus family are 10–20 mJ/cm^2; this dosage will accomplish 99.9% disinfection (i.e., inactivation) under controlled lab circumstances. The virus is frequently concealed or veiled from direct UVC light in real life, limiting UVC's potency. To compensate, researchers are using dosages ranging from 1000 to 3000 mJ/cm^2 to achieve the current CDC disinfection objective of 99.9% deactivation (https://iuva.org/iuva-covid-19-faq). A team of researchers collaborated on the development of an air disinfection system in the cockpit that uses UV radiation and is integrated into an aircraft's ventilation system to ensure the highest level of safety during flight (Pecho et al., 2020). Fig. 42 depicts the HEPA filter mist scenario without extra UV disinfection (left) and with the radiator added (right).

Ultraviolet germicidal radiation (UVGI) is a disinfection method that uses short-wavelength ultraviolet (UV-C or UV-C) rays to kill or

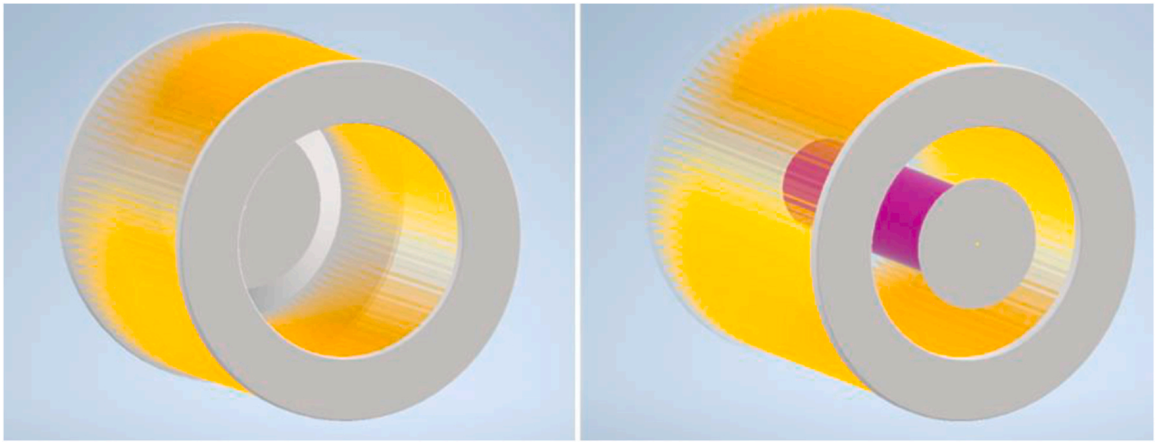


Fig. 42. A HEPA filter without disinfection (Left) and with a UVC emitter (right) (Pecho et al., 2020).

Fig. 43. In-Duct air disinfection system.

Table 3
The susceptibility of COVID-19 to UV (Walker and Ko, 2007).

Airstream disinfection			
Microbe	Type	Diameter µm	UV dose for 90% reduction µJ/cm^2
Coronavirus (incl. SARS)	ssRNA	0.11	611
Influenza A virus	ssRNA	0.098	1935

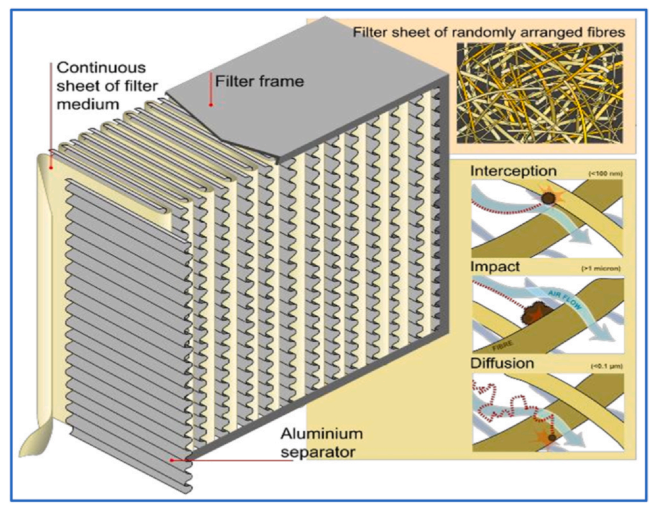


Fig. 44. HEPA air filter with its trapping particles mechanism (Roy et al., 2009).

inactivate microorganisms by destroying their nucleic acids and disrupting their DNA, rendering them unable to perform their functions cellular vitality. UVGI is used in a variety of applications, such as purifying food, air, and water. The scientific community does not yet have a particular deactivation dosage for the COVID-19 virus (SARS-CoV-2). However, we know that utilizing direct UVC radiation at a wavelength of 254 nm, the dosage values for comparable viruses in the same SARS virus family are 10–20 mJ/cm^2; this dosage will accomplish 99.9% disinfection (i.e., inactivation) under controlled lab circumstances. The virus is frequently concealed or veiled from direct UVC light in real life, limiting UVC's potency. To compensate, researchers are using dosages ranging from 1000 to 3000 mJ/cm^2 to achieve the current CDC disinfection objective of 99.9% deactivation (https://iuva.org/iuva-covid-19-faq). UVGI (Ultraviolet Germicidal Irradiation) is one of the most effective technologies for limiting the spread of airborne bacteria, according to the CDC. Dilution ventilation, laminar and other in-room flow regimes, differential room pressurization, tailored ventilation, source capture ventilation, filtration (central or unitary), and UVGI are some of the measures recommended by ASHRAE to combat disease transmission (upper room, in-room, and in the airstream). Germicidal UV irradiation is particularly effective against Coronavirus. The susceptibility of coronavirus to UV is shown in the table below. When compared to influenza (common cold) virus, it multiplies by more than three times. Fig. 43 illustrates the erection of UV in the duct. Table 3 explores the susceptibility of COVID-19 to UV (Walker and Ko, 2007).

5.2.2.2. Dry air purification systems with air filter. Air filters are vital for air quality because they act as a barrier against viruses and other microparticles. The filter that has been employed is greatly determined by the purpose for which it is utilized. Pollen is 9–80 m in size, mold spores are 3–50 m in size, fine ash is 0.7–60 m in size, bacteria are 1–10 m in size, tobacco smoke is 0.1–7 m in size, and viruses are up to 0.1 m in size (Satheesan et al., 2020; Nazarenko, 2020). The type of filter required varies on the particle size, but very small particles require a deep, bulky, and expensive filter with a high barrier to air passage and significant energy consumption. In the event of a pandemic, the filter utilized must be capable of preventing particles containing the Coronavirus (COVID-19). Filters smaller than 0.01 µm must be preceded by another filter to keep proportionally larger particles, and appropriate mounting frames must be used to prevent dirty air from escaping from the edges. There are many different types of air filters that are categorized based on their particle separation effectiveness and the size of the porosity that can separate particles. The HEPA filter is one of the most essential of these

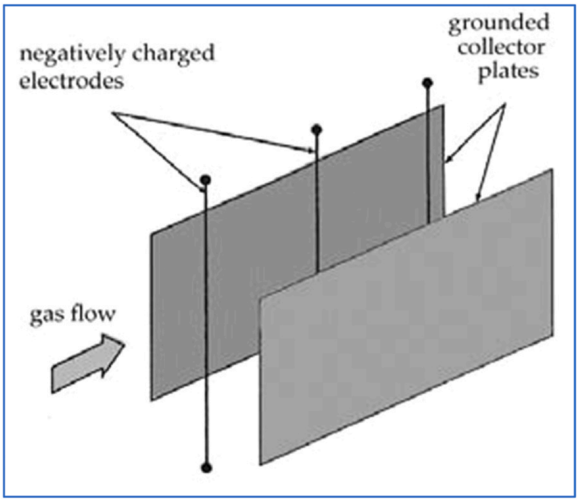


Fig. 45. Schematic of electrostatic smoke precipitator (Roy et al., 2009).

types of air filters because of its great effectiveness in filtering microscopic particles with high efficiency of up to 99%. HEPA filters are distinguished by their ability to separate particles with a diameter of less than 0.3 μm, allowing them to separate droplets emitted from human exhalation by their proximity to the filters with high efficiency, where the diameter of these drops reaches five microns or more efficiently up to 99.97%.

It has a 99.97% efficiency in eliminating particles fewer than 0.3 μm from contaminated air, with a flow rate of 255–680 cubic meters per hour depending on the blockage of their pores (Roy et al., 2009). HEPA filters is a type of pleated paper and has a very dense network of glass fibers. When using HEPA filters, it is common to employ a pre-filter to extend the time between replacements. Pre-filters are essentially a fibrous mesh with greater pore diameters than standard filters. Fig. 44 manifests a HEPA air filter with its trapping particles mechanism (Roy et al., 2009).

One type of electronic air filter is electrostatic smoke precipitators (ESP) that create an electric field to ionize the particles that pass through them. Fig. 45 shows this type of air filter. Moreover, Fig. 46 displays a schematic of an electrostatic air filter (ES) with washable electrostatics and filtration (Liu et al., 2017b).

An electrostatic precipitator air filter varies from a HEPA filter in that it removes any size of particulate matter from the contaminated air as opposed to mechanical filters (HEPA) which put constraints on the size of the filterable particulate holes (Allam and Elsaid, 2020).

6. Review summary and corrective recommendations

The whole world was grieved during the past year and the current due to the loss of many relatives and friends as a result of the spread of the global pandemic, the COVID-19, around the whole world, and he did not leave a home except and grieved him with the loss of a loved one. The world has made many attempts to try to stop the rate of virus spread by studying the reasons that lead to the acceleration of the spread of the global pandemic and issuing effective and mandatory recommendations to limit the spread of the virus until a vaccine is reached that protects humanity from this deadly epidemic. Most of the sectors, due to rising temperatures, have become dependent on-air conditioning systems as a means to achieve a sense of comfort, and it has shifted from a means of achieving well-being to a basic means of feeling thermal comfort. Disabling heating, ventilation, and air conditioning (HVAC) systems are not recommended to reduce the transmission of the virus. In this case, the filtration and ventilation processes achieved by the heating, ventilation, and air conditioning (HVAC) systems can reduce the concentration of airborne COVID-19 and thus the risk of transmission through the air. Air supply systems can reduce virus transmission through filtration integrated with HVAC systems. HVAC systems are a vital requirement for human comfort in summer and winter while controlling temperature, humidity, and air speed at satisfactory values, and controlling the air supply from solid particles and dust for a high quality of fresh air (IAQ). Because of this new situation of the spread of the coronavirus, HVAC systems need to be reviewed and their suitability studied for the new state of the pandemic. Thus, a review of construction, design, and maintenance is required to examine whether they have a positive impact on the spread of the epidemic. The present review paper demonstrates that the lockdown had several positive effects on the environment and energy consumption. Until a quantity of effective vaccines is available to reduce the risk of infection and limit the ongoing pandemic, improved ventilation may be a critical component in limiting the spread of COVID-19. The ventilation system can be effective in removing airborne infectious agents if it is properly designed and kept clean to maintain the correct pressure among the functional units. The critical recommendations listed below may be considered for improving the A/C systems and ventilation processes to face COVID-19.

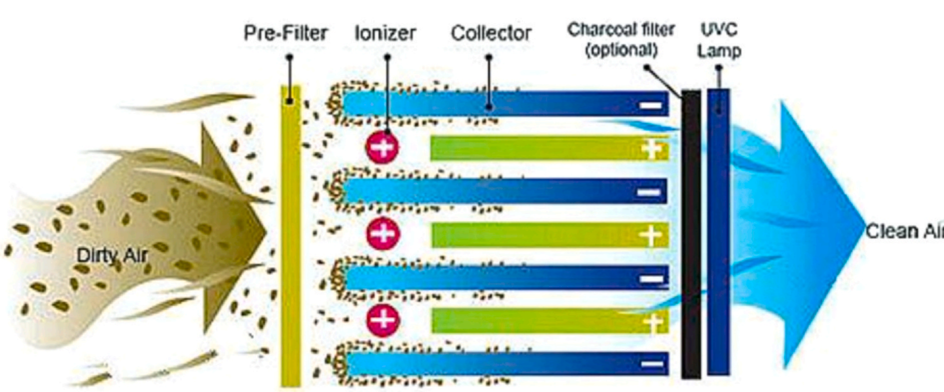


Fig. 46. Schematic of electrostatic air filter (ES) with washable electrostatics and filtration (Liu et al., 2017b).

1. Upgrade filters to MERV 13 if the system can handle the air resistance.
2. Circulate outside air prior to occupancy and after, especially while cleaning and disinfection are occurring.
3. Inspect and maintain local exhaust ventilation in restrooms, kitchens, cooking areas, labs, etc.
4. Increase exhaust ventilation from restrooms above code minimum rating.
5. Work with building engineer or HVAC specialist to generate air movement that goes from clean-to-less-clean air through positioning of air supply and exhaust air diffusers and/or dampers.
6. Use fans and place them safely and carefully in or near windows so that they do not cause potentially contaminated air to flow directly from person to person and, in the case of a ceiling fan, reverse the flow direction to draw the air upwards.
7. Open windows and doors if it are safe, weather allows, and include more outside time during the day.
8. Reduce occupancy in areas where outdoor ventilation cannot be increased to the optimal amount.
9. Ventilate building or room 2 h before and after occupancy.
10. Portable HEPA air cleaners can supplement ventilation and are most critical in rooms with poorer ventilation or in isolation areas.
11. The equivalent of at least 5–6 air changes per hour is recommended.
12. Use fans for ventilating is an acceptable solution that should throw air away from people. Moreover, HVAC units should be pointed so they do not blow air across occupants (e.g., from one individual to others).
13. Air filtration should be maximized in the space 2 h before and after occupancy.
14. Do not use ozone generators, electrostatic precipitators and ionizers, or negative ion air purifiers because they can produce harmful by-products.
15. HEPA filters should be cleaned/replaced regularly as recommended by the manufacturer and on a regular schedule and HEPA air filters should be replaced with nanofibrous air filters or enhanced electrostatic air filters.
16. Consider that UVGI is only a primary filtration stage, although is germicidal but not capable to kill or inactivate infectious microorganisms such as coronavirus.
17. Avoid recirculation of air in HVAC systems by shutting off return air dampers by diverting return air from central air conditioning systems to the exhaust air path and feeding 100% fresh air with decentralized independent air conditioning units installed in isolation rooms for patients COVID-19.
18. Exhaust air path must be at a height of at least 5 m from the end of the top of the building and increase the size of the exhaust fans.
19. Reducing levels of air pollution inside polluted places and cities, especially industrial ones, by implementing strict, compulsory, and sustainable environmental policies at the international level.
20. Exhaust air should be adjusted to greater than the supply air through the central A/C systems so that a negative pressure of at least 2.5 Pa (preferably > 5 Pa) is achieved in the zones.
21. Set the conditioned room temperature between 25 °C and 27 °C while maintaining the relative humidity between 50% and 70%.
22. Commitment to regular maintenance procedures of HVAC equipment and the necessity to wear appropriate personal protective equipment and wrap all spent and damaged materials such as old filters and dispose of them safely by burning (OSHA 3990-03 2020).

Conflict of interest statement

The authors report that there are no personal or financial conflicts or relationships with individuals or research or commercial institutions that would adversely affect the publication of the present research work. We would also like to note that this research was done to become important to the extent that it contributes to providing solutions to confront the spread of the deadly COVID-19 epidemic.

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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