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An overview of SARS-CoV-2 transmission and engineering strategies to mitigate risk

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ABSTRACT

The spread of the COVID-19 pandemic has profoundly affected every aspect of our lives. To date, experts have acknowledged that airborne transmission is a key piece of the SARS-CoV-2 puzzle. Nevertheless, the exact mechanism of airborne transmission of SARS-CoV-2 remains unclear. Recent works have shown the spreading of SARS-CoV-2 through numerical modeling and experimental works, but the successful applications of engineering approaches in reducing the spread of SARS-CoV-2 are lacking. In this review, the environmental factors that influence the transmission risk of SARS-CoV-2, such as ventilation flow rates, humidity, and temperature, are discussed. Besides, additional macro and micro weather factors, regional and global transmission, and the variants of the spread of SARS-CoV-2 are also reviewed. Engineering approaches that practically reduce the risks of SARS-CoV-2 transmissions are reported. Given the complex human behavior, environmental properties, and dynamic nature of the SARS-CoV-2 virus, it is reasonable to summarize that SARS-CoV-2 may not be eradicated even with the timely implementation of interventions. Therefore, more research exploring the potential cost-effective ways to control the transmission rate of SARS-CoV-2 may be a worthwhile pursuit to moderate the current crisis.

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1. Introduction

The emergence of COVID-19, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pneumonia, poses a global threat and challenges to communities as well as healthcare systems. A rapid infection control response is essential to contain and mitigate the risk of nosocomial transmission and outbreaks. Current reports and evidence suggest that SARS-CoV-2 is highly contagious and transmits rapidly in communities [1]. As of today, the COVID-19 pandemic is not yet out of the woods due to the emergence of SARS-CoV-2 variants (the recent outbreak of CH.1.1, BQ.1, XBB, XBB. 1.9.1, XBB.1.16, XBF, BA.2.75, and XBB.1.5 Omicron subvariants) with increased transmission capacity and immune escape potential [2]. At the time of writing, 633 million cases of SARS-CoV-2 infections have been reported worldwide, with 6.84 million deaths. The U.S.A, India, France and Germany have reported among the highest number of cases compared to other countries. Notably, the rapid emergence and growth of notorious variants of SARS-CoV-2 in highly vaccinated populations have put the effectiveness of the vaccine in doubt. Hence, researchers worldwide are working at record speed to find the best ways to keep up with the ever-increasing transmission rate of SARS-CoV-2.

Social distancing and frequent hand washing are among the strategies used to reduce the transmission of SARS-CoV-2. Based on the latest update (as of May 7, 2021) [3], the primary routes of SARS-CoV-2 transmission can be categorized into (1) inhalation of viruses, (2) contact of mucous membranes with hands that are soiled by virus-containing respiratory fluids and contaminated surfaces (though, the later shows possible but not a significant risk factor). Reports and evidence from the WHO have confirmed that SARS-CoV-2 is transmitted via contact, aerosol and droplet route [4–7]. Droplet transmission occurs when people are in close contact with individuals showing respiratory symptoms such as coughing or sneezing. Therefore, social distancing has become the basis of public health advice. Despite the similar strategy, different organizations implemented different safe distances between people to reduce transmission (WHO - 1 m, CDC and National Health Service (NHS) - 2 m) [8]. According to WHO, infective respiratory particles that are deposited on the ground or are suspended in low concentrations at 2 m from the source are unlikely to cause transmission [8]. Droplet transmission may also occur through fomites (inanimate surfaces or objects) [9]. However, a recent study reported the transmission of SARS-CoV-2 via the fomite route is insignificant [10]. Therefore, further investigations are required to confirm such a claim.

Preliminary evidence shows that the virus spreads in smaller particles from exhaled air, known as aerosols [9]. These aerosols are tiny and easily remain aloft in the air, leading to airborne transmission and posing a risk of exposure [11,12]. Due to its highly contagious nature, preventive measures such as increased ventilation rate, improved natural ventilation, avoiding staying in another person's direct air flow and minimizing the number of people sharing the same environment should be adopted to reduce the risk of infection [11]. In 2020, 239 scientists from different disciplines, such as environmental science, respiratory science, and architecture, appealed to the medical community and relevant authorities (local or international) to acknowledge the potential for airborne spread of SARS-CoV-2, citing increasing evidence that patients were infected by viruses in microscopic respiratory droplets (microdroplets) at short to medium distances (up to several meters or room-scale).

The WHO defines droplets with particle diameters of $\geq$ 5–10 μm and aerosols as $<$ 5 μm [13]. Airborne transmission refers to the presence of viruses in aerosols $<$ 5 μm that are present in the environment (these aerosols can remain suspended in the air for a prolonged period and travel over 1 m) [11]. These tiny aerosols could originate from the evaporation of larger droplets or

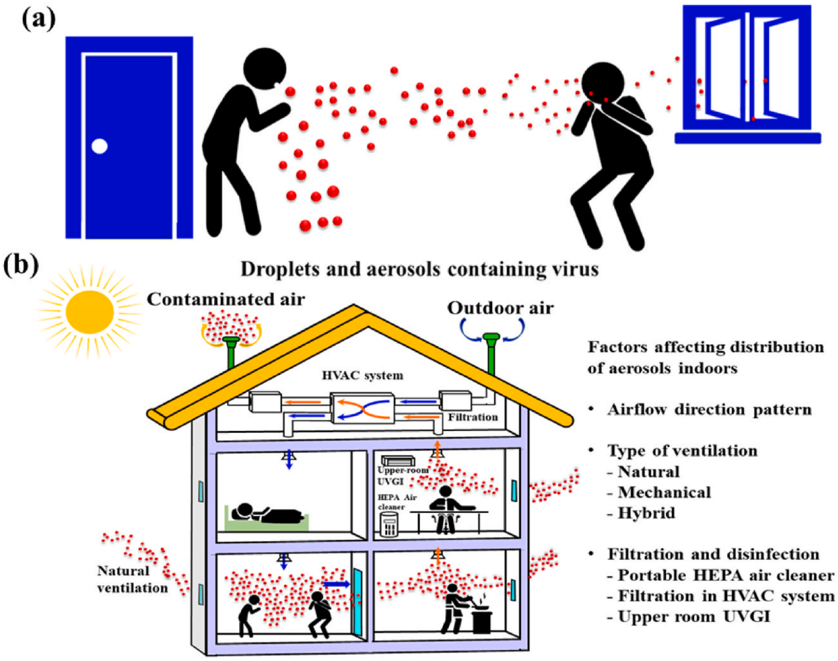

Fig. 1. (a) Larger respiratory droplets deposit on a surface nearer to the source (droplet transmission), while smaller aerosols can travel long distances indoor (airborne transmission). (b) Schematic diagram illustrating factors affecting indoor airborne transmission [11,12].

attach/condense on dust particles. Nevertheless, both forms of transmissions can be generated as a continuum of particle sizes during respiratory activities and do not demonstrate distinct behavior. Such small droplets travel freely in the air, carrying viral content up to tens of meters from the source (Fig. 1**).** This spreading route often goes unnoticed as asymptomatic individuals emit aerosols <10 μm in size and produce few droplets. Therefore, understanding the exact transport mechanism is key for preventing outbreaks and designing new social behaviors to minimize the transmission.

Studies have shown that the SARS-CoV-2 virus can be detected in the air through airborne transmission [11]. An early study investigated the transmission of coronaviruses in aerosols or their survival on various surfaces by estimating the rate of viral decay and confirmed the possible modes of transmission for SARS-CoV-2 were aerosol and fomites [14]. It was reported that the virus could remain viable and infectious in aerosols for days or 48 h (depending on the inoculum shed). Such observation was supported by another clinical study, showing positive SARS-CoV-2 in swab samples of toilet bowls and sinks while air sampling in the room remains negative [15,16]. This study has shown that viral shedding in fecal matter could be a potential route of nosocomial transmission [17].

In view of the growing evidence suggesting that SARS-CoV-2 transmission is airborne, this study aims to systematically review engineering approaches to reduce the risk of indoor SARS-CoV-2 transmission by regulating airflow, physical and environmental parameters. Furthermore, other possible measures to reduce the incidence of SARS-CoV-2 transmission, such as personal protective equipment, disinfectants, and air filtration technologies, are also identified in this review. In addition, macro and micro weather factors, regional and global transmission, and variants in the spread of SARS-CoV-2 are also discussed.

2. Classification of airborne transmission

2.1. Long-range and short-range

Long-range airborne transmission [18] and short-range airborne transmission [19] are two ideologies of the airborne transmission of SARS-CoV-2. Transmission is considered short-range when the distance is within 1.5 m [20], whereas long-range transmission covers a distance of 1.5 m or more [21] as shown in Fig. 2. Recent research has proposed long-range airborne transmission as an extension of short-range airborne transmission [22]. In such cases, the transmission route of SARS-CoV-2 may be long-range, but the volumetric exposure is equivalent to those of short-range transmission due to the restriction of ventilation rate and an increase in the ratio of infected people to susceptible people. Another study has suggested that humans are exposed to a higher risk of infection, particularly in indoor environments with large occupancy, where occupants have relatively shorter distances from each other and probably poor ventilation. Therefore, the author posits that short-range airborne transmission is the dominant route and that long-range transmission is not likely to occur if sufficient ventilation is applied [23]. Other similar works have also stressed short-range transmission as the primary route for SARS-CoV-2 infection [24]. However, in some specific cases, such as disease outbreak on enclosed environments like cruise ships, simulation models have shown that short-range and long-range transmission have contributed equally (35% each) [25]. While there is no conclusive evidence regarding the primary airborne transmission route of SARS-CoV-2, numerous studies have emphasized the critical role of ventilation in reducing transmission rate.

2.2. Numerical modelling

The COVID-19 pandemic has posed unprecedented challenges to global health, the economy, and the environment. As a result, researchers from various fields, including environmental sciences, biotechnology, mechanical engineering, disease prevention, and others, have turned numerical modeling of particle transport, such as computational fluid dynamics (CFD) simulation, to better understand the airborne dispersion of the virus in different situations and buildings. Fig. 3 provides an example of the CFD modeling used to analyze the transmission routes of viruses in a pediatric ward of one of the hospitals in Malaysia.

The effects of different ventilation conditions, as studied through CFD modelling, can help prevent the transmission of SARS-CoV-2.

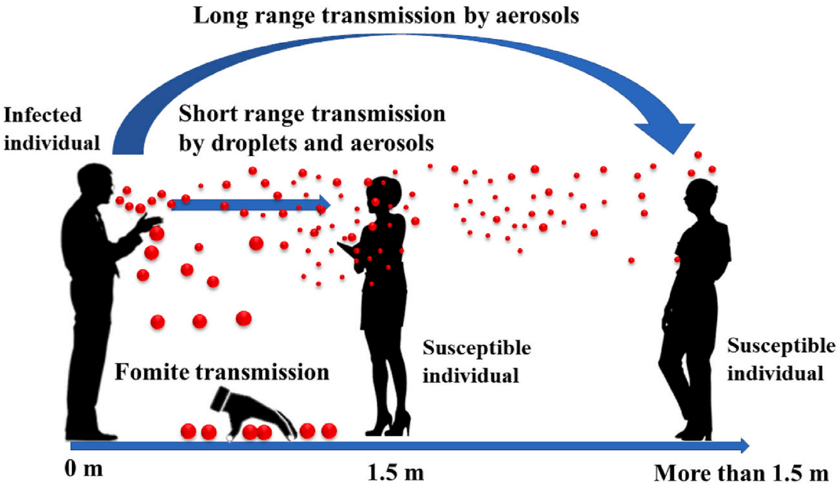

Fig. 2. Long-range and short-range transmission is determined by the distance of virus laden aerosols travel from the source.

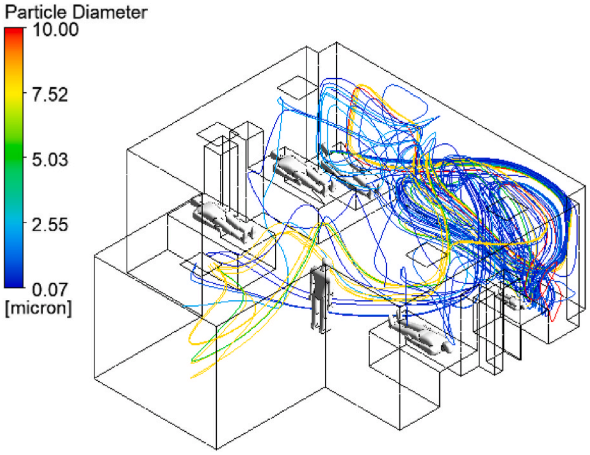

Fig. 3. The use of CFD simulation to predict the airborne transmission of SARS-CoV-2 in a pediatric ward.

For instance, in a hospital setting, the turbulence caused by the air conditioning system can promote the dispersion of the virus in the room, thereby increasing the risk of transmission [26–32]. Li et al. used CFD simulation and tracer gas measurements of ventilation to confirm the airborne transmission of SARS-CoV-2 during the first outbreak in a restaurant in Guangzhou, China [26]. The study revealed that ventilation rate is a crucial factor in the airborne transmission of the SARS-CoV-2 virus. Similar findings were reported in CFD study of two buses during an outbreak in the Hunan Province, China [27]. It was found that passengers were infected by SARS-CoV-2 due to poor ventilation in the buses (1.7 and 3.2 L/s per person).

In hospital settings, Saw et al. found that the SARS-CoV-2 virus can be recirculated in enclosed patient wards equipped with a ceiling cassette without proper return [28]. The authors reported that virus particles could be carried by airflow for up to 6 m. They calculated that aerosols of 1 μm in size take around 8 h to fall from a height of 1 m to the ground level. Therefore, an aerosol arrestor is proposed to mitigate the transmission risk in isolation wards. Saw et al. also investigated the effectiveness of indoor air purifiers (APUs) in mitigating the transmission of the SARS-CoV-2 virus in hospital common wards [29]. It was found that placing multiple APUs near the source at an elevated level increased the overall effectiveness of the APUs. Notably, the placement the APU directly under a supply diffuser should be avoided to minimize blockage of airflow and intake of contaminated air.

Bhattacharyya et al. and Ren et al. studied the feasibility of mixing aerosol sanitizer into the air conditioner to kill the virus [30,31]. It was found that the high turbulence flow generated by the air-conditioner is effective in killing viruses in a confined isolation room. The size of the particles is an important criterion determining the dispersion of the virus in the air conditioner room [32]. Particles smaller than 20 μm appear to follow the airflow, while particles larger than 45 μm tend to deposit near the source. It is recommended that the outlet of an air conditioner should be installed near the polluted source and area where large particles are likely to be deposited. Alternatively, installing a local exhaust ventilation system placed directly above the patient's face helps reduce droplets and contaminated air in the room [33].

CFD simulations were also used to assess the transmission risk in supermarkets and grocery stores [34,35]. Vourinen et al. investigated the dispersion of the aerosol and droplet particles in the supermarket using a large eddy simulation approach [34]. It was found that the SARS-CoV-2 virus was aerosolized and remained infectious for at least 3 h [36]. The dispersion of the aerosol particles depends on the airflow characteristic and temperature distribution pattern in the location [34,35]. Foster and Kinzel evaluated different mitigation strategies, such as face masks, ventilation strategies, air purifiers, and desk shields, to reduce the transmission risk in the classroom [36]. They found that face masks and ventilation systems with an air purifier work more effectively in reducing the transmission risk than using a desk shield [37,38]. It took approximately 12–20 s for a person without a field shield to get infected with the SARS-CoV-2 virus. The infection time is reduced to 11 s if the ventilation rate is poor with no air movement.

The quanta emission rate infection risk models developed by Buonanno et al. were used to assess the transmission risk of SARS-CoV-2 [39]. The risk model (Equation (1)) was applied to investigate the spread of the SARS-CoV-2 virus in Italy in various properties such as pharmacies, supermarkets, restaurants, post offices and banks before and after the lockdown. Mechanical and natural ventilation were taken into consideration in the model. The model showed that the presence of an infected person in an enclosed environment for 10 min poses a high transmission risk. The exposure risk for mechanical and natural ventilation is approximately 1.2% and 2.8%, respectively. Hence, good ventilation is desired to reduce the risk of transmission.

$$ER_q = c_v \bullet c_i \bullet V_{br} \bullet N_{br} \bullet \int_0^{10\mu m} N_d(D) \bullet dV_d(D) \tag{1}$$

ER_q represents quanta, h^{-1}
c_v represents viral load in the sputum, RNA copies mL^{-1}

c_i represents the conversion factor defined as the ratio of infectious quantum to the infectious dose in viral RNA copies
V_{br} represents the volume of exhaled air per breath, cm^3
N_{br} represents breathing rate, breath h^{-1}
N_d represents the droplet number concentration, part. cm^{-3}
$V_d(D)$ represents the volume of a single droplet (mL) as a function of droplet diameter.

On the other hand, Wang and Yoneda used a concentration model to predict the dispersion of the virus from a confined source space to an uncontaminated area [40]. The increase in the air exchange rate is reported to reduce the time limit. The time-dependent penetration factor of the indoor environment P(t) and penetration factor P_d are important parameters when the air exchange rate is less than 1.20 h^{-1}. Besides, P(t) is also significant when the air exchange rate equals 1.20 h^{-1}. Shrestha et al. used CONTAM software to model the dispersion of airborne SARS-CoV-2 aerosols in the US Department of Energy buildings and evaluate different mitigation strategies [41]. The study showed that unventilated stairwells have a higher aerosol concentration, while building flushing techniques are ineffective in reducing the risk of transmission. The use of face masks, a high percentage of outdoor air supply, portable HEPA filters, ultraviolet germicidal irradiation disinfection and MERV-13 or higher air filters are effective strategies to reduce the risk of transmission. Cheng et al. used CFD analysis to explain the SARS-CoV-2 outbreak in Luk Chuen House, Hongkong [42]. This case demonstrates cross-corridor virus transmission involving four hotel room units, resembling the outbreak patterns in worldwide quarantine hotels. Therefore, it is recommended that quarantine hotel corridors should have a right prevailing wind direction or at least maintain positive pressure and sufficient ventilation.

2.3. Experimental works

The understanding of the SARS-CoV-2 virus transmission route hinges on viral dispersion. Therefore, accurate knowledge of aerosol dispersion through systematic experimental studies will be of great value in preventing and controlling an emerging public health emergency in the future. Deng et al. experimented with the transmission of the virus in a breathing microenvironment [43]. The experiment uses carbon dioxide as a surrogate of SARS-CoV-2-laden aerosols. The model indicated that the total volume ventilation methods work better in removing the SARS-CoV-2 virus under unstable and neutral conditions, while local ventilation methods fare better in stable conditions. Besides, the study suggested that a ventilation rate above 3.0 air changes per hour (ACH) is more effective in reducing the risk of transmission via a dilution effect.

Faleiros et al. measure the airflow expelled by a person with and without a surgical mask [44] using particle image velocimetry. The experimental data were used to develop the TU Delft COVID-app to model droplet evaporation, expiratory activities, different convection conditions, and thermal coupling. The simulation results show a two-order reduction in the risk of inhaling particle sizes less than 5 μm when face masks are used. Approximately 85% of the total viral load was found to be associated with particles less than 5 μm during talking and singing [45]. Most of the airborne SARS-CoV-2 outbreaks are linked to singing compared to talking. Specifically, it is reported that loudness significantly affects the number of aerosols generated. Aerosol transportation highly depends on temperature, humidity, ventilation rate and inactivating chemicals (ozone) content [46].

Wang et al. investigated the SARS-CoV-2 outbreak cases in Luk Chuen House, which involved two vertical column flats connected by two-stacked drainage systems [47]. According to the study, 12 out of 43 cases were transmitted through aerosols. The main cause of transmission was due to the leakage of aerosols into the drainage stacks generated by the vertical sub-cluster. A similar condition was also noticed in two vertical apartments in Seoul, Korea, where the virus was transmitted through the air duct and spread in the building via the stack effect in a vertical shaft [48]. This further implies the possible occurrence of long-range aerosol transmission. Shah et al. modeled the dispersion of exhaled aerosols using polydisperse microscopic particles with a manikin [49]. A significant amount of aerosols was detected at a distance of 2 m. The study also reports that R95 and KN95 masks provide 60% and 46% filtration efficiency, respectively, while cloth and surgical masks only provide 10%–12% filtration efficiency.

Wang et al. used experimental aerosol data and modified the Wells-Riley equation to estimate the probability of in-flight infection in B777-200 aircraft [50]. The results show that the likelihood of infection without masks is approximately 4.5% and 60.2% for mild and severe scenarios, respectively, within 2 h of flight. Besides, the estimated infection probability (without masks) increased from 24.1% (mild scenario) to 99.6% (severe scenario) for a 12-h flight. On the other hand, the probability is reduced to 73% and 32% for high and low-efficiency masks, respectively. Edwards et al. compared the exhaled aerosol of humans and non-humans with and without SARS-CoV-2 infection [51]. The study found that the exhaled aerosol particles were affected by the degree of SARS-CoV-2 infection and elevated BMI-years, a multiplication product of BMI and age. Out of 194 persons, approximately 18% of humans accounted for 80% of the exhaled bioaerosols. The results are in line with the classical super spreader infection distribution of 20:80.

Van Doremalen et al. evaluated the stability of SARS-CoV-2 and SARS-CoV-1 viruses in aerosols and various surfaces [52]. In the study, a Bayesian regression model was used to predict the decaying rates of the virus. It was found that SARS-CoV-2 and SARS-CoV-1 viruses remained in an aerosol mode for 3 h. The reduction in infectious titer reduces from $10^{3.5}$ to $10^{2.7}$ $TCID_{50}$ per liter of air and from $10^{4.3}$ to $10^{3.5}$ $TCID_{50}$ per milliliter of air for SARS-CoV-2 and SARS-CoV-1, respectively. It was found that SARS-CoV-2 is less stable on copper and cardboard but can last 72 h on plastic and stainless-steel surfaces. Viable SARS-CoV-2 was not detected on the copper surface after 4 h, and no viable SARS-CoV-2 was detected on the cardboard surface after 24 h. Kutter et al. examined the transmission routes of SARS-CoV and SARS-CoV-2 using ferrets [53]. The authors found that SARS-CoV and SARS-CoV-2 are transmitted through the air over a 1-m distance. Smither et al. aerosolized the SARS-CoV-2 England-2 variant to determine its survival duration in tissue culture under varying humidity conditions [54]. It was found that the virus is more stable in the medium with relative humidity (RH) of 40–60% in the tissue culture medium, while the reverse trend is observed for the artificial saliva at RH 68–88%. The experimental result agrees well with the Washington variant. The virus was detectable after 90 min. Fears et al. [55] aerosolized the SARS-CoV-2 virus to compare its dynamic aerosol efficiency with SARS-CoV and MERS-CoV in four different aerobiology laboratories. A Goldberg drum simulated the environment to offset the particle settling velocity and keep aerosols suspended in the air. The study concluded that the virus remained infective for up to 16 h. Table 1 summarizes the main characteristics and findings of airborne transmission of SARS-CoV-2 in indoor environments. Many of the studies reported that the main transmission mechanism of SARS-CoV-2 in indoor environments is via tiny aerosols. Detection of the virus will never be null as long as there is a source of generation (SARS-CoV-2 positive patient), regardless of the ventilation rate and the environmental parameters. Nevertheless, long-range transmission of the virus can be effectively reduced by ventilation and practicing preventive measures such as wearing a face mask.

2.4. Implication for transmission prevention

To date, all experimental findings have acknowledged a discernible effect of precautionary and preventive measures in containing the spread of SARS-CoV-2. The first advocated preventive strategy is to avoid prolonged duration in an area with a high population [56]. In addition, whenever possible, maintaining an elevated indoor ventilation rate is recommended. However, the preventive measures practised in elderly homes and care centres in the United States (such as the Six Foot Rule and Fifteen Minute Rules) may not be sufficient to lower the transmission rate of SARS-CoV-2 under natural ventilation [57]. Wearing a moderately high-quality mask such as N95 is another useful preventive measure [58,59]. Protecting of the eyes using a face shield is also vital in reducing the transmission risk by 10.6% [60].

Furthermore, exercising can also be risky as the infection risk is proportional to the rate of respiration and pathogen output. In comparison, applying air filtration in mitigating SARS-CoV-2 transmission is less cost-effective than using a mask, but it provides more comfort and convenience to the occupants. In the case that an infected person is present in an indoor environment, the countermeasure is to quarantine the infected person, and the indoor air must be contained and cleared. From another perspective, if the indoor space is shared intermittently, then regular SARS-CoV-2 testing must be done within the cumulative exposure time (CET) recommended by the authorities [57].

3. Engineering control to minimize the airborne transmission

3.1. Importance of ventilation

Ventilation is paramount in governing the distribution of airborne diseases, especially in an indoor environment with the risk associated with prolonged exposure duration and decreased turbulence level. Recent studies have consistently suggested the effective transmission of SARS-CoV-2 indoors compared to outdoors due to ventilation and airflow factors. For instance, 33.8% of passengers were infected with SARS-CoV-2 on a 2-h bus journey in Ningbo, China [61]. Another indoor outbreak of SARS-CoV-2 was reported on the "Diamond Princess" cruise ship in February 2020, where a quarter of the ship's population was infected [62]. Both studies highlight the importance of effective indoor transmission since individuals are in constant close contact when they move within a confined space, creating an indoor contact network that facilitates the spreading of the virus [63]. Besides the relatively high occupant density in most indoor environments, chances of human-to-surface contact may also promote the route of fomite transmission. Given the high transmission rate in an indoor environment, The Chartered Institution of Building Services Engineers (CIBSE) has suggested ventilation strategies to "dilute" airborne pathogens. The Wells - Riley equation describes the importance of ventilation by the parameter P, which defines the probability of airborne transmission indoors as below:

$$P = \frac{n_I}{n_S} = 1 - \exp\left(-\frac{q}{Q}\Gamma t_s\right) \tag{1}$$

where n_I is the probability of infection by being present in an indoor environment while n_S represents the number of susceptible present in an indoor environment for the specific exposure time interval (t_s), q is the quanta generation rate (the average time for volume flux of exhaled air per person), while Q describes the volume flux of fresh air entering the indoor environment (the ventilation rate of the room with clean air). The parameter "Γ" describes the total emission rate, which is defined below:

$$\Gamma = \sum_{i=1}^{n_E} \gamma_i \tag{2}$$

where n_E is the number of people emitting infectious "quanta" defined as the mean viral load required for an infection to occur at the rate γ_i. From equations (1) and (2), it is evident that there is a close relationship between the infectivity of the pathogens and the strength of the infectious source in an indoor environment. When the term Q, which represents the volume flux of clean air entering an indoor environment, is large, the probability of infection (P) being present in the indoor environment can be significantly minimized.

3.2. Ventilation methods

Two modes of ventilation that are commonly adopted are mixing ventilation and displacement ventilation (Fig. 4). In mixing ventilation, fresh air is constantly supplied to an indoor environment to lower the contaminant concentration within the space. As shown in Fig. 4, the jet of fresh air is usually supplied from the upper parts of the rooms, such as via ceiling diffusers at high velocities of approximately 2 ms^{-1}, ensuring air circulation within the space. A well-designed mixing ventilation system can maintain a uniform temperature and minimize the contaminant concentration in the room [64]. A significant advantage of the mixing ventilation system lies in the energy-saving capability where heat gained from occupants and electrical equipment in the room is used to heat the incoming air instead of using additional heating sources.

Table 1
Key findings of airborne transmission routes in indoor environments.

Study ID	Purpose	Sampling Techniques	Research type	Parameter	PM size	CT Value	Sampling time	Locations (Continent)	Key outcomes
(Rocha et al., 2021) [10]	Examine of SARS-CoV-2 in the fomite and environment	RT-qPCR	Indoor, measurement	Temperature, humidity	0.22 μm	Not detected	11 months 13 days	South America (Brazil)	SARS-CoV-2 transmission via fomites is insignificant
(Doremalen et al., 2020) [14]	Study the stability of SARS-CoV-2 and SARS-CoV-1 in aerosols	Bayesian regression model	Laboratory	$TCID_{50}$, relative humidity	Not available	20–22	7 days	North America (United States)	Viability of SARS-CoV-2 in aerosols is 3 h
(Ong et al., 2020) [16]	SARS-CoV-2 on various environmental surfaces	RT-PCR	Indoor, measurement	Air flow rate	Not available	Patient: 31.31, 35.33, 25.69 Air: Not detected	2 days	Asia (Singapore)	Air samples were SARS-CoV-2 negative, whereas the surrounding environment was contaminated.
(Chen et al., 2022) [22]	To determine the mechanism of the extended short-range airborne transmission under poor ventilation	Macroscopic droplet nuclei concentration model	Laboratory	Air flow rate, temperature, humidity	d<15 μm	N/A	N/A	Asia (China)	Short-range airborne transmission is significant.
(Li, 2021) [23]	Examine the possibility of SARS-CoV-2 transmission via short range airborne route	The process of epistemology	Theoretical explanation	Ventilation rate	50<d<15 μm	N/A	N/A	Asia (Hong Kong, China)	Long-range airborne transmission only happens during insufficient ventilation or during the prolonged exposure time.
(Azimi et al., 2020) [25]	To evaluate the relative importance of diverse transmission routes for SARS-CoV-2	Markov chain model	Indoor, simulation	The effective incubation period, subclinical infectious period, Symptomatic vs. asymptomatic emissions, Ratio of aerosol vs. droplet emissions, Minimum close interaction, Quarantine infection control efficiency, URT/LRT ID50 ratio	10 μm	N/A	Vary from 1 to 15 days	North America (United States)	Airborne transmission route is likely to explain the majority of SARS-CoV-2 transmission on the Diamond Princess Cruise ship.
(Li et al., 2021) [26]	To study the possibility of SARS-CoV-2 airborne transmission	RT-PCR	Indoor, field measurement, simulation	Temperature, ventilation rate, filtration efficiency, exposure time	5 μm	N/A	2 days	Asia (China)	Long-range aerosol spread of the SARS-CoV-2 in a poorly ventilated and crowded environment.
(Ou et al., 2022) [27]	Investigate the ventilation requirements of possible SARS-CoV-2 airborne transmission	RT-PCR	Indoor, field measurement, simulation	Temperature, ventilation rate, exposure time, distance from the index case, attack rate	N/A	N/A	Field measurement (1 day), tracer measurement (6 days)	Asia (China)	Insufficient ventilation (<3.2L/s/person) and significant exposure time have caused a relatively higher infection rate on one vehicle than the other.

(*continued on next page*)

Table 1 (*continued*)

Study ID	Purpose	Sampling Techniques	Research type	Parameter	PM size	CT Value	Sampling time	Locations (Continent)	Key outcomes
(Saw et al., 2021) [28]	To investigate the SARS-CoV-2 transmission through aerosol using CFD	CFD simulation	Indoor, simulation	Temperature, ventilation rate, particle mass flow rate, mesh size	70 nm–10 μm	N/A	5 days, 48 h interval	Southeast Asia (Malaysia)	Dispersion of SARS-CoV-2 virus–laden aerosol throughout the room is affected by strong exhalation and airflow.
(Saw et al., 2022) [29]	Effectiveness of the indoor air purifier in controlling SARS-CoV-2 virus transmission	RT-qPCR	Indoor measurement, simulation	Temperature, ventilation rate, particle mass flow rate, mesh size	70 nm–10 μm	Less than 40 (air sample)	10 days, 48 h interval	Southeast Asia (Malaysia)	Single air purifier only has a minimum impact in reducing particle dispersion
(Ren et al., 2021) [31]	The effects of different ventilation on a prefabricated COVID-19 inpatient ward	snappyHexMesh and blockMesh grid measurement	Indoor, simulation	Wind speed, turbulence, kinetic energy	3 μm, 6 μm, 12 μm, 20 μm, 45 μm and 175 μm	N/A	N/A	Asia (China)	The 'U' type inlet and outlet ventilation have the highest removal efficiency for small particles (<20 μm), whereas the ventilation outlet near the pollutant source has the highest removal rate of big particles (>45 μm)
(Prajapati et al., 2022) [32]	Simulation of Covid-19 transmission in an ICU room	ANSYS Fluent CFD software	Indoor, simulation	Temperature, wind speed, transition ration	N/A	N/A	N/A	Asia (India)	The contaminated droplets travelled along a specific streamline along with airflow, hence posing an infection risk to the ICU workers.
(Borro et al., 2021) [33]	Influence of HVAC systems on the air dispersion of aerosols within a closed environment	Coupled Eulerian-Lagrangian	Indoor, simulation	Temperature, relative volumetric flow rate, humidity, Infection-Index (η)	3–750 μm	N/A	N/A	Europe (Vatican)	The HVAC airflow significantly enhances infected droplets diffusion in the whole indoor environment and the removal of particles.
(Vuorinen et al., 2020) [34]	SARS-CoV-2 airborne transmission from aerosol	Computational fluid dynamics modelling	Indoor, simulation	Air speed, air flow angle, air volumetric flow rate, inhaled aerosol number	5 μm<d>200 μm	N/A	N/A	Europe (Finland)	The Monte-Carlo simulations provide clear quantitative insight into airborne transmission exposure time in different indoor environments.
(Zhang et al., 2022) [35]	To demonstrate the aerosol transmission route of SARS-CoV-2 in grocery store	3D computational fluid dynamics	Indoor, simulation	Air volumetric flow rate, temperature, filtration efficiency, mesh generation	0.3>d<3 μm	N/A	N/A	North America (United States)	The coughing aerosol particles can be spread throughout nearly one-quarter of the grocery store in < 6 min.
(Tretiakow et al., 2021) [37]	Development of simulation model in assessing the effectiveness of face shield (visor) in reducing airborne transmission	Computational fluid dynamics	Indoor, outdoor, simulation	Wind speed, mesh size, volume fraction of infectious particles	N/A	N/A	80 s	Europe (Poland)	Face shield significantly reduces the transmission risk of SARS-CoV-2.

(*continued on next page*)

Table 1 (*continued*)

Study ID	Purpose	Sampling Techniques	Research type	Parameter	PM size	CT Value	Sampling time	Locations (Continent)	Key outcomes
(Ho. C.K., 2021) [38]	Impacts of expiratory and environmental factors on airborne pathogen transport	Computational fluid dynamics	Simulation	Temperature, relative humidity, mass of respiratory droplet, infectious dose, wind speed	N/A	N/A	N/A	North America (United States)	Social distancing, dilution and dispersion of expelled plume, upwind or crosswind of the cough source, and wearing a face mask significantly reduce transmission risk.
(Buonanno et al., 2020) [39]	Estimation of viral load emitted by SARS-CoV-2 infected subjects	Gammaitoni and Nucci model	Indoor, simulation	Quanta emission rate, inhale rate, ventilation rate, viral load	1.8, 3.5, 5.5 µm	N/A	3 h	Europe (Italy)	Proper ventilation is the key to preventing the indoor transmission of SARS-CoV-2.
(Shrestha et al., 2021) [41]	To study the reasons for the varying concentration of airborne viruses in different parts of building	CONTAM software	Indoor, modelling	Aerosol rate, deposition rate, air flow rate	0.1 µm	N/A	N/A	North America (United States)	Unventilated stairwells have higher concentrations of airborne viruses. The use of masks, HEPA air filter, and disinfections effectively mitigate airborne viruses' transmission.
(Cheng et al., 2022) [42]	To explain the contribution of virus airborne transmission to the COVID-19 outbreak	ANSYS Fluent	Indoor, simulation	Wind angle, wind speed, temperature	N/A	N/A	72 h	Asia (Hong Kong, China)	The flats of immediate downstream with windows and doors connected from the flat of COVID-19 patients are at high-risk of exposure to COVID-19 transmission. However, positive pressure and sufficient ventilation could reduce the risk of cross-corridor infection.
(Deng et al., 2021) [43]	Effect on the transmission of exhaled infectious airborne SARS-CoV-2 aerosols in the breathing microenvironment between two people	Reynolds averaged Navier-Stokes model	Indoor, laboratory, simulation	Air flow rate, temperature, CO_2 concentration	N/A	N/A	30 min	Asia (China)	Limited space air stability influences the removal of airborne SARS-CoV-2-laden aerosols.
(Coleman et al., 2021) [45]	To determine viral loads in respiratory aerosols of varying particle size	G-II exhaled breath collector, RT-qPCR	Indoor, Laboratory	Air drawn rate, temperature, day of illness, viral load	$d<5$ µm, $d>5$ µm	N/A	30 min (breathing), 15 min (talking and singing)	Asia (Singapore)	Talking and singing produce fine aerosols with more SARS-CoV-2 compared to coarse aerosols. Hence, appropriate measures should be taken to reduce indoor airborne transmission.

(*continued on next page*)

Table 1 (*continued*)

Study ID	Purpose	Sampling Techniques	Research type	Parameter	PM size	CT Value	Sampling time	Locations (Continent)	Key outcomes
(Wang et al., 2022) [47]	Evidence for possible role of washbasins or faecal aerosols and transmission via drainage stacks	Tracer gas dispersion test, complete genome sequencing of SARS-CoV-2, RT-PCR	Indoor	Air flow rate, tracer gas concentration	0.7 μm	N/A	2 h and 9 min	Asia (Hong Kong, China)	The foul gas leakage from the drainage system into the indoor environment via stack aerosol could be important for SARS-CoV-2 transmission.
(Hwang et al., 2021) [48]	To establish evidence for airborne transmission of COVID-19	RT-PCR	Indoor	Air ventilation rate, mechanical ventilator, temperature	N/A	Negative (household's ventilation grilles and drains)	N/A	Asia (Korea)	Vertical airborne route is possible. Aerosol transmission of SARS-CoV-2 under insufficient ventilation conditions is underestimated.
(Shah et al., 2021) [49]	Effects of common face masks and ventilation/air purification in controlling SARS-CoV-2 transmission	Aerosol dispersion model	Indoor, laboratory	Air ventilation rate, pressure level, breathing rate, breathing volume, filtration efficiency	1 μm	N/A	10 h	North America (Canada)	High-efficiency masks are recommended for mitigating airborne transmission. In addition, a higher ventilation rate is required to prevent aerosol buildup.
(Wang et al., 2021) [50]	To identify the probability of infection associated with an exposure time	Wells-Riley model	Indoor, simulation	Quanta generation, exposure time, mask efficiency	N/A	N/A	2 h and 12 h	Europe (United Kingdom)	The ventilation system and wearing masks during a flight reduce the risk of infection.
(Edwards et al., 2021) [51]	To study the effect of SARS-CoV-2 infection results in observable evolution of numbers and sizes of exhaled respiratory droplets in healthy and diseased subjects.	RT-qPCR	Indoor, laboratory	BMI, age, exhaled aerosol particles	5 μm–10 μm	N/A	28 days (COVID-19)	North America (United States)	The control of exhaled aerosols is effective in mitigating airborne transmission.
(Kutter et al., 2021) [53]	To investigate the airborne transmission of SARS-CoV and SARS-CoV-2 between ferrets over more than a meter distance	RT-PCR	Indoor, laboratory	Tissue culture infectious dose, air flow rate	N/A	N/A	20 days	Europe (Netherlands)	SARS-CoV and SARS-CoV-2 can remain infectious while travelling through the air

As shown in Fig. 4, the ventilation creates a stratified environment with the supply of low-velocity air, which relies on buoyancy forces (without mechanical extraction) to drive the air motion within the indoor environment. The supplied air is distributed along the floor until it comes across the thermal plumes from heat sources that lift the air to the breathing area. The contaminated particles in the space are carried to the exhaust grills instead of being recycled within the indoor space, thus, enhancing the effectiveness of ventilation with thermal comfort. The main advantage of displacement ventilation is attributed to its energy efficiency, which can be highly advantageous in high-ceiling buildings or high occupancy applications. Besides, several studies have reported that displacement ventilation is better than mixed ventilation since the infectious particles are pushed upwards out of the breathing zone in a displacement system [65,66].

In contrast, the pathogenic particles are mixed and dispersed within the indoor space in a mixed ventilation system [67,68]. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has reported at least a 20% improvement in air quality with the implementation of displacement ventilation [65], while indoor environments utilizing displacement ventilation showed 25%–90% better air quality in comparison to mixing ventilation systems [66]. Owing to the aforementioned advantages, the Environmental Protection Agency (EPA) has suggested an investigation into "vertical displacement ventilation" or "thermal displacement ventilation" to reduce fan energy. Both methods use natural convection force to lift the pathogenic air particles up and out of the breathing zone in an indoor environment.

In addition to mixing and displacement ventilation, other ventilation strategies can be used to reduce the risk of SARS-CoV-2 transmission indoors. Personalized ventilation is one such strategy that delivers filtered air directly to an individual's breathing zone, reducing their exposure to pollutants and potentially infectious airborne diseases like SARS-CoV-2 [69]. Personalized ventilation can be implemented through miniature air tanks that can be attached to a user's clothing, desk, or chair, allowing them to control the rate and direction of airflow they receive. This approach has effectively lowered the concentration of airborne pollutants and limited the transmission of infectious diseases in settings such as hospitals, nursing homes, and busy public venues [70,71].

Another advantage of personalized ventilation is that it can increase the efficiency of ventilation in areas where traditional HVAC systems may not be effective. For example, conventional systems rely on dilution and mixing to reduce the amount of pollutants in the air, but personalized ventilation can deliver clean air directly to areas that need it the most [72]. Furthermore, personalized ventilation can reduce the risk of cross-contamination by directing clean air towards the individual rather than circulating air throughout the entire space [73,74]. This is particularly important in situations where infectious diseases may be present, and personalized ventilation is a promising strategy for improving indoor air quality and reducing the transmission of airborne pollutants and diseases like SARS-CoV-2.

Protected zone ventilation is another type of ventilation system that can be implemented in larger rooms to maintain a clean and safe environment. It is a hybrid ventilation system that combines displacement ventilation and localized exhaust ventilation to create a clean zone around the breathing area of occupants [75]. The system produces a smooth and low-velocity airflow in the breathing zone, which keeps potentially harmful particles away from the user's face and effectively reduces the level of airborne contaminants, including viruses like SARS-CoV-2 [76]. By reducing the amount of infectious particles in the air, protected zone ventilation helps to limit the spread of diseases such as SARS-CoV-2 in enclosed areas. It achieves this by increasing ventilation with outdoor air in a confined space, resulting in a smaller amount of infectious particles dispersed throughout the air [77]. Moreover, protected zone ventilation systems can be equipped with HEPA filters, which can remove airborne particles, including viruses, from the air and reduce the risk of infection [78].

The controlled airflow created by protected zone ventilation reduces the likelihood of transmission by limiting the dispersal of airborne particles. In addition, this directional airflow moves air from cleaner locations to areas that may be more contaminated, further reducing the risk of infection transmission [79]. Protected zone ventilation also limits the number of people exposed to the disease by reducing the number of people in a confined area. This decreases the likelihood of people being infected with the virus and subsequently spreading it to others [77]. This feature is especially important in environments such as hospitals, where infectious particles are constantly produced. In summary, protected zone ventilation is an effective ventilation strategy that helps to reduce the spread of diseases such as SARS-CoV-2 by creating a clean zone around the breathing area of occupants, removing infectious particles

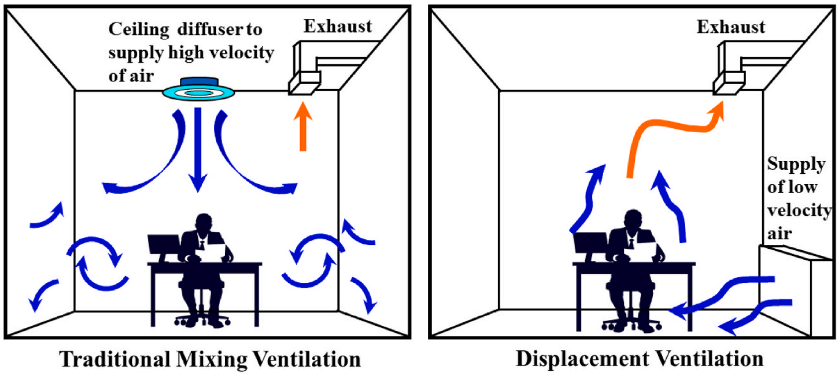

Fig. 4. Schematic illustration of traditional mixing ventilation and displacement ventilation.

Table 2
Summary of the study on the transmission of SARS-CoV-2, including ventilation rate, temperature, and specific humidity.

Study	Ventilation Rate	Ventilation Temperature	Humidity,	Findings	References
Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant	1 L/s	N/A	N/A	With a ventilation rate of 1 L/s per person, airborne transmission of the SARS-CoV-2 virus is achievable in a crowded environment.	[26]
The effects of indoor temperature and humidity on local transmission of COVID-19 and how it relates to global trends	N/A	N/A	<40% RH >70% RH	Temperature does not have significant effect on the virus transmission. Safe humidity level should be less than 70% RH.	[95]
The transmission of SARS-CoV-2 is likely comodulated by temperature and by relative humidity	N/A	5 °C–30 °C	78% RH	High relative humidity can cause epidemics, while mean relative humidity below 78% and continuous daily temperatures above 30 °C strongly attenuate transmission.	[96]
Estimating the impact of indoor relative humidity on SARS-CoV-2 airborne transmission risk using a new modification of the Wells-Riley model	0.5 ACH, 6 ACH	N/A	20% RH, 37% RH, 53% RH, 70% RH, 83.5% RH	Increasing ventilation rate reduces SARS-CoV-2 airborne levels more than indoor RH.	[97]
The COVID-19 pandemic is a global indoor air crisis that should lead to change: A message commemorating 30 years of indoor air	10 L/s for office 250 L/s for gym	N/A	N/A	ASHRAE Standard 62.1 did not consider infection control as their main objective.	[106]
The vaccination threshold for SARS-CoV-2 depends on the indoor setting and room ventilation	Classroom: 1.2–15L/s per person Prison: 1.6–15L/s per person Restaurant: 0.89–15 L/s per person	N/A	N/A	SARS-CoV-2 vaccination thresholds range from 40% for mechanically ventilated classrooms to 85% for naturally ventilated restaurants.	[107]
The effect of temperature on persistence of SARS-CoV-2 on common surfaces	N/A	20 °C, 30 °C, 40 °C	N/A	SARS-CoV-2 virus can survive on the stainless steel, glass, polymer notes and paper notes at least 28 days at 20 °C and 50% RH. But not more than 24 h for cotton surface and not more than 48 h for stainless steel, glass, and bank notes at 40 °C.	[108]
Stability of SARS-CoV-2 on critical personal protective equipment	N/A	20 °C	35–40% RH	SARS-CoV-2 survive up to 21 days on PPE and plastic visor	[109]

from the air, and limiting the dispersal of airborne particles.

3.3. *Ventilation flow rate, temperature and humidity*

The requirement for ventilation flow rate can vary significantly for homes, offices or local transportation such as trains and buses. Although the currently available guidelines on ventilation rate do not consider infection control, some studies have reported that the ideal ventilation rate in shopping malls is 3.9 L/s per person and 2.8 L/s per person in public transportation (e.g. trains and buses). It should be highlighted that the requirement for good indoor air quality requires a minimum ventilation rate of 8–10 L/s [80]. Buildings that are overcrowded, poorly ventilated and not properly sanitized may contribute to a higher risk of disease transmission. As such, Sundell et al. suggested that a ventilation rate of 25 L/s is essential to maintain indoor air quality and for effective infection control [81]. On the other hand, patients requiring airborne isolation precautions should ideally be kept in an airborne precaution room with >12 air changes per hour (ACH) which is equivalent to >80 L/s in a 4 x 2 x 3 m^3 room. The United States Centres for Disease Control and Prevention further highlighted the following criteria for ventilation control in airborne infection isolation rooms [82,83]:

- > 12 ACH for new building and > 6 ACH (equivalent to 40 L/s for a 4 x 2 x 3 m^3 room) for existing buildings.
- Airflow differential of > 56 L/s for exhaust against the supply.
- Sealing of the room, allowing a maximum of 0.046 m^2 of leakage.

Understanding the survival of pathogens disseminated via droplet nuclei is vital in dealing with outbreaks. The viral survival rate highly depends on physical factors such as relative humidity, light and temperature. This can be explained by the stack pressure (driven by buoyancy) generated from the difference in air temperature and humidity between indoor and outdoor air, where the difference develops an imbalance in the pressure gradient between the interior and exterior air columns [84]. The pressure differences cause air movement, which facilitates the transmission of pathogens. For instance, outdoor air can enter the building through the lower opening and escapes from the upper opening when there is a temperature gradient between the indoor and outdoor air. The process is reversed when the room air is colder (denser) than the outdoor air. Since the stack pressure in a room depends on indoor and outdoor temperatures, the ventilation rate through a stack in a room is a measure of the pressure difference that exists between the upper and lower stack openings. The air changes per hour (ACH) and ventilation rate (L/s) for stack natural ventilation can be predicted from the equations (Eq. 3 and Eq. (4)) below:

$$ACH = \frac{0.15\ x\ smallest\ opening\ area\ \left(m^2\right)\ x\ 3600\,\frac{s}{h}\,x\ \sqrt{(indoor - outdoor\ air\ temperature\ (^\circ \mathrm{K}))\ x\ stack\ height\ (m)}}{room\ volume\ \left(m^3\right)} \tag{Eq. 3}$$

$$Ventilation\ rate = 0.15\ x\ 1000\ \frac{l}{m^3}\,x\ smallest\ opening\ area\ \left(m^2\right)\ x\ \sqrt{(indoor - outdoor\ air\ temperature\ (^\circ \mathrm{K}))\ x\ stack\ height\ (m)} \tag{Eq. 4}$$

These equations can be useful when designing a building that relies completely on the natural ventilation system. Applying these equations enables one to calculate the driving forces, such as stack pressure, for optimal natural ventilation. Researchers have proposed three mechanisms to explain the effect of relative humidity on the transmission of the influenza virus indoors:

i. Host level: Breathing dry air causes desiccation of nasal mucosa, leading to epithelial damage and reduced mucociliary clearance. This may reduce the host's susceptibility to viral infections.
ii. Virus level: The stability of the influenza virus in an aerosol may vary according to the relative humidity of the ambient air, where viral stability is maximal at low relative humidity (20%–40%), minimal at intermediate relative humidity (50%) and high at elevated relative humidity (60–80%) [85–87].
iii. Vehicle level (respiratory droplet): At low relative humidity, the formation of droplet nuclei can be facilitated when water evaporates rapidly from exhaled bioaerosols. These small respiratory droplets settle out faster as size increases. Unlike the larger droplets, droplet nuclei <5 μm are likely to remain airborne for an extended duration, increasing the risk of pathogen transmission.

The transmission of the influenza virus is particularly favorable in cold temperatures. This is because the influenza virus is more stable in cold temperatures, including in the nasal passage when the epithelial surface is cooled [88]. The stability of the virus at lower temperatures is attributed to the reduced activity of proteases (i.e., enzymes that catalyze (increase) the reaction rate). When the temperature is higher than 41 °C, domains of ordered and disordered lipids coexist within the virus membranes, with a fraction of lipids within ordered domains increasing with decreasing temperature [89]. Similar findings have been reported with SARS-CoV-2 infection. Studies have shown an increased risk of SARS-CoV-2 infection and transmission at low temperatures [90,91]. Nevertheless, numerous studies have claimed no significant relationship exists between temperature and the transmission of SARS-CoV-2 [92–94]. Nevertheless, the importance of relative humidity and temperature control, particularly in an indoor environment, is of prime importance to curb the risk of infectious disease transmission, which can be achieved with a well-designed ventilation system. Besides, Park et al., reported that temperature have no significant effect on the transmission of SARS-CoV-2. On the other hand, the virus could survive for long period of time in humidity levels less than 40% RH and above 80% RH. Hence, the safe level for humidity is below 70% RH [95]. Raines et al. concluded that temperature above 30 °C and relative humidity less than 78% RH strongly attenuate the transmission of SAS-CoV-2 [96]. Moreover, Aganovic et al. used the modified Wells-Riley model to predict the effect of relative humidity ono the settling of the respiratory droplets [97]. It was found that at a relative humidity range of 23%–53% and ventilation rate of 0.5 ACH, the infection risk of the SARS-CoV-2 is at minimum. Increasing the ventilation rate to 6 ACH will further reduce the infection risk by half. Hence, installing of humidifier does not help to reduce the infection risk in indoor environments, while ventilation plays a major role in mitigating transmission risk.

Another way to combat airborne diseases is to utilize adequate ventilation filtration, which reduces viral concentration in the environment and reduces the chance of human infection due to PPE failures or in enclosed public transit [98]. Air conditioning (AC) devices are not designed to remove virus-sized particles (on a nanoscale). Thus, there is a demand for air filtration technology (i.e. HEPA and ULPA filters) to help reduce the rate at which a virus spreads [99]. In a closed setting or building, adequate ventilation is critical for eliminating exhaled infectious air, lowering the total concentration and any additional exposure breathed by other users. In this regard, several studies have been conducted on optimal ventilation dispersion, including the ideal positioning of supply and exhaust vents to ensure sufficient dilution is achieved [100–102]. The fundamental aim of these investigations is to reduce airborne contaminants by introducing fresh air supply. However, there are situations when local obstacles to this operation arise due to the presence of partitions or curtains in offices and hospitals. Additional solutions may be required if these limitations are in place to achieve the efficacy of ventilation needed.

Modifying the system can increase the rate of ventilation. A heating, ventilating, and air conditioning (HVAC) system provides air circulation. To lessen the risk of airborne disease transmission, HVAC system control mechanisms may typically be adjusted to increase ventilation to a certain amount in occupied zones at a minimal cost. However, the modification process is not straightforward as these systems are complex and are commonly designed specifically for buildings with unique operating conditions. Apart from the ventilation rate, other factors need to be considered for the modification process, including temperature, relative humidity, airflow dispersion, and direction [103]. HVAC professionals can tailor such processes to meet special requirements, such as mitigating the chances of airborne transmission. An example of the adjustment done would be at the hospital ward ventilation system, where the system is modified to produce a negative pressure in the isolation ward [104]. The modification of the system enables several rooms to become neutrally or slightly positively pressurized when the pressures within the ward vary.

In addition, it has been found that indoor transmission of SARS-CoV-2 typically occurs at a distance of 0.7 m–1 m between two individuals. However, transmission may occur at greater distances in poorly ventilated rooms with a flow rate of less than 3L/s. The minimum ventilation rate required for humans at rest is 10 L/s, while vigorous activity requires a higher ventilation rate of approximately 250–490 L/s. Although CO_2 sensors can be used to monitor ventilation rates, they may not indicate the amount of virus generation from singing, loud speaking and strong coughing, which may not have significant impact on the CO_2 generation [105]. It has been observed that infection control is not the top priority in setting ventilation system standards, such as those outlined in ASHRAE 62.1 [105,106]. Although vaccination could reduce the severity and frequency of superspreading events in an indoor setting, enhancing the ventilation rate is also necessary to promote healthy indoor air quality. The threshold for vaccination in naturally ventilated classrooms, prisons and restaurants is 63%, 77% and 85%, respectively. On the other hand, the threshold of vaccination in mechanically ventilated classrooms, prisons and restaurants is 40%, 69% and 75%, respectively. By increasing the ventilation rate to 15 L/s per person, the threshold for vaccination in naturally ventilated and mechanical ventilated venues is reduced. The threshold for classrooms, prisons and restaurants is reduced to 5%, 40% and 56%, respectively [107]. It was found out that the SARS-CoV-2 virus could survived on the stainless steel, glass, polymer notes and paper notes for at least 28 days at ambient temperature of 20 °C and relative humidity of 50%. Besides, the virus could survive on the cotton surface for 7 days [108] and survive on plastic and N95 for up to 21 days at room temperature and relative humidity of 50% [109].

Table 2 presents the results of the study on the transmission of SARS-CoV-2, including information on the ventilation rate, temperature, and specific humidity.

3.4. *Effectiveness of the indoor air purifier (HEPA filtration) and disinfection devices (e.g., germicidal ultraviolet (GUV) or ultraviolet germicidal irradiation (UVGI) – in the duct)*

The ongoing pandemic for the past two years manifested the need to understand, design and operate accordingly to ensure good indoor air quality. Aerosols generated from infected persons in indoor environments of health care facilities, offices, and aircraft are of major concern, causing WHO and government bodies to recommend airborne precautions [110,111]. For instance, air filters have gained vast attention in the last two years concerning the implemented airborne precautions, particularly HEPA filters. Studies proved that these filters could remarkably reduce exposure to virus particles, droplets and aerosols. Many researchers evaluated the efficiency of HEPA filters, concluding that they are effective in capturing airborne viral particles as well as particulate matter of varying sizes and ions present in contaminated environments. HEPA filters are typically interlaced with multi-layers made up of fibrous media, either polymer or fibrous glass. These filters are assessed for their mechanism, manufacture, ability to operate in various environments and the rate of aerosol productivity. The four mechanisms involved in filtration, i.e., diffusion, interception, inertial impaction, and sieving, are considered notable features of these filters compared to other air filters. For example, while diffusion can effectively remove small particles, all other three techniques are effective on larger particles [112].

These filters are capable of removing 99.97% of particles with a size of 0.3 μm in diameter. In general, a HEPA filter can remove droplets from the cough and sneeze of an infected patient range above 5 μm. Virus particles not attached to the droplets with a size of 0.12 μm can also be conceivably filtered by HEPA. ULPA (ultra-low penetration air) filters are considered more efficient for the smaller virions, removing 99.99% of the aforementioned 0.12 microns-sized particles [98]. Besides, Liu et al. reported two distinct sizes of SARS-CoV-2 aerosols, peak concentration of the aerosols appears majorly in two regions, one in the submicron region (diameter ranging between 0.25 and 1.0 μm) and the other in the super micron region (diameter more than 2.5 μm) [113]; sizes which fall in the range that can be effectively filtered using HEPA filters. A study by Chen et al. also highlighted that HEPA could effectively filter these sizes, where 95% is removable for smaller particles, whereas 100% is filtered for particles having a diameter of 2.5 μm [114].

Clean Air Delivery Rate (CADR) is directly proportional to the air filters' filtering efficiency. Many researchers have consistently reported the high efficiency of HEPA filters in filtering virus particles. These filters can reduce the concentration of harmful gases such

Fig. 5. Upper-room UVGI installed in an office in Malaysia.

as CO_2, CO and fungal spores, and airborne particles. This imparts health benefits such as decreased coagulation, systematic inflammation, blood pressure and improved lung functions. Air purifiers, with sufficient CADR and low power consumption, are considered affordable for maintaining healthy indoor environments. With the continuous surge of SARS-CoV-2 cases, hotspots such as airports, workplaces, educational institutions, hospital environments and closed vehicles particularly need a safer environment. Considering the viability and low power consumption of HEPA filters, authorized bodies such as the Centre for Disease Control globally have recommended the usage of these air filters.

Besides air filters, disinfection devices are also considered a good additional measure to control the spread of SARS-CoV-2 virus. Chemical and/or physical and ultraviolet (UV) disinfectant devices have been commonly used in healthcare settings. Before SARS-CoV-2 outbreak, ultraviolet germicidal lamp was used for sterilizing water systems and surgical instruments during the measles outbreaks and other airborne diseases outbreaks [115]. Ultraviolet germicidal irradiation (UVGI) radiation and short-wave ultraviolet rays (wavelength ranging from 100 to 280 nm) have been extensively studied for disinfection against human pathogens in the past [116–118]. It is a short wave of ultraviolet rays used to inactivate microorganisms' wavelength, where maximum effectiveness was reported at a wavelength of 265 nm [117]. UVGI causes significant changes in virus nucleic metabolism, affecting the important functions for their survival and limiting their ability to grow and multiply. This makes UV disinfection devices efficient for abating virus particles [118]. Tseng and Li evaluated the effectiveness of UVGI on the inactivated virus and reported that 2–5 mJ/cm^2 of UVGI doses could inactivate ssRNA viruses (similar to SARS-CoV-2) [118]. Other studies have reported UV dosage ranging from 0.7 to 4.0 mJ/cm^2 to effectively kill 90% of the SARS-CoV-2 virus [115]. Various other strategies have also been implemented for applying UV rays, such as UV lamps, ventilation systems fitted with UVGI systems and portable air filters with UV internal lamps. Fig. 5 illustrate the upper-room UVGI installed in an office building.

However, there are many uncertainties in guidelines and standards of dosage requirements, and standard design and testing still need further research to comprehend the characteristics and susceptibility of virus particles.

3.5. *Emerging technologies*

As the COVID-19 pandemic continues to grow, innovative developments and measures to contain the outbreak are also increasing. The World Health Organization (WHO) has recommended the adoption of physical and chemical elements to reduce contamination, such as masks and basic hygiene routines, along with surface cleaning. Wearing protective gear and masks, improving interior ventilation, and chemical disinfection are common measures [119,120]. Considering the relevance of air and surface pollutants in the propagation of the virus, research into antiviral and antibacterial surfaces, as well as cleaning equipment and technologies, must be emphasized.

In overcoming surface contamination problems, research on self-cleaning surfaces mostly focuses on developing surface modification or functionalization. This development aims to obtain anti-adhesive or antibacterial qualities to prevent contamination. This method has significant advantages compared to traditional disinfection methods. For instance, the self-cleaning method provides continuous disinfection on environmental surfaces, a broad spectrum of microbial activities and low toxicity to humans [116]. Furthermore, in contrast to touchless technology or traditional cleanup, antimicrobial surfaces provide a long-lasting layer of protection that goes beyond disinfection for up to three months. Additionally, the surface's antimicrobial charge decreases soon after contact, preventing it from spreading and contaminating other surfaces or persons [121,122]. Several modern methods for creating anti-adhesive and antibacterial surfaces have been discussed previously [123].

Furthermore, the application of natural anti-adhesive or self-cleaning surfaces has been studied for possible use in creating micro/nanostructured interfaces [124,125]. Applying copper brasses to most surfaces or treating typical surfaces in contact with Cu has been discovered to be particularly beneficial [126]. Metal-loaded composite materials are well-known for providing regulated and long-lasting ionic release in various applications [127]. The key to tuning surface antibacterial and antiviral characteristics is to emit ionic copper in a controlled manner [128].

Nanotechnology opens up wide possibilities for developing more effective and promising products. Advancements in nanotechnology allow for the development of novel materials that are more convenient, robust, and secure in the face of biological and chemical threats [129], particularly in combating airborne infectious diseases. Nanotechnology-based compositions offer promising methodologies that benefit from their unique characteristics, such as high surface-to-volume ratio, easy surface modification, improved physical and chemical stability, unique optical characteristics, and targeted and controlled release functionality, which can contribute to reduced toxicity and higher efficacy. These characteristics make them favorable for the effective prevention, treatment, and diagnosis of viral infections. Several types of research have demonstrated that nanoparticles, such as Ag [130], Cu [131], Au [132], Fe [133], and others, have extensive antiviral properties, which can be valuable in medications and water or air cleaning.

Poor PPE and incorrect PPE recommendations can be partly accountable for the rise of viral infectious diseases. It was discovered that metal-grafted graphene oxide (GO) has very good antibacterial characteristics. Perreault and colleagues developed a possible therapy using GO grafted with metal nanoparticles that achieved a 4-fold increment of antimicrobial activity [134]. To improve the efficiency of PPE using nanomaterials, copper oxide-impregnated masks were developed to reduce the possibility of influenza virus infection in the surroundings without compromising the masks' filtering capacities [135]. It is important to note that copper salt-treated masks and PPE show great potential in combating the spread of airborne disease. The efficacy of such materials is attributed to their nanophases and reference compounds. In addition to anchoring nanoparticles in polymer matrices, using copper salts to impregnate PPE parts is an ideal technique for preventing the possible toxicity of the nanomaterial on the respirators and masks [126].

Metallic nanoparticles can inactivate viruses before the viruses infiltrate host cells [136]. In a study, SiO_2 surface coated with Ag (SA) nanoparticles was coated on a medium air filter to evaluate pressure drop, filtration efficiency, and antiviral ability of the nano-coated filter [137]. The SA-coated filter with antiviral properties allows for the inactivation of airborne virus particles. Based on the study, the filtration performance and pressure drop showed improvement when a lower medium flow rate and a higher coating dose of SA particles were applied. The increased antiviral efficacy of SA particles results in virus particles losing their infectivity [137]. Nevertheless, it was found that the anti-virus performance dropped as the virus deposition time increased. Moreover, the dust trapped on the filter could reduce the filter's anti-virus efficiency. Therefore, an additional study was done using the dust load to evaluate the performance further. It was found that filtration capability and pressure drop rose as dust content increased [138]. Such reduction in the antiviral capacity could have been due to the direct contact between Ag nanoparticles (NPs) and virus particles on the surface of the coated filter.

The EVA-SiO_2-Ag composite shown a high antibacterial activity against *Escherichia coli*, *Staphylococcus aureus* and SARS-CoV-2. This material can also be used to fabricate reusable mask [139]. Filtration media should contain high gas fluxes at low static pressure loss, along with increased particle removal and viral entrapment or deactivation levels. Nanofiber-based filtration exhibited the characteristics of high aerosol filtering efficiency and low-pressure drop characteristics, resulting in better filtration performance [140]. It was discovered that the filter's efficiency increases when a smaller nanofiber diameter is used. Specifically, carbon nanotubes (CNTs) with sizes ranging from a few nanometers to just a few tens of nanometers are suitable alternatives for nanofiber filters. A group of researchers has constructed the world's first mass-produced air filter with High-Efficiency Particulate Air (HEPA)-like pressure drop and effectiveness that is also self-sanitizing. The air filter demonstrated filtration effectiveness of up to 99.999%, and ultra-thin materials with low areal density (0.1 g/m^2) showed a pressure decrease equivalent to conventional technologies [141].

In short, nanotechnology's usefulness in the fight against viruses remains underappreciated. However, the applications of nanomaterials in filtration systems to inactivate airborne viruses are worth exploring. Besides looking into the option of isolation and quarantine, social distancing and hand hygiene, researchers believe incorporating such technology could confer additional benefits in reducing airborne transmission. Table 3 summarize various engineering strategies that can be employed to lower the risk of SARS-CoV-2 indoor transmissions.

4. Environmental factors on SARS-CoV-2 transmission

4.1. Microclimate

The impact of microclimate or microenvironment on SARS-CoV-2 transmission is significant, as many infections occur in local indoor environments, such as car cabins, classrooms, offices, hospitals, and healthcare centres. Studies have shown that viral load can build up in an enclosed car cabin within 15 min [145], and aerosols suspended in the air can contain viable viruses for up to 3 h [146]. The transmission risk in the car cabin is influenced by airflow patterns and air exchange between the driver and passengers. A simulation study showed that airflow patterns significantly impact the air changes per hour (ACH). Under configurations of all windows opened, partially opened windows, and all windows enclosed, the ACH varies from 250 to 62 [145]. Adequate ventilation rate due to air circulation depends on simultaneous opening of the entrance and exit and a good pressure gradient between them [147, 148]. At the same time, the relative position of occupants near the entrance or exit and the air-conditioning inside the car also causes resistance to airflow. Therefore, air circulation could be at mode of transmission of viruses in the form of aerosols. It is estimated that the transmission of viral-loaded aerosols from an infected driver to a passenger is 11% when all windows are enclosed.

In comparison, none of the aerosols reached the passenger when all windows were opened. If the passenger is infected with the disease and emits aerosols, the aerosols reaching the driver are estimated to be 8% in an environment with fully enclosed windows. The difference in the amount of aerosol between the driver and the passenger depends on the airflow direction of the air-conditioning (from

Table 3
Engineering strategies to mitigate the transmission risk of SARS-CoV-2 [139,141–144].

Strategies	Features
Improved ventilation	• Increase the percentage of outdoor air supply to achieve minimum ventilation rate of 10 L/s. • Indoor carbon dioxide level less than 1000 ppm. • Humidity level 40–60% RH. • Correct air flow direction from clean to less clean area. • Keep away the devices that generate a strong air flow that will direct the air from person to person.
Germicidal UV	• Using UVC disinfection systems such as in-duct air disinfection, in-duct surface disinfection, upper-air disinfection and portable UVC for room decontamination. • UVC light with wavelength of 265 nm and avoid UVC lamp that produce ozone.
Improved filtration	• Selecting at least MERV-13 filter along with the recommended ventilation air rate.
Portable HEPA air cleaner	• Using HEPA air cleaner with HEPA filter grade of H13–H14 or a filter with removal efficiencies of 99.97%. • Selection of HEPA air cleaner according to the size of the room and existing ventilation rate in the room. • Clean air delivery rate should at least cover the gap between the minimum requirement and the measured ventilation rate.
Enhanced cleaning and disinfection	• Frequent cleaning and disinfection of high-touch surfaces to reduce the spread of the virus
Nanotechnology	• Applications of nanomaterials in filtration systems to inactivate airborne viruses
Physical barriers	• Plexiglass screens, can be installed to separate individuals and reduce the spread of the virus through respiratory droplets

front to back). In general, opening more windows reduces the probability of infection in such a microclimate. However, there are circumstances where an open window configuration may not be practical, for instance, in an airplane. Hence, alternatives to reduce the transmission risk must be considered.

4.2. Macroclimate and meteorological variables

The contributing factors that lead to large-scale outbreaks could not be explained by a mere microclimate. Across the region of Amazonia, a distinct difference in the SARS-CoV-2 spreading rate between the less populated northern and highly populated southern countries was observed [149]. It was found that social mobility and social conditions alone could not be the deciding factor for the difference in SARS-CoV-2 infection rate across the region. Other factors, such as ambient temperature and relative humidity appear to play a dominant role. The study shows that high relative humidity (measured as mixing ratio), ranging between 20 and 25 g of water vapor per kilogram of air, contributed significantly to the high transmission rate of SARS-CoV-2 in the region near the Amazon Forest. However, ambient temperature had no noticeable impact [149]. High relative humidity facilitates the survival of the SARS-CoV-2 virus suspended in the air or deposited on surfaces via water absorption. However, this finding contradicts other documented studies [150–152] in temperate countries, which demonstrate a negative correlation between SARS-CoV-2 transmission and ambient temperature and relative humidity.

Nevertheless, a positive correlation between temperature, humidity and dew point with SARS-CoV-2 transmission was reported in Singapore [153]. Lin et al. [154] argued that high relative humidity promotes the transmission of SARS-CoV-2 only when the temperature is low. A negative correlation between SARS-CoV-2 infection rate and atmospheric pressure, temperature, and relative humidity was found in another study [155]. Other climatic variables such as solar radiation, precipitation and wind speed on SARS-CoV-2 contamination, population density and movement were also investigated [156]. Among these variables, wind speed showed a significant negative correlation with SARS-CoV-2 transmission, whereas population density and movement seem to demonstrate a strong link with SARS-CoV-2 transmission. In the U.S. and China, the effect of atmospheric pollutants on SARS-CoV-2 transmission was investigated, and a significant positive correlation was found [157,158]. In the European region, it was found that anticyclonic atmospheric condition may also contribute to the spread of SARS-CoV-2 during the early outbreak [159].

4.3. Regional and global transmission

The outbreak of SARS-CoV-2 started at a local wet market in Wuhan, the Huanan Seafood Market, with at least 41 people contracting SARS-CoV-2 in December 2019 [7]. The disease quickly spread across Hubei province and the rest of the country. The pandemic outbreak period coincided with the Chinese Lunar New Year; hence, it is thought that the heavy traffic across the country could have facilitated the transmission of the disease [160]. Although the Chinese government had prohibited the movement in the infected areas, several people intentionally went under the radar or unknowingly carried the disease from China, causing the spread of the disease to different continents. ASEAN countries are closest to China, hence exposed to a higher risk of disease outbreaks. Singapore was the first ASEAN country to report SARS-CoV-2. The spreading of the disease started from a tour group, company conference and religious gathering. Later, the surge in SARS-CoV-2 cases in Singapore was attributed to the foreign workers' cluster, where there was noncompliance with social distancing among the workers in their dormitories. In addition, it is a great challenge to restrict the movement of foreign workers in the country since Singapore heavily depends on the imported workforce to operate their essential services. Other ASEAN countries that were severely affected by the pandemic include Indonesia, Malaysia, Thailand, and the Philippines. These countries (ASEAN-5) have the most active business and economic activities compared to the other ASEAN countries, hence the fast-spreading rate [161].

The initial detection of SARS-CoV-2 in Europe was documented in France on January 24, 2020. Subsequently, the prevalence of this pandemic was observed to be particularly high in the southwest and central regions of the France [162]. A study suggests that the mobility of air passengers strongly influences the spread of SARS-CoV-2, which was reflected in countries like Italy, France, Spain and Germany [163]. The North American region also found a similar trend [164]. These countries did not impose immediate travel restrictions when SARS-CoV-2 first emerged in China, speeding up disease transmission. In Latin America and the Caribbean (LAC) region, Brazil was the first country to be detected with SARS-CoV-2 in February 2020, a few weeks behind the pandemic outbreak in other continents. During the pandemic, the main issue is the LAC region's poor sanitation and water scarcity. Limited access to clean water hindered personal hygiene, such as hand washing and fecal-oral transmission of SARS-CoV-2 [165]. From the global perspective, it was found that mobility has a significant role in the transmission of SARS-CoV-2. Hence, effective measures like work from home policies are still recommended to minimize human movement to curb the spread of the pandemic.

4.4. Variant

Coronaviruses, including SARS-CoV-2, exhibit high mutational rates. Specifically, these viruses undergo continuous nucleotide substitutions at a rate of 1×10^{-3} per year [166]. The variation in SARS-CoV-2 arises from single-point mutations, recombination, insertions, and deletions, which ultimately impact its pathogenesis [167] and accelerate the infection rate worldwide. The first publicly recognized mutation of SARS-CoV-2, the Alpha variant (B 1.1.7), was detected in the UK and has a 43–90% higher transmission rate than the strain originally discovered in Wuhan, China. Although morbidity caused by this variant is lower, the higher infection rate has resulted in a higher hospitalization rate [168]. The Alpha variant has since spread to more than 114 countries. The subsequent dominant variant, the Delta variant (B.1.617.2), was first documented in India. This strain is of greater concern, as it is 50% more transmissible than the Alpha variant and has a 26% higher risk of evading the immune system [169], resulting in higher risk of hospitalization. The Delta variant is also suspected of having a higher mortality rate than the previous strain [170]. However, vaccination can still protect against disease severity by around 90% [171] for 12 weeks [172]. Furthermore, new lineages of the

Omicron variant, such as BA.4 and BA.5, are contributing to a wave of reinfections. These new Omicron subvariants are considered particularly efficient spreaders of the disease. The BA.5 and BA.4 variants appear to be more effective at evading the protection provided by vaccines and previous infection. Strict safety measures, particularly controlling airborne transmission, and exploring ideas to redesign the currently available vaccines are the key to mitigating the surge of SARS-CoV-2 infection and the fatality rate.

There is a link between SARS-CoV-2 transmission and environmental factors such as climate and geography. Specifically, climatic factors like temperature, humidity, and ventilation can impact the survival and transmission of the virus. Studies have shown that low temperature and humidity exceed 80% RH can increase the survival of SARS-CoV-2 on surfaces and in the air, leading to a higher risk of transmission [173,174]. On the other hand, higher temperatures can reduce the survival of the virus and decrease the risk of transmission [175,176]. In terms of ventilation, an engineering strategy to reduce the risk of transmission involves increasing the supply of outdoor air, improving air filtration, and avoiding air circulation in enclosed spaces. Proper ventilation can help dilute the concentration of the virus in indoor air and reduce the risk of transmission. For example, research has shown that humidity levels between 40%RH to 70% RH can help reduce the transmission of the virus, and engineering control by adjusting the HVAC system is needed to ensure the humidity in the indoor environment always at its optimal condition [95–97]. Similarly, increasing ventilation rates according to the types of activities in the indoor environment, using high-efficiency air filtration systems, and minimizing air recirculation can also help reduce transmission risk. These engineering strategies are particularly important in indoor spaces with poor ventilation or high occupancy rates, such as healthcare facilities, public transportation, and commercial buildings.

Overall, the link between the engineering strategies to reduce the risk of SARS-CoV-2 transmission and environmental factors such as climate highlights the importance of considering a holistic approach to infection prevention and control. By taking into account the impact of climate on transmission risk and incorporating appropriate engineering solutions, it is possible to create safer indoor environments and reduce the spread of the virus.

5. Conclusion

In this article, relevant findings related to the various variables associated with the spread of the SARS-CoV-2 pandemic, the classification of airborne transmission and the prevention-mitigation of virus infection were reviewed. Many studies have unequivocally confirmed that respiratory droplets are mixed uniformly in indoor spaces. In light of this body of evidence, we have summarized some safety guidelines for mitigating airborne transmission indoors as the follows:

- Ensure good ventilation and positive pressure in an indoor environment, for instance, an 8–10 L/s ventilation rate for relaxing activities and more ventilation rate for heavy activities space such as gym.
- Ensure humidity level less than 70% RH.
- Apply higher efficiency vertical displacement ventilation in an indoor environment to remove SARS-CoV-2 aerosol.
- Reduce exposure time in a high-density population area.
- Wearing high filtration efficiency masks such as KN95 could reduce the risk of transmission, especially from an infected person, as talking and singing release a significant amount of aerosol.
- Nanotechnology, HEPA air filtration, and 254 nm UV disinfection can be effective against SARS-CoV-2.

The general recommendation is to provide specific engineering approaches to reduce the risk of indoor transmission of SARS-CoV-2, which includes increasing the supply of fresh outdoor air, improving air filtration using MERV-13 filter, avoiding recirculation air in an enclosed space, adding portable HEPA air cleaner to clean the air in a room and using 254 nm UVGI features such as in-duct UVGI or upper-room UVGI. These engineering related strategies can help dilute the concentration of the virus in indoor air, reduce transmission risk, and create a safer indoor environment. Moreover, the impact of environmental factors such as climate should also be taken into account in the design of engineering solutions to reduce transmission risk. While there are several emerging technologies in the market, such as ionizers, reactive oxygen air cleaners, photocatalytic oxidation (PCO), electrostatic precipitators, UV-222nm air purifiers, ozone generating air purifiers, etc, it is essential to obtain concrete scientific evidence to demonstrate their effectiveness as compared to increase the filtration efficiency or outdoor air. In Additional, it is crucial to ensure that these technologies do not generate harmful compounds or by-products that could pose a threat to human health. Cross-disciplinary research has been conducted to investigate the airborne transmission of SARS-CoV-2 worldwide. Despite the high amount of SARS-CoV-2-related research published recently, our current knowledge and understanding of this novel coronavirus remain limited. At this point, there is a lack of research on the variation in the correlation between these variables and the survival of the SARS-CoV-2 virus. Intensive studies on SARS-CoV-2 airborne transmission will be useful to highlight new information and perspectives on cost-effective measures to curb the spread of SARS-CoV-2.

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.

Data availability

No data was used for the research described in the article.

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