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Review

Ventilation Strategies for Highly Occupied Public Environments: A Review

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Abstract: In urban public transportation and highly diversified air environments, air pollutant exposure is becoming an increasing concern in terms of public health and personal safety. Herein, the scientific literature on air quality and virus transmission in densely crowded environments is reviewed to determine effective control methods. The research results are classified on the basis of different crowded environments. Much research has been conducted on pollutants in subways and buses. High particulate matter concentrations in public transportation are still a serious problem, but few studies on the spread of viruses exist. With existing types of ventilation systems, increasing local exhaust may be an efficient way to remove pollutants. Air quality sensors should be distributed in densely crowded spaces to achieve real-time display of pollutant concentration data. When pollution levels exceed the safe values, scientifically designed ventilation and filtration schemes should be implemented to reduce the pollution levels. Occupant activities are among the important factors that make pollutant transmission more complex. The analysis results herein contribute to the assessment of indoor pollutant concentrations and the protection of occupants from cross-infection.

Keywords: crowded places; ventilation strategies; pollution control

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1. Introduction

With economic development and urban expansion, people's commuting distances are increasing, so the time spent on public transportation is increasing. The expansion of global air travel has overcome geographic barriers to disease vectors [1]. Passenger health is influenced by the cabin environment [2]. Airplane cabins provide a conducive environment for the transmission of COVID-19 [3]. Crowded economy-class cabin seats increase the risk of airborne disease transmission between sick and healthy passengers [4]. Of particular note is the emergence of COVID-19, which is transmitted mainly through droplets and aerosols [5,6]. Due to the high occupant density in an airplane cabin, the required total air exchange ratio is much higher than that in a building.

In typical offices, outdoor particulate matter <2.5 μm (PM 2.5) is the main source of indoor PM 2.5 [7]. Sangiorgi et al. reported that more than 80% of indoor PM 2.5 in office buildings comes from outdoors [8]. Mechanical ventilation filtration systems in office buildings are used to reduce indoor particulate matter exposure [9]. In the United States and Singapore, 90% of the indoor air in office buildings is recycled and filtered [10]. In China, a small number of office buildings directly use fresh air systems to provide filtered fresh air [11]. Previous research has found that crowded classrooms, apart from PM 2.5, are also associated with high levels of several chemicals, such as methanol and benzene [12,13]. Moreover, poor ventilation rates may lead to high levels of fungal particles in overcrowded places. Researchers have found that CO and PM levels were positively associated with students' absence rates [14,15]. Indoor pollutants, including particulate pollutants, can affect student attendance and learning efficiency [16,17]. Many research teams have measured the concentration of pollutants in the classroom, and natural ventilation by opening windows is the main method [18,19]. A significant decrease in CO was found, which led to a reduction in respiratory illnesses in students [20]. But that would only be correct if the windows were actually opened and not left closed (to conserve heat). In addition to CO, NO_2 emitted by motor vehicles in inner cities may cause excess morbidity, especially related to asthma symptoms [21]. The levels of various pollutants were found to be higher indoors than outdoors [22]. Additionally, suggestive evidence links the classroom-level ventilation rate with students' test results in math [17,23]. Therefore, the health of occupants is extremely susceptible to the influence of outdoor pollutants, and due to the crowded nature of classrooms, the contaminants cause higher levels of exposure for occupants.

The effectiveness of filtration systems for PM 2.5 purification in the area of human activity and therefore respiration has received widespread attention. The PM produced by commercial aircraft not only has a significant impact on the outdoor environment of terminal buildings [24], but also easily transfers from outdoors to indoors through mechanical ventilation systems [25].

The literature on airborne transmission for different modes of transportation and transportation hubs is relatively limited. Due to their unique physical structure and high passenger flow within the transportation infrastructure, subway lines have a high risk of epidemic transmission [26,27]. The CO_2 level was found to be linearly related to the number of passengers according to a correlation analysis [28]. It is important to consider commuter route choice in exposure assessment studies. The external environment has the strongest influence on air quality in subway cabins. The piston wind from the tunnel makes it easier to transport particulate matter into a subway station for a subway without platform screen doors.

The purpose of this study is to evaluate the health risks of crowded spaces. The list of acronyms is shown in Table 1. This study reviewed the air quality and virus and pollutant transmission risks in three types of highly occupied public environments: (i) transportation hubs, (ii) public transportation, and (iii) crowded spaces (classrooms and offices). However, there have been few studies on controlling virus and pollutant transmission in areas such as buses, subways, and subway stations, so this issue needs further analysis.

Table 1. List of acronyms.

Particulate Matter	Ultrafine Particles	Volatile Organic Compounds	Polycyclic Aromatic Hydrocarbons	Black Carbon	Culturable Airborne Bacteria	Air Conditioning	Mechanical Ventilation	Natural Ventilation	Displacement Ventilation	Personalized Ventilation	Platform Screen Doors
PM	UFPs	VOCs	PAHs	BC	CAB	AC	MV	NV	DV	PV	PSDs

2. Overview of Highly Occupied Public Environments

A minimum of 30 m^3/h per person is required in common environments. Highly occupied public environments gather a large number of people in some time periods, and an air supply of 20–30 m^3/h per person is needed. In addition, the highly occupied public environments have larger spaces, the personnel activities are more complex, and the social distance is shorter. Personnel activities may increase the pollutant transmission distance. During the COVID-19 pandemic, public safety in crowded places became a great concern.

People's work and studies are closely related to densely crowded environments, as shown in Figure 1. Means of transportation are usually boarded in transportation hubs, which contain dense and highly mobile populations. This complex environment increases the risk of personal exposure. Commuters can easily carry viruses and bacteria from transportation hubs to public transportation, where crowds are dense and the social distance is short, which increases the risk of cross-infection. Finally, controlling the level of pollutants and reducing the risk of personal exposure in the air environment of densely crowded spaces such as classrooms and offices is urgently needed.

The relevant review articles on pollutant exposure in highly occupied public environments are shown in Table 2. Droplets are large heavy particles that transfer from person to person in close proximity and are the main reason for the need to socially distance (say 1–2 m). They usually fall to the ground. The other main and more insidious mode of transfer of virus particles is small and lighter-weight aerosols that can drift within enclosed interior spaces of airflow and cause infection to others.

Table 2. Summary of review articles about pollutant exposure in highly occupied public environments.

Classification	Highly Occupied Public Environments	Research Object	Main Conclusions
Crowded places	Classroom	NO_2, O_3, PM, VOCs, bacteria	Occupancy activities caused a large fraction of virus transmission due to the resuspension of previously deposited matter [29].
	Hospitals, Schools, Offices	Infectious diseases	Ventilation is positively associated with airflow direction control in buildings [30].
	Homes, Schools, and Hospitals	Humidity, influenza virus, VOCs	Humidity and temperature can be adjusted to achieve a satisfactory work environment [31].
	Public Spaces	Aerosol	The range of typical indoor aerosols can be used as a reference for biosensors designed to improve public safety [32].
Public transport	Pedestrians, Car, Bus, Massive Motorized Transport	Black carbon, carbon monoxide, coarse particles, fine particles, NO_2	Pedestrians have higher levels of inhaled pollutants than commuters using motor cabins [33].
	Taxi, Bus, Subway, Busy Street	PM, CO, NO_2, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs)	There are differences in measurement methods and a lack of uniform measurement standards [34].
	Walk, Cycle, Car, and Bus	PM 2.5, ultrafine particles (UFPs), and black carbon	The concentrations of PM 2.5, ultrafine particles (UFPs), and black carbon (BC) in Asian cities are higher than those in the USA and Europe [35].
	Cycle, Car, Subway, and Bus	PM, BC	The levels of a bus passenger's exposure to PM and BC largely depend on the bus route chosen [36].
	Walk, Bicycle, Car, Bus	PM 2.5, BC, UFPs, CO	Car drivers are exposed more than pedestrians [37].
	Walking, Cycling, Bus, Car, and Taxi	PM 2.5, BC, UFPs, CO	Pedestrians are exposed to lower levels of UFPs and CO than people inside vehicles [38].
	Bicycle, Bus, Automobile, Rail, Walking, and Ferry Modes	UFPs	Exposure to UFPs can have acute effects on health-compromised individuals [39].
	Subway	PM	Underground PM is more toxic than urban PM [40].
	Subway	PM	The dust in a subway system is more toxic than ambient airborne particulates [41].
	Subway	CO, PMs, VOCs	The ventilation mode, passenger numbers, and surrounding pollution level outside of a metro station could have important effects on the metro air quality [42].
	Aircraft	Airborne expiratory contaminants	Most researchers have applied Lagrangian models to analyze transient phenomena [43].
	Aircraft	Droplets, SARS	Most diseases have an incubation period that is longer than the period of air travel [44].
Transport hub	Transportation and Transportation Hubs	Respiratory viruses	Air transportation appears to be important for accelerating influenza propagation [45].
	Subway Stations	High temperature, high humidity, PM, VOCs	Ventilation can spread air pollutants through a complex airflow [46].
This study	Classroom, Office, Subway station, Airport, Bus, Subway, Aircraft	CO, PM, droplets	The pollutant concentration detection system should be combined with the air-conditioning system in crowded places. Passenger flow had a great influence on pollutant transport in transport hubs.

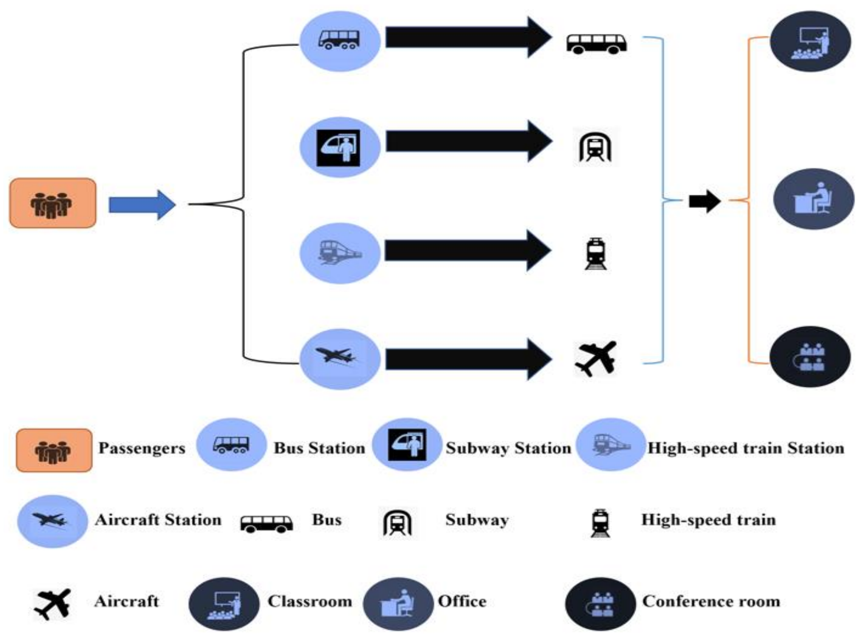

Figure 1. Structure of highly occupied public environment.

The average concentrations of PM 2.5 and total suspended PM that people taking subways are exposed to are 8 and 12 times those to which taxi drivers are exposed, respectively [41]. Moreover, uniform measurement standards are rarely applied to Asia [34,35]. Future work should place an emphasis on confirming the contribution of ultrafine particle (UFP) exposure to total PM exposure during transportation [39]. Exhaled droplets are transmitted in indoor environments, either directly or through air distribution [47]. PM, black carbon (BC), CO, fungal particles, bacteria, and viruses are frequently the main pollutants identified in subways.

Occupant density and occupant activities have a high impact on indoor air quality. The level of indoor aerosols is mainly affected by indoor population density, outdoor air level, and ventilation type [48]. Considering the coupled relationship between the indoor environment and ventilation, internal ventilation strategies should be determined according to outdoor conditions [46]. Currently, there are insufficient data to assess the relationship between the ventilation rates of highly occupied public environments and airborne infectious diseases, and there is a lack of quantitative research on the impact of occupant activities on pollutant transmission. Therefore, future work should focus on investigating the health risks posed by air pollutants and further developing advanced ventilation strategies to improve air quality in crowded places. The main indoor air pollutants in classrooms include viruses, PM, and volatile organic compounds (VOCs).

Poor ventilation and crowding are environmental factors that affect the risk of airborne infection in ground public transportation [49,50]. In the absence of sufficient air renewal, high transmission of influenza may occur in confined spaces. Therefore, the concentration in underground or closed stations may be several times higher than the concentration in the surrounding air [51–53]. Due to the metal wear of wheels and brake shoes in subway tunnels, the level of Fe-containing particles and black carbon level (PM, BC) are high in subway stations [54–57]. In this paper, PM, BC, and viruses are studied as major pollutants in transportation hubs.

3. Classrooms and Offices

3.1. Classrooms

As students spend spending almost one-third of each day studying in the classroom, their activities including sweating, breathing, and movement have a great impact on indoor air quality and lead to a high concentration of bacteria and a high level of CO_2.

In addition, serious respiratory symptomatology is closely associated with a high level of CO_2 [58]. Results have shown that some painting and collage materials in classrooms emit high concentrations of VOCs. Moreover, previous research has found that crowded classrooms are associated with high levels of several chemicals [12,13]. Viruses are also common pollutants found in classrooms. A previous study found that the students in classrooms without daily cleaning were more than twice as likely to be infected with a virus compared to students in classrooms with daily cleaning [59]. Therefore, cleaning classrooms every day is important for decreasing virus levels. An earlier intervention is having hand sanitizer freely available. Additionally, maintaining an indoor temperature above 20 °C with 50% or 80% relative humidity may be a way to mitigate the transmission of the influenza virus. The possibility of a relationship between temperature and relative humidity for viruses was revealed in 2020 in terms of specific enthalpy; today, this approach is widely recognized [60–62]. The resuspension of floor dust is an important contributor to the quantity of bacterial aerosols during occupancy.

Table 3 summarizes the various concentrations of indoor air pollutants detected in classrooms with different HVAC types and different occupant densities. Ventilation control strategies are thought to be a feasible way to control the levels of indoor air pollutants. In addition, in regard to ventilation, mechanical ventilation (MV) with automatically operable windows is assumed to play an essential role in reducing CO_2 levels. However, if windows cannot be opened, a suitable outdoor fresh air supply rate should be guaranteed to maintain good indoor air quality.

Table 3. Reviews on pollutants in classrooms.

Classification	HVAC Type	Pollutants	Concentrations	Occupant Density (m^2/per)	Main Conclusions
Air Conditioning (AC)	Fan coil + OA	CO_2 (ppm) PM 2.5 (μg/m^3)	729.75 ± 71.29 85.83 ± 24.44	4.15 ± 0.26	Inadequate filtration efficiency as well as redundant outdoor air supply rates [63].
	VAV + OA	CO_2 (ppm) PM 2.5 (μg/m^3)	716.41 52.06	4.23	
	AC	CO_2 (ppm)	1596	2.24	Lack of outside fresh air in air-conditioned classrooms may be the reason for high CO_2 concentrations [64].
	AC	CO_2 (ppm) Airborne dust (μg/m^3) Viable fungi (cfu/m^3)	1433.62 ± 252.80 659.22 ± 102.80 367.00 ± 88.13	NA	Poor air renovation causes a high level of CO_2 in AC classrooms [65].
	AC (split-type AC units or fully mechanical central AC system)	SO_2 (ppb) NO_2 (ppb) H_2S (ppb) Formaldehyde (ppb) Acetaldehyde (ppb)	0.823 15.81 4.99 58.58 2.69	NA	A high level of formaldehyde in classrooms indicates there are indoor sources [66].
	AC (window-type AC)	PM10 (μg/m^3) CO_2 (ppm)	97.93 1266.65	1.45	Air-conditioning systems can control indoor PM10 levels [67].
	AC	CO_2 (ppm) CO (ppm) Total volatile organic compounds (TVOCs) (ppb) CH_2O (ppm) PM10 (μg/m^3)	1372.05 ± 264.26 0.605 ± 0.16 158.46 ± 44.48 0 56.68 ± 17.24	NA	Outside particles infiltrate the classroom and cause a high level of PM10. High occupant density in air-conditioned classrooms causes a high level of CO_2 [68].

Table 3. *Cont.*

Classification	HVAC Type	Pollutants	Concentrations	Occupant Density (m^2/per)	Main Conclusions
	AC (water cooling tower)	PM10 (μg/m^3) CO_2 (ppm)	94.26 1870.83	1.17	Air-conditioning systems can cause high levels of carbon dioxide [67].
Mechanical Ventilation (MV)	MV	O_3 (ppb) NO (ppb) NO_2 (ppb) PM0.3–0.4 (μg/m^3) PM1.6–2.0 (μg/m^3)	30.25 ± 6.7 9.33 ± 14.25 11.75 ± 6.89 53,598 ± 31,637.12 324.18 ± 137.62	NA	The high levels of pollutants suggest the building's airtightness is so poor that is not able to provide protection against outdoor pollutants [69].
	MV	PM10 (μg/m^3) CO_2 (μL/L)	169.72 ± 66.22 748.9 ± 249.54	1.59 ± 0.54	Crowded classrooms and insufficient ventilation are important factors affecting indoor air quality [67].
	MV (automatically operable windows with exhaust fans)	CO_2 (ppm)	662 ± 96	1.98	Using chalk and marker boards increases indoor air pollutants. CO_2 was effectively reduced in classrooms with automatically operable windows [70].
	MV (two ceiling-based supplies and one extract) MV (variable-speed fan) MV (variable-speed fan+ automatic windows)	CO_2 (ppm) CO_2 (ppm) CO_2 (ppm)	761 ± 39.60 1100 ± 320 853 ± 268		The mechanical ventilation system provides a more effective way of reducing CO_2 levels but does so at the expense of occupant control [71].
Natural Ventilation (NV)	NV (with ceiling fan and windows open)	CO_2 (ppm) CO (ppm) TVOC (ppb) CH_2O (ppm) PM10 (μg/m^3)	661.86 ± 84.59 0.36 ± 0.11 55.12 ± 36.81 0.015 ± 0.01 252.70 ± 81.49	NA	Outside particles infiltrate the classroom and cause a high level of PM10. High occupant density in air-conditioned classrooms causes a high level of CO_2 [68].
	NV (window opening)	O_3 (ppb) NO (ppb) NO_2 (ppb) PM0.3–0.4 PM1.6–2.0	30.75 ± 11.09 2 ± 1.63 3.75 ± 4.19 49,742.5 ± 35,536.61 171 ± 50.94	NA	The high levels of pollutants suggest the building's airtightness is so poor that is not able to provide protection against outdoor pollutants [69].
	NV (single-sided ventilation)	CO_2 (ppm)	1219 ± 360.90	NA	The mechanical ventilation system provides a more effective way of reducing CO_2 levels but does so at the expense of occupant control [71].
	NV (single-sided double opening)		1447 ± 350.72		
	NV (cross-ventilated)		1255 ± 588		
	NV (cross-ventilated stack effect)		1581.5 ± 358.05		
	NV	PM 2.5 (μg/m^3) PM 10 (μg/m^3) CO_2 (ppm)	178.25 ± 21.87 165.75 ± 31.38 1507.25 ± 302.41	1.73 ± 0.08	Building defects as well as occupants' activities are associated with indoor air quality [72].
	NV	PM 10 (μg/m^3) PM 2.5 (μg/m^3) PM 1.0 (μg/m^3)	566.82 ± 373.33 212.90 ± 181.55 177.23 ± 163.32	NA	Occupants' activities lead to resuspending of PM10 and PM 2.5 and delay their settling [73].
	NV NV (free-running ventilation) NV (manual airing)	CO_2 (ppm) CO_2 (ppm) CO_2 (ppm)	2783 2006 ± 194.57 1292.33 ± 199.09	2.2 2.2 2.2	A ventilation system with a heat recovery device may be a suitable method to guarantee the CO_2 levels and energy consumption below the guidance [74].

Table 3. *Cont.*

Classification	HVAC Type	Pollutants	Concentrations	Occupant Density (m^2/per)	Main Conclusions
	NV	CO_2 (ppm)	2717 ± 792.6	NA	The ventilation efficiency in these classrooms is very poor, and opening doors has a significant effect on reducing the CO_2 levels indoors on a short-term basis [75].
	NV	CO_2 (ppm)	1195 ± 311.27	3.04 ± 0.50	A large number of students and a long class duration (more than 60 min without break) may be the reason why the CO_2 levels are high [76].
	NV (manually operable windows)	CO_2 (ppm)	803 ± 184	2.25	Using chalk and marker boards increases indoor air pollutants [70].
	NV (automatically operable windows)	CO_2 (ppm)	732 ± 131	2.06	The classrooms with automatically operable windows had lower CO_2 concentrations [70]. CO_2 was effectively reduced in classrooms with automatically operable windows [70].
	NV	CO (ppm) CO_2 (ppm) PM 10 (μg/m^3) TBC (CFU/m^3) TVOCs (μg/m^3) HCHO (ppm)	1.32 ± 1.51 1228.81 ± 798.65 106.67 ± 90.62 1463.39 ± 1269.92 374.06 ± 337.03 0.10 ± 0.15	NA	Building materials and furnishings may emit chemicals that lead to high levels of indoor air pollutants [77].
	NV	CO_2 (ppm) Airborne dust (μg/m^3) Viable fungi (cfu/m^3)	520.12 ± 37.25 215.12 ± 68.20 1001.30 ± 125.16	NA	Outdoor fungi infiltration led to a high concentration of viable fungi in the NV classrooms [65].
	NV	CO_2 (ppm)	708	2.24	Lack of outside fresh air in air-conditioned classrooms may be the reason for high CO_2 concentrations [64].
Mixed	NV NV + MV NVAC	CO_2 (ppm)	1905 1052 1464	NA	Adding mechanical ventilation to the ventilation system is a good solution to ensure indoor air quality [78].

In many cases, the fresh air supplied by HVAC systems is inadequate [79]. It is assumed that CO, SO_2, NO, and NO_2 from heavy traffic infiltrate indoor rooms due to poor building airtightness. In addition, there is a close correlation between particle concentration and occupant density, which is mainly due to the delayed settling and recovery of suspended particles caused by occupant activity and movement.

A summary of the levels of CO_2 and PM10 exposure under different ventilation strategies is shown in Figure 2. The CO_2 concentration is always above 1000 ppm in rooms with natural ventilation (NV) or air conditioning (AC), which indicates that ventilation is still very poor in these classrooms. Rooms with NV have the highest levels of CO_2, followed by rooms with AC and MV, while rooms with MV have the lowest levels of CO_2. The high concentration of CO_2 in rooms with NV indicates that NV cannot fully meet the ventilation requirements for crowded spaces. The CO_2 concentration in air-conditioned rooms is also high, indicating that the outdoor fresh air supply in air-conditioned rooms is insufficient. High concentrations of PM10 occur in rooms with NV, followed by rooms with MV and AC, showing that outdoor pollution is the main source of high concentrations of indoor pollutants and that AC helps control the concentration of PM10. Insufficient outdoor air filtration efficiency and building defects are also responsible for high levels of indoor PM.

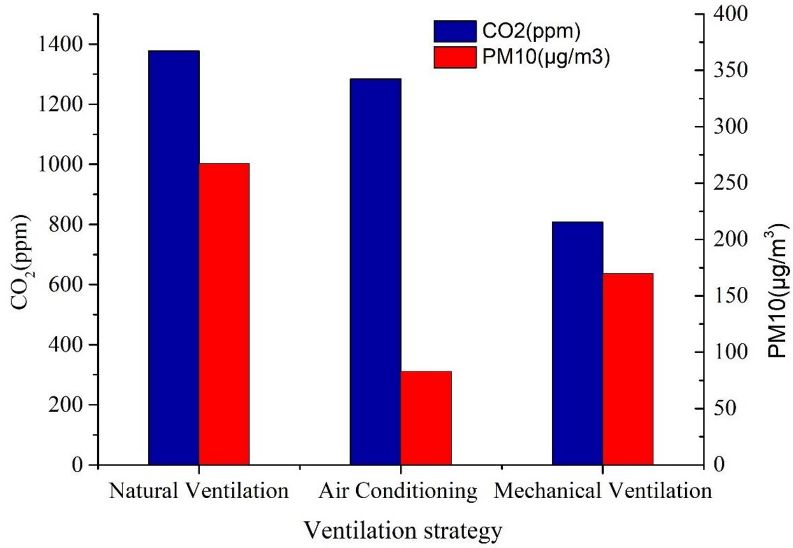

Figure 2. Summary of levels of CO_2 and PM10 exposure under different ventilation strategies in classrooms (data from Table 2).

Opening windows can effectively remove UFPs from a classroom. In addition, an accessory exhaust outlet below the breathing zone helps lessen the levels of particles in the breathing zone [80]. Replacing a traditional AC system with a central AC system enables CO_2 levels to be maintained at standard levels and provides adequate fresh air [64]. In contrast, a variable-speed mechanical fan controlled by indoor CO_2 levels may be more environmentally friendly than a central AC [81]. Therefore, by controlling the temperature and the amount of outdoor fresh air supply through a real-time temperature sensor and a CO_2 sensor, a special MV system with a constant-flow fan outdoors can significantly reduce the levels of CO_2 in classrooms without compromising thermal comfort.

3.2. Offices

Table 4 shows the effects of various ventilation strategies on indoor air pollutants in offices. An increasing number of advanced air supply systems are being used for office air quality control. In large office buildings, different ventilation strategies are adopted in different seasons. Sometimes NV is more effective than AC, depending on the concentration of outdoor pollutants.

Table 4. Overview of ventilation strategy effects on indoor air pollutants in offices.

Ventilation Strategies	Methods	Ventilation Rate/Person	Results
Displacement ventilation (DV)	Experiment	NA	Almost a quarter of the occupants were uncomfortable when a vertical temperature difference was present [82].
MV	Investigation	From 7 to 70	There was no correlation between MV and sick building syndrome [83].
NV	Experiment	NA	A new type of NV—diffuse ceiling ventilation—achieved ventilation and cooling requirements with minimum ventilation [84].
Personalized ventilation (PV)	CFD simulations	7.5	Transient parameters be changed by variable-frequency air supply, which can improve air quality [85].
Combined ventilation system (DV + PV)	Experiment	82	Precise control of the temperature of air supplied by DV and PV is very important [86].
Underfloor air distribution	Experiment	NA	For open-plan offices, underfloor air distribution is more suitable than mixing systems [87].
Confluent jet ventilation	Experiment	15–30	Confluent jet ventilation produced better results than mixing and displacement ventilation [88].

By investigating the average I/O ratio of PM 2.5, Zhu et al. [89] found that indoor PM 2.5 mainly comes from outdoor sources. Traffic conditions are the main source of outdoor pollution that affects the level of indoor PM [90]. Cheng [91] found that the coarse particles in office buildings originate from indoor activities. The clean air delivery rates of the air purifiers are determined by the air volume, the efficiency of the air purifier, and air distribution in the room [92]. Ren et al. proposed that the clean air delivery rate (CADR) in Chinese office buildings should be in the range of 10–33 $(m^3/h)/m^2$ to effectively control indoor PM 2.5 [11]. The presence of people is also the main factor influencing the indoor environment, while resuspension activities are the most significant source of particles with a size larger than 1 μm [93].

3.3. Discussion

Students' walking has a great influence on the concentration of coarse particles in the classroom [94]. Occupants' indoor activities not only resuspend these particulates but also delay their deposition/settling, resulting in higher ambient indoor concentrations [95]. Taking shoes off when entering a building can reduce particle mass concentrations [96]. For aerosol particles, the concentration of coarse particles increases with occupant activity [97].

PM mainly comes from outdoors, but indoor suspended PM is greatly affected by students' activities. Although the research on classroom indoor air quality is becoming increasingly advanced, a quantitative study of crowd behavior factors influencing the environment has not been performed. With intelligent buildings becoming a trend in architectural development, systems allowing real-time monitoring of pollutant concentrations are being installed in intelligent buildings to provide timely feedback. A complete pollutant concentration monitoring–feedback–exclusion system should be established to ensure the safety and comfort of the indoor environment.

4. Transport Hubs

4.1. Subway Stations

The PM concentration of the ground-level indoor environment in a subway station is affected by the piston wind of the tunnel. The use of platform screen doors (PSDs) reduces PM levels and metal concentrations [98–101]. In some indoor environments, the concentration of PM underground is higher than that at ground level [102,103]. Due to the small amount of air infiltration and the weak effect of exhaust, the deeper the subway platform is, the higher the PM 2.5 concentration [104]. Therefore, forced MV in tunnels can also maintain the air quality in subway stations [105,106]. The concentration of PM 2.5 in subway systems varies greatly in different seasons, due to the concentration variations of outdoor PM [107]. The concentration of culturable airborne fungi (CAF) in the air is positively correlated with the depth of subway stations [108,109]. However, the density of fungal spores in subway stations is within acceptable sanitation levels for public buildings [110].

A ventilation control system equipped with a PM10 feedback device can increase the concentration of PM10 on a platform from an unhealthy level for sensitive people to a moderate level [111]. Biological aerosols account for only a small part of total aerosols (typically <1%) [112]. Due to the variation in the number of passengers in transit, culturable airborne bacteria (CAB) concentrations appear to vary over time [113]. Anthropogenic sources are the major source of bacteria in subway stations, and airborne bacterial communities may be toxic [114]. However, considering the crowded conditions during peak hours, there is a risk of mold allergic reactions for some categories of underground passengers. With the proliferation of advanced methodologies for short-term traffic flow prediction, intelligent transportation systems have been maturing [115,116]. However, high passenger flow has a great effect on air quality, and there is a lack of quantitative research.

4.2. Railway Stations

Bacteria in train stations change with the seasons; from spring to winter, the number of bacteria rises, and the number of fungi peaks in autumn [117]. Enclosed railway stations that serve diesel trains have poor air quality, and the resulting exhaust emissions harm passengers [118,119]. Many workers spend a few hours in the subway station every day. They are exposed to large amounts of steel dust, so they may face more health risks than other members of the commuting public. Using green energy could eliminate diesel trains. In this way, the health of passengers is less likely to be adversely affected.

4.3. Terminal Buildings

The air quality satisfaction levels of travelers are highly correlated with the CO_2 concentration in airport terminals [120]. There are limited data on the exposure of passengers to particulate pollutants in terminal buildings. In one study, the PM 2.5 levels in an airport were much higher than the regulatory limits set by the WHO during all of the tested seasons and were exceedingly influenced by the outdoor air [121]. In addition, a simulation study of the spread of influenza in an airport terminal revealed the possibility of spread among a large number of passengers [122]. The SARS-CoV-2 virus spreads very quickly between cities, and the transmission rate is proportional to the closeness of the city air transport networks [123]. Thermal scanning, which can identify passengers with fever, allows for passengers exhibiting symptoms of COVID-19 infection to be tested before they board a plane. This method is very effective. However, queuing for scanning could be a major source of contagion. In addition, the influenza virus is suspected to spread on the way to the airport and during the stay in the airport terminal; the 14-day incubation period of the influenza virus shows that it is difficult to determine the exact time and place of transmission. This increases the risk of infection in crowded public spaces.

4.4. Discussion

There is little research on the indoor air quality of transportation hubs. Compared with classroom and office environments, the indoor environment of public transportation hubs is not only affected by disturbances created by passenger flow but also strongly influenced by the dispatch frequency of public transportation. Higher passenger flow easily leads to contaminant transmission and increases the risk of cross-infection.

There is almost no research on the characteristics of pollutant transmission caused by crowed flow in transportation hubs. It is difficult to quantify the concentrations of pollutants due to the dynamic changes in passenger flow, which increases the difficulty of studying the characteristics of pollutant transmission. It is recommended that transportation big data be used to forecast passenger flow and control indoor air quality.

5. Public Transport

5.1. Subways

The aerosols in a subway tunnel are the source of particles on the platform and in the train, which reveals that coarse particle transportation mainly occurs through the door [124]. Therefore, the average concentration close to the door is higher than that in the seating area. However, there is no consistent conclusion on the relationship between passenger density and PM concentration. Gao et al. [125] found that the concentration of PM 2.5 decreases as the number of passengers increases, possibly because passengers inhale PM 2.5. The chemical and toxicological features of PM 2.5 and coarse PM vary by method of public transportation. When assessing public exposure, the dose and toxicity of pollutants may be better indicators than the PM mass level [126,127]. Gong et al. [128] found that the number of passengers also affects the concentrations of VOCs and PM 2.5 in a subway. Subway microbial communities mainly originate from oral commensal microbes and human skin [129]. The bacterial communities in the air were similar in the train, on the platform, and in the lobby [130]. Therefore, enhancing the ventilation system during rush hours may help control exposure.

5.2. Buses

The level of indoor pollutants in a school bus is much higher than that outdoors [131,132]. Opening doors and windows leads to high PM 2.5 and PM10 mass concentration changes [133–135]. The doses of inhaled contaminants were lower for electric bus passengers than for passengers of other transportation modes. A regression model revealed a positive correlation between exposure to PM10 and the number of bus passengers ($r = 0.05$, $p < 0.01$) [136]. Due to the exhaust from the bus itself, the carbon monoxide content in the cabin is higher than the carbon monoxide content in the surrounding environment/roadside, but they are significantly correlated [137].

The concentration of outdoor contaminants strongly affects the concentration of indoor contaminants [138,139]. Therefore, the airtightness design of a vehicle cabin should be improved to reduce the intrusion of vehicle exhaust gas [140]. The most effective ventilation strategy is to use AC and close windows while driving, which can minimize exhaust gas exposure [141,142]. When a filter is used, the concentration of contaminants in a cabin is significantly reduced compared to that when a filter is not used [143]. Minimizing commute times and periodically replacing filters for a bus can significantly reduce personal exposure to pollutants [131]. Air filtration can significantly reduce the risk of personnel exposure. Therefore, we strongly recommend that schools and governments adopt these policies to protect the health of all those using school buses. But that would also apply to any other bus service.

This study compared the exposure determined in some studies for different modes of commuting (bus and subway). The pollutant concentrations in a bus and subway on the same route are shown in Figure 3. On the basis of the comparison of PM 2.5 concentrations, the same pollutant concentration varied greatly on different routes. The concentration of PM 2.5 is lower than the WHO standard in only a few cities. The subway is a travel mode with a low pollutant concentration.

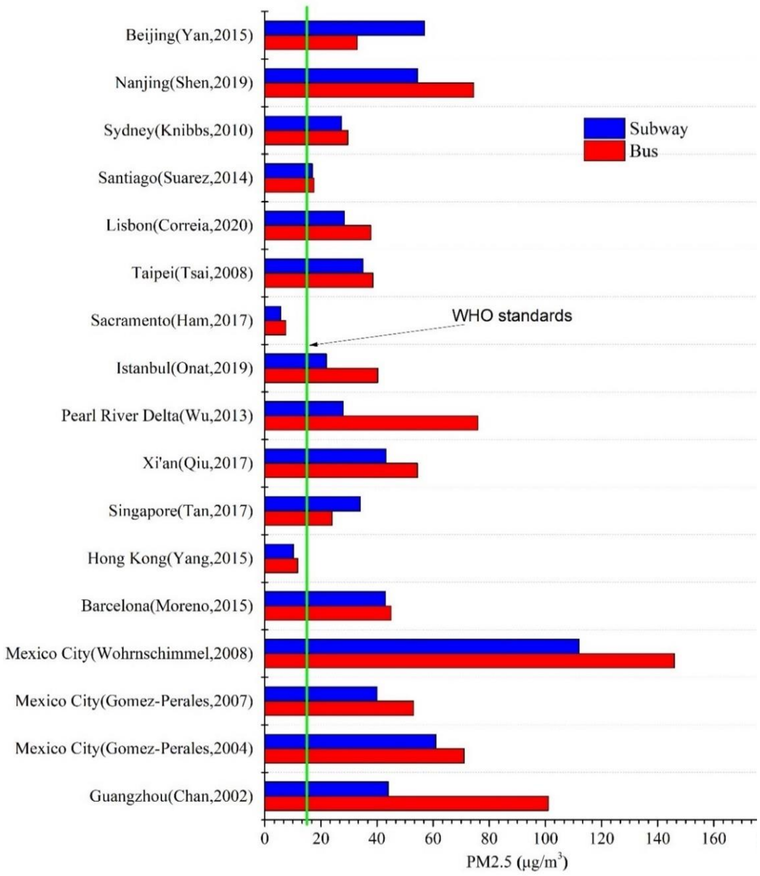

Figure 3. Comparison of the PM 2.5 concentration in subways and buses (data from [101,144–159]).

Due to the roadside sources contributing to high PM concentrations in roadway transportation environments, the PM 2.5 concentrations of Beijing and Singapore are higher. The concentrations were not considerably different between subway and bus journeys in Barcelona. However, the average exposure concentrations of the London underground system are 3–8 times those of other surface transport modes [160]. This difference may be due to the level of ventilation and the spatial design of the subway station but was not true for certain elements (such as Fe and Mn) [41]. Similar results were obtained in Correia et al.'s [159] research (metro, $37.8 \pm 20.8\ \mu g/m^3$, and bus, $28.4 \pm 5.3\ \mu g/m^3$). To reduce the exposure to air pollutants in subway systems, screen door platforms, air purifier units, and high-efficiency air filters are effective measures [161–163]. However, because outdoor subway environments greatly differ, more research should be conducted to determine the optimal purification strategy.

Pollutant concentrations in buses and subways on the same route are shown in Figure 4. A comparison of the CO concentrations indicates that the levels in most cities are below WHO standards. The CO concentrations in Mexico City's buses are higher than the WHO standard because of the high concentration of CO in the public transportation system of Mexico City and the serious exhaust emissions from motor vehicles on the bus routes. The use of high-efficiency h10 filters to replace common filters can improve the air quality in a cabin and reduce the passenger inhalation dose [164]. Future research should further distinguish the relative influences of weather, traffic, route, and vehicle ventilation parameters to properly inform policies and mitigation measures on the most significant determinants of commuter exposure to PM.

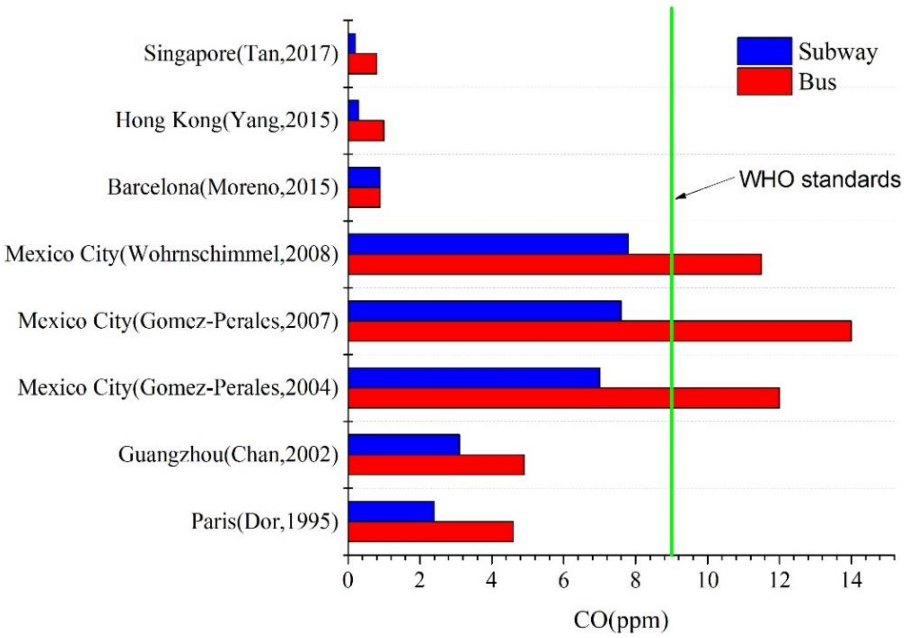

Figure 4. Comparison of CO concentrations in subways and buses (data from [101,144–149,165]).

5.3. High-Speed Trains (HSTs)

There is little research on the indoor air quality of HSTs. The diffuser type significantly affects the airflow distribution in a train cabin [166]. Because the passenger thermal plume is coupled with the supplied airflow, a few contaminants may be confined to the area around a passenger [167,168]. A multi-objective optimization platform has been developed to optimize indoor air quality in HST cabins [169]. When a passenger coughs in the cabin, the droplets spread quickly in the longitudinal direction. The larger droplets usually fall to the ground within 1–2 m, hence the need for social distancing. The smaller and lighter aerosols spread out into the indoor space and disperse via airflow.

5.4. Aircraft

On aircraft, the main gaseous pollutants are ozone, carbon oxides, and volatile organic compounds. During the boarding phase, the carbon dioxide concentration is higher than that during the flight phase, possibly due to insufficient ground ventilation on many flights [170]. Controlling the concentration of VOCs and CO_2 and ventilation strategies are important ways to create an acceptable cabin environment [171]. The main source of formaldehyde in airplanes is the ozone reaction [172]. Twenty-nine percent of TVOCs may be related to humans and service in aircraft cabins [173]. The peak values of VOCs in flight usually occur before takeoff and during cruising [174]. The main particulate pollutants with potentially infectious viruses and bacteria come from exhalation activities, such as coughing and sneezing [175]. Although the PM concentration was low for most flights investigated, peaks were measured during deboarding and boarding. An environmental control system and a ground AC cart are necessary to reduce the concentration of pollutants [176]. The distribution characteristics of PM < 3 μm are almost the same as those of gaseous contaminants [177]. Therefore, the location and size of the pollution source have an important impact on the transmission of pollutants in an aircraft cabin. The occupant density is an important consideration.

By comparing DV and mixed ventilation, Zhang et al. [178,179] found that the use of multiple air inlets is able to ameliorate the velocity distribution uniformity in the cabin. The method of installing localized suction orifices close to the occupant exhausts contaminants from the aircraft cabin before they become entrained in the bulk airflow [180,181]. A DV system is more efficient at removing the smallest droplets by air extraction, but for larger droplets, its efficiency will be reduced [182]. Wisthaler et al. [183] found that cleaner air units effectively reduced the concentration of most organic pollutants. Therefore, the implementation of DV in vehicles has been questioned. The smallest droplets can remain airborne for a long time in the form of aerosols. The estimated risk of inhalation infection is much higher than the risk of contact infection.

5.5. Comparisons

A comparison of contamination in different public transport sectors is shown in Table 5. The PM 2.5 concentration in an aircraft is still high and is caused by passenger activities. Subways have the highest fungal concentration, followed by buses and then airplanes, because a subway, as a special underground environment, has a high dampness level and carries the most passengers. The xylene levels found in buses and subways are higher than those found in airplanes because gasoline is the main fuel for ground transportation vehicles. As with aircraft, office buildings can also vary in terms of air quality depending on various factors such as the ventilation system, maintenance practices, presence of indoor pollutants, and outdoor air pollution levels. Some office buildings have well-maintained ventilation systems with air filters that help remove pollutants. However, older buildings or those with inadequate maintenance may have lower air quality.

Table 5. Contamination comparison in different public transport modes.

Pollutants	Aircraft	Bus	Subway
CO (ppm)	2.57 [184]	2.9 [140]	0.1–2.3 [185]
PM 2.5 (μg/m^3)	91 [186]	74.4 [157]	64.1 [187]
VOC (ppb)	0.227 [188]	5.9–8.63 [141]	0.14–3.89 [189]
Bacteria	NA	NA	2083 [190]
Fungi (CFU/m^3)	60 [184]	248 [143]	483 [190]
BC (μg/m^3)	NA	2.5–19 [131]	4.1 [191]
PAHs (μg/m^3)	NA	32–400 [131]	8.7 [187]
NO_2 (ppb)	11.3 [184]	44–220 [131]	NA

The activity of passengers is very complex, and resuspension caused by occupant movement is one of the main pollution sources. Passenger behavior also affects the transmission of contaminants in public transportation [192,193]. Passenger activities have a significant impact on resuspension and deposition on the surface of passengers [194,195]. The occupants' adjustments of the seatback angle increase the risk of longitudinal transmission of contaminants [196,197]. A passenger cough affects more passengers in an aircraft cabin during the ascent [198]. The potential health risks caused by passenger behavior need further assessment.

5.6. Virus Transmission

The evaluation of droplet/virus effects on public transport is shown in Table 6. Droplets are larger particles, typically larger than 5–10 μm in diameter. These droplets are usually generated when an infected person coughs, sneezes, talks loudly, or exhales forcefully. They are relatively heavy and tend to fall to the ground or surfaces within a short distance (typically within 1–2 m from the source) due to gravity. They are the reason for the need to socially distance. The overall airflow plays the most important role in droplet transport in public transportation areas. A cough jet will bring the aerosol to the seat in front of the cougher. Transmission occurs when a person comes into direct contact with the respiratory droplets containing the virus and inhales them or touches contaminated surfaces and then touches their face (eyes, nose, or mouth). This mode of transmission is considered short-range and requires close proximity to the infected individual. An increase in the ventilation rate can reduce the exposure of passengers near the source of pollution but increases the aerosol diffusion distance and the exposure of passengers farther away [199–201]. Therefore, contact tracing includes close contacts and passengers seated two seats away. However, contact tracing to four rows on either side of the index case is a reasonable compromise. Aerosols are generated when an infected person breathes, talks, sings, or exhales even without forceful actions. These particles are lightweight and can remain suspended in the air for an extended period, potentially traveling longer distances and spreading throughout an enclosed space. The longer the flight is, the more people are expected to be infected, especially in the economy class.

Table 6. Evaluation of droplet/virus effects on public transport.

Space	Contaminant	Method	Transmission Range/Results	Ref.
Aircraft	Influenza	Investigation	Two rows	[202]
	Droplets	CFD simulations	Four rows	[203]
	Aerosols	Experimental study	Two rows	[204]
	Droplets	Investigation	Five rows	[205]
	Influenza	Investigation	Two rows (42%)	[199]
HST	Droplets	CFD simulations	Seven rows	[167]
	Droplets	CFD simulations	Five rows	[168]
	Tuberculosis	Wells–Riley model	Well—Riley model should integrate quantum generation rate	[206]
Minibuses, Buses, and Trains	Tuberculosis	Wells–Riley model	The highest risk of infection was on the train	[207]

Close contact and long hours on a train may have been one of the reasons for the transmission of the influenza virus. The spatial relationship between the occupant and the flow field greatly affects the spread of droplets generated by coughing [208]. When there is longitudinal airflow in the cabin, the droplets will disperse farther, and more passengers increase the chance of infection [167,168]. Improving the ventilation of public trains appears to be a useful way of mitigating the chances of influenza infection [209]. If infected persons wear masks, the ventilation rate could be reduced to 25%, which leads to less than 1% infection probability [210]. The literature concerning airborne infections in various transportation infrastructures is relatively limited and is mainly related to commercial air travel.

5.7. Discussion

In buses and subways, doors are opened frequently, and outdoor pollutants are high, resulting in relatively high internal pollutant concentrations. The issue of effectively reducing the concentration of indoor PM has not yet been resolved. A high-speed train has fewer openings, reducing the impact of outdoor pollutants. An airplane is also a closed environment, and pollutants mainly come from the indoor environment. Public transportation is a crowded place, and the risk of virus transmission is extremely high. For the success of airborne infection control interventions, it is critical to interrupt the chain of infection transmission. Therefore, using a filter mask could help protect others from virus transmission.

6. Summary of Ventilation Strategy

A reasonable air change rate in a highly occupied public environment may be a good evaluation index, as shown in Table 7. However, increasing the air change rate of the large space will inevitably increase the cost. Therefore, it is a more appropriate method to control pollutants through a reasonable ventilation strategy. The ventilation efficiency in classrooms and offices is NV < MV < AC, but the indoor pollutant level is still high. Therefore, air purifiers are a more effective ventilation strategy. In transportation hubs, indoor pollutants come from the outdoors. Therefore, reducing outdoor pollutant infiltration and increasing filters are more effective ventilation methods. In buses and subways, due to the frequent opening of doors, pollutants also mainly come from outdoors. Reasonable control of the time of opening the door is an effective control strategy. Forms of public transportation, such as HSTs and aircraft, have small spaces and high air change rates. Therefore, their indoor air quality is higher than that of other highly occupied public environments.

Table 7. Evaluation of ventilation characteristics of highly occupied public environments.

	Classroom	**Office**	**Terminal Buildings**	**Subway Stations**	**Subways**	**Aircraft**	**HSTs**
Personnel density (m^2/person)	0.75–1.2	3–6	8.5–10	0.8–1.25	0.125–0.33	0.45–2	0.65–1
Air change rate (m^3/h)	2.5–4.5	2–6	6–15	4–6	30	20–35	6–12

Continuous monitoring of indoor conditions is important for indoor environmental control systems. Therefore, installing air quality sensors can help employers choose the best ventilation strategy. Displacement or personal ventilation systems combined with mixed ventilation are an effective way to reduce cross-contamination. Therefore, advanced air distribution can reduce exposure to airborne infectious diseases. Research on the impact of crowd activities in transportation hubs on pollution transmission is still lacking. Due to the high density of passengers, the PM concentrations caused by passenger activities are high. The activities of occupants are diversified in transportation hubs, which makes it difficult to quantify characteristic behavior. The resuspension of particles caused by occupant movement is an important factor affecting the transmission of pollutants in crowded places.

7. Conclusions

This study reviewed the air quality and ventilation strategies in three types of highly occupied public environments: transportation hubs, public transportation, and crowded spaces (classrooms and offices). As concluding remarks, the following are relevant:

1. Air quality sensors should be distributed in densely crowded spaces to obtain a real-time display of pollutant concentration data. When the pollution level is beyond

the safe level, scientifically designed ventilation and filtration schemes should be implemented to avoid the inhalation of highly concentrated pollutants.
2. Crowding causes high risks of exposure. Local exhaust strategies have been validated for improving indoor air quality in transportation vehicles and buildings.
3. Due to the use of mixed ventilation in crowded spaces, particulate pollutants with potentially infectious viruses and bacteria are rapidly diluted and spread. It is difficult for ventilation systems to effectively control their transmission. It is necessary to promote the wearing of masks in public places during periods of high influenza activity or epidemics.
4. The current research mainly focuses on the characteristics of PM in subway stations and railway stations. There is still a lack of research on viral spread related to air quality in transportation hubs, subways, and buses. It is recommended that indoor air quality be preprocessed in advance.
5. The pollutant transmission characteristics caused by crowd activities in crowded spaces have not been well studied. Occupant activities (passenger flow) have a great influence on pollutant transport in transport hubs, which is mainly manifested in particle resuspension.

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