Ventilation strategies and design impacts on indoor airborne transmission: a review

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Abstract

The COVID-19 outbreak has brought the indoor airborne transmission issue to the forefront. Although ventilation systems provide clean air and dilute indoor contaminated air, there is strong evidence that airborne transmission is the main route for contamination spread. This review paper aims to critically investigate ventilation impacts on particle spread and identify efficient ventilation strategies in controlling aerosol distribution in clinical and non-clinical environments. This article also examines influential ventilation design features (i.e., exhaust location) affecting ventilation performance in preventing aerosols spread. This paper shortlisted published documents for a review based on identification (keywords), pre-processing, screening, and eligibility of these articles. The literature review emphasizes the importance of ventilation systems' design and demonstrates all strategies (i.e., mechanical ventilation) could efficiently remove particles if appropriately designed. The study highlights the need for occupant-based ventilation systems, such as personalised ventilation instead of central systems, to reduce cross-infections. The literature underlines critical impacts of design features like ventilation rates and the number and location of exhausts and suggests designing systems considering airborne transmission. This review underpins that a higher ventilation rate should not be regarded as a sole indicator for designing ventilation systems because it cannot guarantee reducing risks. Using filtration and decontamination devices based on building functionalities and particle sizes can also increase ventilation performance. This paper suggests future research on optimizing ventilation systems, particularly in high infection risk spaces such as multi-storey hotel quarantine facilities. This review contributes to adjusting ventilation facilities to control indoor aerosol transmission.

Keywords: Airborne Transmission; COVID-19; Indoor Air Quality (IAQ); SARS-CoV-2; Ventilation design features; Ventilation Strategies

1. Introduction

Considering all world issues, it is not far from the truth that the COVID-19 outbreak would be called one of the world's biggest issues in the 21st century. When the World Health Organization (WHO) declared COVID-19 as a Public Health Emergency of International Concern (PHEIC) on January 30th, 2020 [1, 2], few people probably could have imagined the SARS-CoV-2 would infect around 290 million and kill more than five million people by Dec 31st, 2021 [3]. The infection statistics indicate that the outbreak has quickly spread worldwide, which caused governments to consider containment strategies, such as national and regional lockdowns, to respond to this pandemic, unprecedented since the flu pandemic in 1918 [4]. These strategies attempted to restrict virus spread by stopping the movement of people and/or isolating potentially infected people to specific indoor spaces. Various studies from medicine and other relevant fields have also investigated how to stop further or reduce COVID-19's negative impacts, for example, by controlling infections in indoor spaces.

Viruses are typically transmitted in four different modes: physical contact (i.e., handshake), fomite (i.e., cloths and furniture), droplets (5 to 10μ), and aerosols (less than 5μ) [5, 6]. Aerosol transmission is highlighted as the most important route for virus-laden respiratory particle transmission [7]. One effective way to control aerosol transmission and reduce indoor infection probability is to supply clean air and dilute contaminated air using ventilation systems [8, 9]. On the one hand, the literature underlines well-designed ventilation as an appropriate way to control spreading viruses [10-14] and improve Indoor Air Quality (IAQ) by removing particles [15], including pathogens and aerosols [16-19]. On the other hand, air recirculation by ventilation is the main route for aerosol transmission, increasing infection risks [7, 20]. Ventilation also affects indoor airborne transmission indirectly by changing indoor temperature and humidity [21-24]. The WHO has repeatedly underlined ventilation as a critical element in enhancing IAQ and indoor well-being due to the strong evidence of ventilation impacts [25-28].

Despite the strong evidence of ventilation influences on airborne transmission, aerosols movement was almost neglected in designing ventilation systems, which caused scientists to call for a shift in the ventilation paradigm [29, 30]. There is a need to select proper ventilation strategies for this ventilation paradigm shift and investigate how to design ventilation systems to distribute clean air instead of facilitating aerosol spread in indoor environments [31]. The literature shows that some studies investigated ventilation impacts on viruses and contaminations spread, mainly addressing the effects of different ventilation strategies [32-35] and their design features [36-38]. The present review paper critically reviews the relevant articles published in the 21st century after major epidemics, including Severe Acute Respiratory Syndrome (SARS), H1N1 influenza epidemic, the Middle East Respiratory Syndrome Coronavirus (MERS-CoV), and COVID-19, to investigate literature findings of effective ventilation strategies and critical design features that majorly affect airborne transmission in indoor environments. The current review concludes with literature findings, innovative and practical ventilation strategies, design, and knowledge gaps. Section 2 describes the literature search strategy and databases. Section 3 reviews the literature based on the impacts of ventilation strategies in various indoor environments under two categories: clinical and non-clinical spaces. Section 4 examines the utilized evaluation and prediction methodologies in previous research. Section 5 discusses the main findings and suggests possible future work based on the knowledge gaps. Finally, Section 6 draws conclusions based on the review outcomes.

2. Review Methodology

Aligned with the study's objectives, for the period from January 2001 to December 31st, 2021, 931 documents were found using Scopus: TITLE-ABS-KEY ("Ventilation" *or* "HVAC" *AND* "Airflow" *AND* "Airborne" *or* "COVID" *or* "Coronavirus" *or* "Virus" *or* "SARS-COV" *or* "Pathogens" *or* "Particles" *AND* LIMIT-TO (SUBJAREA: "ENGI", "ENVI", and "ENER"). Figure 1 indicates the detailed procedure employed for shortlisting the relevant publications.

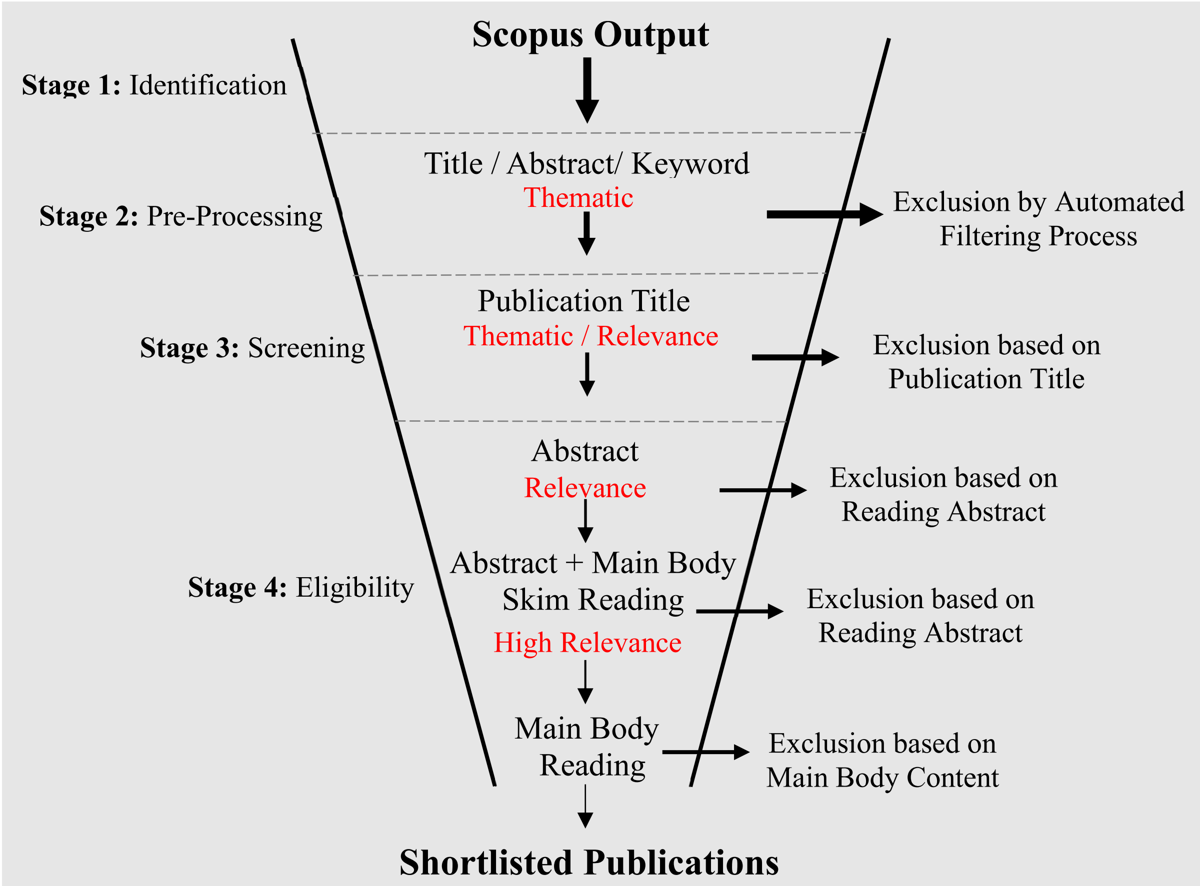

Figure 1. The applied approach for shortlisting relevant articles

In the current review paper, 131 documents (98 articles, 10 conference papers, and 23 review papers) were shortlisted as the review source utilizing the applied approach, shown in Figure 1. Publications were excluded if the focus was on the ventilation type or design impacts on an indoor airborne spread. The details of shortlisted documents and the annual statistic of published papers in Clinical (C) and Non-Clinical (NC) areas are illustrated in Table 1 and Figure 2.

Table 1. Shortlisted documents (reference numbers)

	MV		NV & MMV		PV		Other	
	C	NC	C	NC	C	NC	C	NC
Article	45, 46, 47, 50, 54, 55, 56, 57, 61, 62, 63, 65, 66, 67, 68, 69, 70, 72, 73, 74, 76, 77, 78, 79, 80, 113, 114, 115 & 116	12, 16, 18, 24, 37, 81, 82, 83, 84, 87, 88, 89, 90 91, 92, 93, 95, 96, 98, 101, 103, 110, 112, 117 & 240	34, 141, 142, 143, 145, 148, 149, 152 & 157	20, 125, 136, 158, 159, 161, 169, 170, 171, 172, 174, 175, 177, 180, 181, 184, 185& 187	194, 202, 203 &209	191, 201, 197, 206, 212, 214, 216, 217, 218, 219, 221 & 222	229, & 230	225, 231 232, 233 & 237

Conference	53 & 71	43 & 86	N.A.	N.A.	N.A.	N.A.	N.A.	198
Commentary, Note & Review	58 & 60	8, 32, 107, 204 & 224	153	N.A.	N.A.	N.A.	19, 134, 140, & 207	11, 20, 29, 30, 35, 38, 160, 188, 192, 193 & 226
Total	33	32	10	18	4	11	6	17
Percentage	25.2%	24.4%	7.6%	13.7%	3.1%	8.4%	4.6 %	13.0 %

Figure 2 illustrates the distribution of all 931 published papers from 2001 (top) and 131 shortlisted documents (bottom), correlated against the four pandemics that occurred during that period.

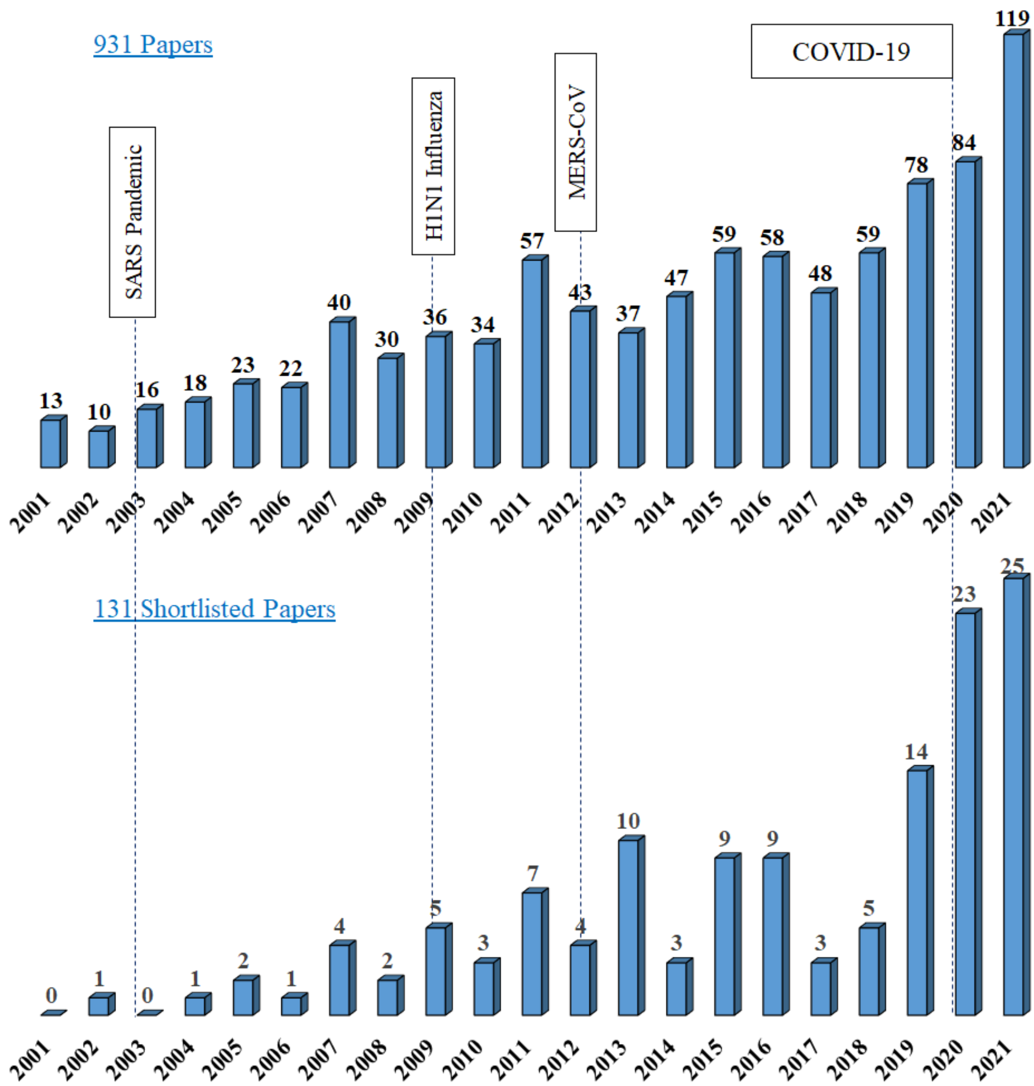

Figure 2. Publications regarding ventilation impacts on airborne transmission before (top) and after shortlisting (bottom) (Scopus Database, December 31st, 2021)

Figure 2 illustrates more studies have recently addressed ventilation impacts on airborne transmission, particularly since the COVID-19 outbreak. This figure also shows smaller peaks in the number of publications following the H1N1 and MERS-CoV pandemics. There was an increase in publications regarding ventilation influences on airborne transmission after 2004 when SARS ended (see Figure 2, top). This figure indicates that ventilation is addressed as a key element after major epidemics, highlighting its importance. Figure 3 also illustrates the concept of the current review paper.

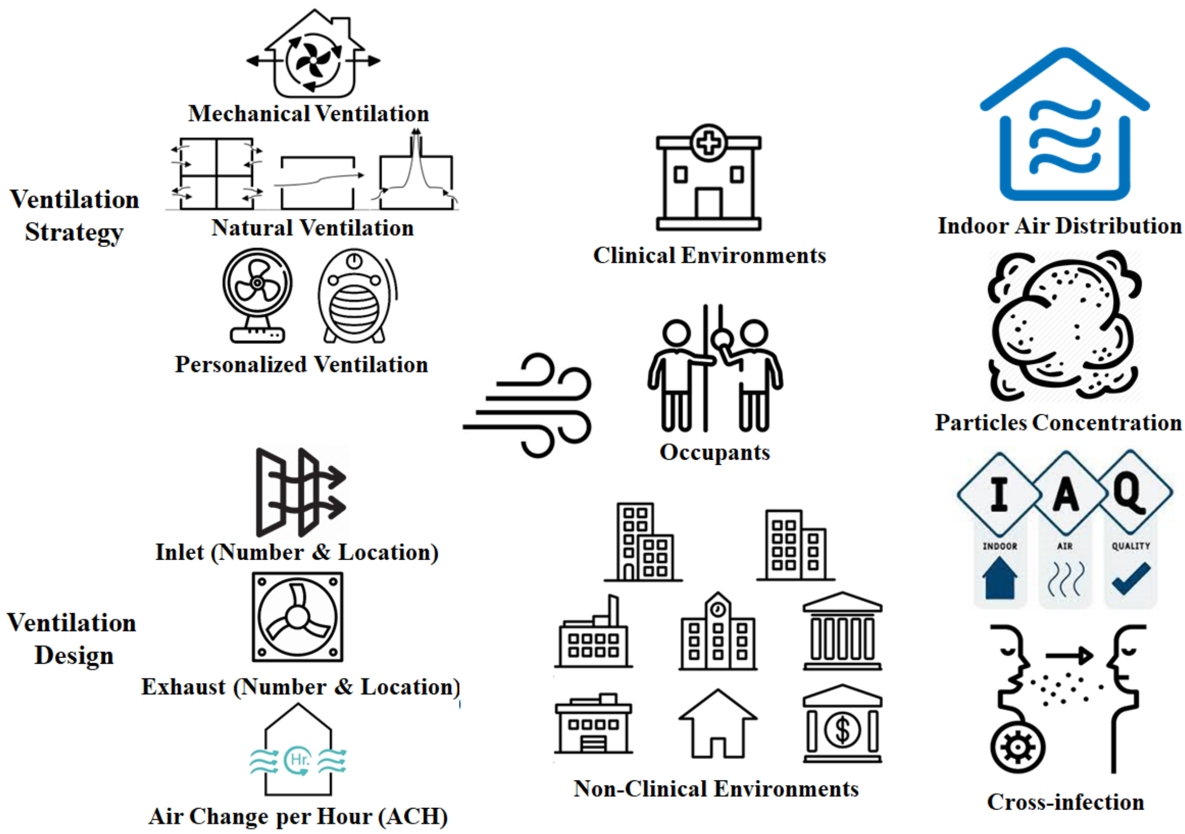

Figure 3. Conceptual Diagram of the review study

3. Ventilation Strategies Impacts

In the literature, ventilation strategies are mainly divided into three categories: Mechanical Ventilation (MV), Natural Ventilation (NV), and Mixed-Mode Ventilation (MMV) [39-43]. Personalized Ventilation (PV) has also been introduced more recently as a new development in the Heating, Ventilation, and Air Conditioning (HVAC) field [44], which can significantly improve inhaled air quality. Figure 4 shows the proportion of shortlisted articles that addressed each ventilation strategy (top) and the annual number of published articles on each type (bottom).

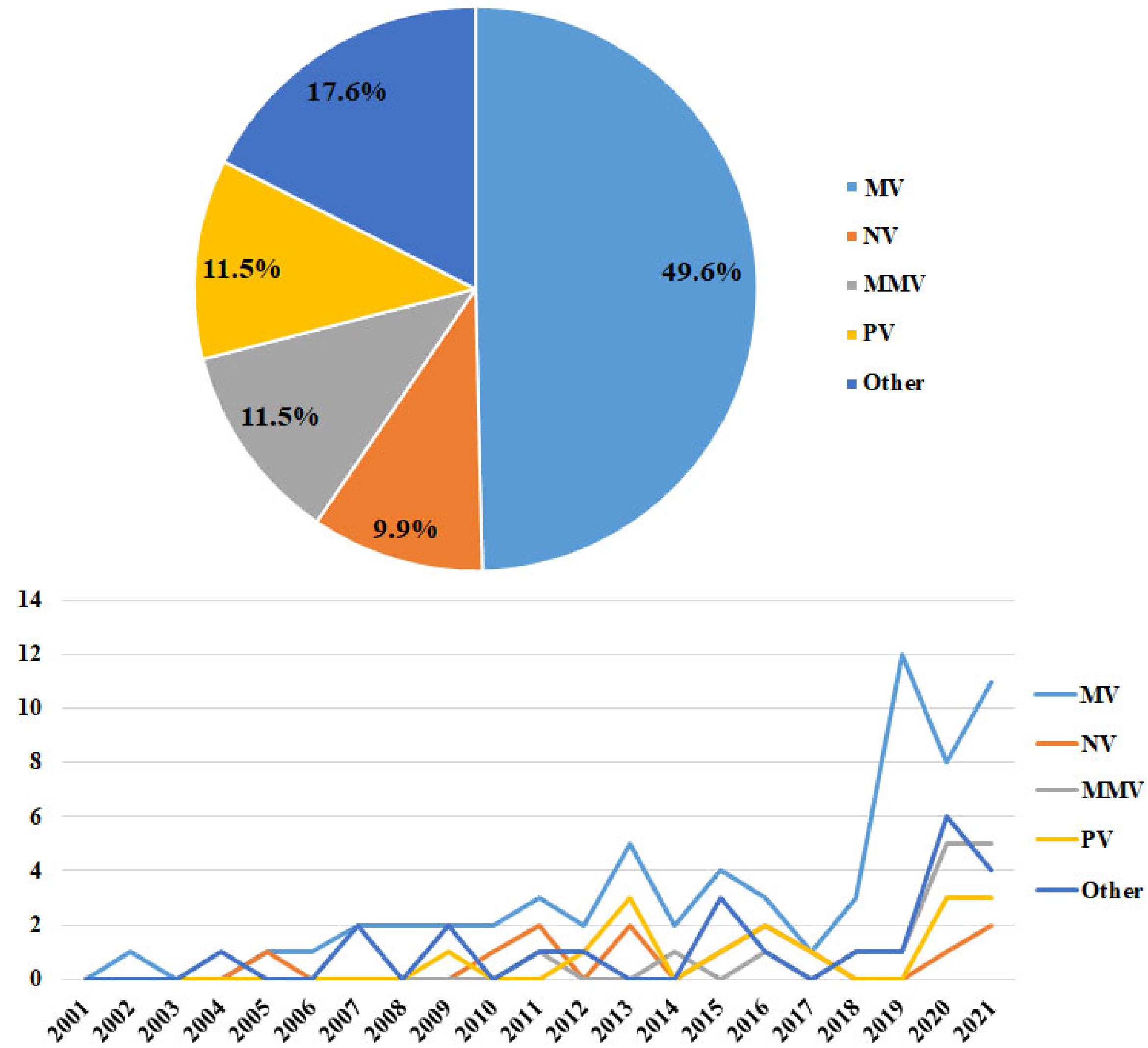

Figure 4. The proportion of studies focused on ventilation types (top) and the annual number of published articles on each strategy (bottom)

Figure 4 (top) indicates that around half of the shortlisted documents before December 31st 2021, focused on the impacts of MV on airborne transmission. Figure 44 (bottom) reveals around 17.5% of the articles examined airborne transmission without mentioning the ventilation type (NA), or they used a Miscellaneous (Misc.) strategy named "Other", which addressed the air distribution induced by a ventilation system.

The following sections (3.1 to 3.3) will address the principal ventilation strategies of MV, NV and MMV (or hybrid ventilation), and PV discussed in the literature. Section 3.4 will also examine the articles that focus on ventilation impacts on airborne transmission. Since most published documents focus on clinical environments like hospitals to investigate the effects of ventilation systems, this review article divides each section into clinical and non-clinical areas.

3.1 Mechanical Ventilation (MV)

Figure 4 and Table 1 display that around half of the existing literature investigated MV systems' impacts on airborne transmission. Among these studies, 50.7% of documents focused on clinical areas and 49.3% addressed non-clinical environments, mainly public buildings. This literature shows that published papers on MV impacts have primarily been developed to address two critical points. First, these studies investigated the practical strategies (i.e., different ventilation types) to remove contamination and reduce infection threats using MV systems. Second, these articles characterized MV design parameters, such as the size and location of inlet and outlet, to increase ventilation performance in reducing airborne infections. Hence, the following sections first examine ventilation strategies that impact airborne transmission, and then, ventilation system design features' influences are reviewed.

3.1.1 Clinical Environment

The literature shows that innovative, high-efficient, and well-designed MV approaches in clinical environments can reduce contamination in clinical indoor spaces. Lin et al. [45] experimentally evaluated the impacts of using ceiling returns and skirts on preventing surgical contamination recirculation in a hospital's Operating Room (OR) using Particle Image Velocimetry (PIV) & Smoke flow visualization. This study improved a conventional ventilation design for an OR and revealed that ceiling returns control contamination distribution to the non-sterile zone. Findings disclosed that using a long skirt is a useful way to avoid shortcutting the supply air into the ceiling return. Berlanga et al. [46] experimentally investigated the implications of the Displacement Ventilation (DV) strategy, as a practical strategy for clinical environments [47, 48], for airborne infection control in a test chamber representing a standard hospital isolation room. This article has tested DV performance in removing contamination in three different Air Change per Hour (ACH). For this, Contaminant Removal Effectiveness (CRE) and two ventilation performance indices: air change efficiency and local air change [49], were compared under three different ACH. The results proposed DV as a feasible strategy to remove contaminants and suggested higher ACH does not guarantee improving performance and CRE indices. DV systems' effects on reducing infections were also highlighted by Yin et al. [50]. This study conducted a full-scale experiment in a test chamber representing a hospital OR and compared DV and mixing ventilation performance in improving IAQ. The results highlighted DV might be a better strategy if the exhaust location was selected with regard to the restroom.

A recently developed ventilation concept, named Protected Occupied Zone Ventilation (POV) [51, 52], has been addressed by researchers as an effective system to reduce pathogen transmission in clinical environments. POV is a strategy that divides an indoor area into different sub-zones using plane jets to decrease infection risks [53]. Aganovic et al. [54] numerically and experimentally examined indoor air distribution and occupant draught sensation in a hospital ward under POV. The results emphasized internal barriers (i.e., walls), supplied-air velocity, and patients' location in relation to air supply in POV systems can affect air distribution and contamination spread in clinical environments. These findings were supported by Wang et al. [55]. This study suggested air curtains to reduce aerosol transmission in a hospital ward. This article investigated air curtains' performance on exhaled air quality using a full-scale experiment in a field chamber representing a hospital OR. This study also conducted 3D steady-state and transient CFD simulations of air velocity and N_2O concentration around occupants using. It highlighted that a closer distance between the source of contamination and the air curtain, in addition to higher jet velocity, could significantly reduce pathogen concentration. This paper has not investigated dynamic situations when clinical staff have to frequently move from one area to another and make a break in the air curtain, which could be examined in future studies.

Hospitals frequently use insolation rooms that are under negative pressure to control infections. The literature shows that creating negative pressure is an intelligent strategy to prevent spreading pathogens from the airway [56]. For example, Offermann et al. [57] modified the ventilation system to create negative pressure, named surge control strategy, to decrease the contamination travel to the hallway. This study measured particle concentration in the baseline and modified ventilation strategy through a full-scale experiment in a test chamber representing a patient room. This research illustrated a significant decrease in particle number, per cm^2, through openings, which caused negative pressure. This technical note recommended considering an anteroom between the patient and public hallway and/or closing the door to patient rooms to reduce bioaerosol distribution and the number of infections. The results indicated that hallway protection efficiency was greater than 98% due to the negative pressure of the hospital ward.

Emmerich et al. [58] reviewed the literature regarding best practices and strategies to decrease pathogen spread in hospitals and other healthcare spaces. This article provided an overview of current control strategies, hospital design practices, and tools and approaches to answer two questions: (1) what are the practical strategies to minimize airborne transmission under MV; and (2) When should decontamination methods be applied, and where are the best locations for installing these tools? The results underlined decontamination methods, such as Ultraviolet Germicidal Irradiation (UVGI) and filtration, are practical approaches to reducing infection. This article also displayed that producing variable air flowrate based on building leakage (non-organized NV) by an MV system can lead to better pressure control and contaminations removal in an indoor environment.

Many studies characterized MV's design parameters to increase efficiency in removing contaminants and reducing infection threats [59]. One of the critical MV design parameters in refreshing indoor air and removing pathogens is ACH [60-62]. Despite previous findings in the literature that suggested a higher ACH guarantees pathogen concentration reduction [63-65], Wang et al. [66] showed the higher ventilation rate might not lead to higher IAQ without considering airflow patterns in designing MV systems. This article compared bacteria carrying particle concentration (colony-forming units) in four different ACH and three different ventilation strategies: a recently developed ventilation strategy, named Temperature-controlled Airflow (TAF), common turbulent mixing ventilation, and Laminar Air Flow (LAF) using Lagrangian Discrete Phase Model (DPM) in a hospital's OR. The outcomes suggested TAF can remove aerosol better than LAF if associated with a proper ACH. This conclusion is supported by other literature [67]. These results also reinforced the findings of an experimental study by Pantelic et al. [68] in a test chamber representing a healthcare room. This study emphasized that ACH should not be regarded as the sole indicator of the MV system's effects on airborne distribution because other factors are also influential. This study underlined local airflow pattern as a critical parameter that significantly affects infection risks. It also revealed that airflow magnitude, direction, and the location of supply and returns grills, may significantly impacts exposure threat in a hospital environment. These results are aligned with findings of an article by Anghel et al. [69] that indicated increasing ACH and using High-Efficiency Particulate Air (HEPA) can remove contaminants in clinical areas under Variable Air Volume (VAV) HVAC.

Ventilation systems refresh indoor air by introducing outdoor air through an inlet(s) and removing "old" or "stale" air through exhaust(s). The number and location of inlets and outlets can significantly affect MV performance in eliminating contaminants. Several studies have addressed these critical design features of MV systems. Ren et al. [70] and Sahu et al. [71] showed that MV's exhaust location is crucial for removing contamination in clinical environments, supported by the literature [72]. Ren et al. [70] used 3D steady-state and transient CFD simulations and compared contaminants dispersion using an Eulerian-Lagrangian model under three different ventilation designs (three inlet and outlet locations with an identical ACH). This study compared particles' fate based on their size in a prefabricated COVID-19 inpatient ward. It displayed that standard MV systems are more successful in removing small particles like viruses (< 20 μm) than larger elements (D > 40 μm) due to depositing larger matters on the surfaces. This article suggested cleaning targeted areas and removing large particles by installing exhaust(s) close to polluted sources in hospital wards. This conclusion is supported by other literature [71, 73]. These studies suggested that a higher location of the opening, as well as an exhaust location close to patient beds, can limit pathogen spread in clinical indoor spaces. Villafruela et al. [74] also underlined inlet and outlet locations as the critical design parameters that play a vital role in particle removal. This study numerically evaluated the effects of MV design based on three indices: air renewal (minimum to actual replacement time), contamination removal (contaminant concentration average in the exhaust air to room), and infection risks (number of infections to susceptible infection) in the entire isolation room of a hospital and specific regions in this room. This article also highlighted air diffuser types as a crucial factor significantly affecting indoor airflow patterns and contamination removal.

Supplied air velocity has always been a key MV feature that considerably affects airborne transmission in indoor areas. Romano et al. [75] numerically and experimentally investigated the impacts of different air velocities produced by a unidirectional MV system on particle concentration (PPM/m^3) at various measuring points in an Operating Theatre (OT) with a standard layout, DIN 1946-4 [76]. The results suggested MV system with variance air flow diffusion can maintain a protection grade against particle loads. The outcomes supported the findings of [35, 77, 78] and demonstrated that retrofit options and using obstacles could effectively affect airflow distribution and particle concentration. The literature also recommended that adjusting air velocities in relation to exhaust location can improve the MV performance in removing aerosols. For example, Thatiparti et al. [79] modelled aerosol depression, which started from a patient's cough, in an Airborne Infection Isolation Room (AIIR) using 3D steady-state and transient CFD. This study revealed that the contamination route from patient to exhaust is vital in controlling infection risk. The simulation showed aerosols were quickly removed in the zones with high exhaust velocity close to the outlet grilles. The results also indicated that a common MV system could remove one part of the distributed cough aerosols in less than one second; however, in two seconds, the remaining aerosols infected the health worker in an AIIR. The research concluded that typical MV systems could not remove around 40% of aerosols, highlighting the need for a better design by optimizing exhaust location concerning the supplied air velocity. This article has also not suggested a specific ventilation system for these carefully designed rooms, probably because of difficulties associated with conducting measurement and research (i.e., cost).

Some studies characterized ventilation system design features and compared them based on their impacts on airborne transmission. Memarzadeh and Weiran [60] numerically compared the effects of ventilation design features (ACH and the distance and path between the contaminant sources and exhaust) on contamination concentration (ppm) over 1000 seconds in a hospital's isolation room. The results visualized the transmission path and revealed that an indoor distribution pattern is more critical for controlling particle concentration than the supplied airflow velocity. This transient Computational Fluid Dynamic (CFD) simulation showed that keeping possible distance between health workers and patients effectively reduces infection risks, particularly in higher flow rates. Li et al. [80] also numerically compared bioaerosol spread in a hospital ward and an insolation room in Hong Kong during the SARS outbreak using Eulerian-Lagrangian CFD simulations. This modelling highlighted DV as an effective strategy to remove smaller particles like viruses while larger particles remained on the surfaces. This study highlighted a need to improve the MV system by balancing flow rate in supply diffusers and exhaust grills to reduce particle concentration and cross-infection risk in an isolation room.

3.1.2 Non-Clinical Environment

Although MV's impacts on airborne transmission in clinical environments seem critical due to higher infection risks, the contagion hazard is serious in non-clinical public spaces [81]. Some studies investigated public areas with specific functions, such as public transport and office areas [82-85] and other indoor spaces, such as test chambers, without specifying their functionalities [86, 87]. Similar to the clinical section, this section will review articles in two categories: (1) MV strategies performance and (2) effects of design features on MV performance in removing aerosols in indoor environments.

In 2019, before the COVID-19 outbreak, a group of world-renowned researchers reviewed the literature on typical ventilation modes and advanced air distribution techniques and investigated their theories, limitations, and solutions [8]. This article categorized ventilation strategies based on airflow characteristics into two main groups: thoroughly mixed and non-uniform (e.g., stratified, piston, and task zone). Ventilation strategy performances and appropriate ventilation approaches for heating were also addressed, resulting in a comprehensive framework regarding air distribution under various ventilation strategies. Mixed and non-uniform strategies were widely addressed to investigate their impacts on infection risks. Ai et al. [88, 89] experimentally examined the effects of different MV strategies (i.e., stratum, mixing, and DV) and air distribution on cross-infection. This study compared exposure time in different scenarios (i.e., ACH, diffuser type, location of infected and exposed, temperature, and physical distance) over a full-scale experiment in a test chamber representing a general room. These articles illustrated a large discrepancy between aerosol spread and time-averaged exposure under horizontal air distribution (stratum) and two other applied strategies: mixing and DV in different physical distances. The experiments revealed that infection risk might not be reduced by a longer distance between infected and exposed in a short period event because of the extremely dynamic spread of exhaled air, supported by other literature [90]. Decreasing the interaction between supplied air and exhaled flow intensifies the risk of infection between close occupants. Xiaoping et al. [91] simulated an office building when two human manikins (infected and exposed) seated in front of each other to investigate the impacts of mixed, DV, and Under Floor Air Distribution (UFAD) on airflow patterns and droplet concentration, inhaled fraction, and CO_2 concentration. This study showed the inhaled dose of smaller droplets is the lowest under DV, while the least inhalation of larger droplets was recorded under UFAD. Akbari & Salmanzadeh [92] also emphasized providing clean air and using air cleaners to improve IAQ in an office area. This study numerically investigated pollution removal from an office building using the tracer gas method. Mean age of air, clean air delivery rate, and airflow pattern were examined through different ventilation strategies: UFAD, mixing, and wall-mounted air vents with and without air cleaners. This study suggested locating air cleaners in high concentration contaminants zone in indoor spaces, particularly under UFAD.

The literature contains new ideas in terms of developing occupant-based ventilation strategies. Melikov et al. [93] suggested controlling the airborne source to reduce airborne transmission. This short communication illustrated how a break in a classroom (i.e., where all occupants leave the classroom for a period of time) could reduce airborne transmission and infection risk. The outcomes indicated shorter occupation time and a longer breakout can significantly reduce the particle load within the classroom. The results highlighted that an intermittent occupancy strategy could be applied as a strategy to decrease exposure risks. Other literature has also reached the same conclusion [94]. Olmedo et al. [87] experimentally examined the downward vertical MV influences on infection probability in a field chamber, representing a general room, when two breathing manikins stood face to face. The distance between these manikins was also changed under different ventilation strategies (DV, mixing ventilation) and downward and upward flow to observe the effects on indoor climate specifications (temperature and air velocities), exhalation profile [73], and particles concentrations. This study showed that the micro-environment between manikins was not affected by the downward MV, as the ventilation airflow could not penetrate this environment. The measurement also indicated occupants' contamination exposure risks increased under downward MV when the distance between manikins had been reduced. The results of this study can be used to inform COVID-19 response to physical distance.

The literature shows that using physical barriers and partitions as a strategy in indoor public spaces can effectively control airborne transmission [95]. Ren et al. [96] numerically and experimentally investigated the impacts of using barriers with different heights on airborne transmission as a low-cost infection risk mitigation strategy in an open office area. This study used the recently developed infection model [97] to investigate the individual risk of infection in an office environment. The results revealed that the height and location of barriers in relation to the air outlet are the most influential parameters for controlling the airborne spread. This outcome was also supported by the literature that showed equipped a classroom with seat partitions for individuals and evaluated their implications for indoor airborne transmission with regards to supplied air velocity [98]. This article also revealed that upsurging the supply air rate increases the velocity of droplets moving in the airflow direction and decreases droplets' trapping time between the partitions; therefore, solid barriers should be selected concerning MV design features such as air velocity.

Using filters for MV systems has recently attracted researchers' attention as an effective strategy to reduce the airborne spread in public environments [99-102]. Azimi and Stephens [103] empirically estimated HVAC filtration influences on indoor contaminant distribution using the modified Wells-Riley equation [104], broadly applied in the literature to predict airborne transmission [105-107]. This study modelled influenza spread in a hypothetical office area to evaluate the required operational cost of applying filters and anticipate their impacts on reducing infection risk. Different Filters with diverse Minimum Efficiency Reporting Values (MERV) ratings (e.g. low (MERV 1 to 6), medium (MERV 7 to 11) and high-efficiency filters (MERV 13 to 16)) in an HVAC, suggested in the literature [108], were compared over infection risk and cost. The results revealed that high-efficient filtration might be a cost-effective strategy for reducing infection probability compared to similar outdoor air ventilation, while the finer air filters typically increase energy usage due to the need for a stronger fan. This finding is supported by [102], which emphasizes that increasing the ventilation rate is not an energy-efficient strategy without appropriate filtration. This study underlined high-efficiency MERV filters as the best option to decrease contamination spread at a reasonable price. New guidelines like a technical guideline by the Victorian Government in Australia [109] have recently been developed that suggest appropriate filters (MERV rate) for HVAC systems based on indoor space functions (i.e., hospitals) to reduce the spread of viruses such as COVID-19.

As mentioned earlier, the second part of this section reviews articles investigating the influences of MV design parameters, such as ACH and ventilation rate, on airborne transmission in non-clinical spaces. Blocken et al. [16] measured aerosol and CO_2 concentration, as well as indoor specifications (temperature and humidity) through a full-scale experiment in a gym to reveal human activities and air purification impacts on particle concentration. The measurements compared aerosols concentration (µg/m3) in a gym without air purifiers and ventilation with three main situations: using ventilation alone, applying air cleaners without ventilation, and using both ventilation and air purifiers. The results revealed that an ACH 4.5 times higher than the required ACH in Dutch building regulation was not enough to prevent particle concentration growth in a half an hour period in ventilation only scenarios. The outcomes highlighted air cleaning is more practical than ventilation in reducing particle concentration. This study underlined using air cleaning and ventilation system as the most efficient strategy that removed aerosol concentration by 90%, depending on the size of particles. An empirical investigation of ACH impacts on particle concentration by Faulkner et al. [110] revealed that the effects of ACH should be investigated with regard to existing particle size. This study showed that escalating ACH leads to a lower concentration of small particles while having minor effects on larger particles due to surface depositions. This finding is supported by the literature that indicates ACH impacts on particle concentration directly depend on virus-laden droplet size [111]. The outcomes showed increasing the ventilation rate reduced the concentration of small particles; however, this escalation of the ventilation rate did not decrease the concentration of larger particles. Shao et al. [112] experimentally investigated particle dispersion through different ventilation rates and Fan Filter Units (FFU) in a test chamber representing a cleanroom. Although more clean air reduces Volatile Organic Compounds (VOCs) and CO_2, the aerosols and O_3 levels increased in the indoor space. This study also emphasized the critical impacts of supplied air volume, size and location of inlet and outlet, and location of contamination source on particle distribution.

3.1.3 Concluding Remarks

The following remarks can be concluded from the reviewed literature regarding the impacts of different MV strategies on airborne transmission:

- MV strategies, including UFAD, DV and POV, should be associated with a proper design of parameters (i.e., supplied-air velocity and location of inlet and exhaust) to control virus-laden respiratory particles transmission and minimize infection risks [54].
- The literature recommended physical distancing and shorter occupation time as a strategy to

reduce infection risks, especially in non-clinical public areas [93].

- Employing barriers like partitions [96, 98], a buffer zone between spaces with higher and lower infection risk and spaces under negative pressure [57], and engineering controls like filtration [69, 100] are suggested as practical strategies to remove contaminations.
- Future studies on the practical strategies, such as intermittent occupancy, physical distancing, and wearing masks in educational areas, with regard to their effects and disadvantages are recommended.

Regarding MV design parameters, the following can be concluded:

- Although ACH is a critical parameter that provides clean air and dilutes contaminated air, it is not the only influential parameter. Indeed, MV systems should be designed considering ventilation rate, airflow pattern, and inlet and exhaust number and position to control airborne transmission [63, 68, 75, 113].
- The number and location of inlets and exhausts and the balance and distance between airflow rate, as well as the exhaust distance to the contamination source, can play a significant role in removing airborne contaminants from indoor areas [37, 50, 60, 69-71, 79, 89, 110, 113-117].
- MV performance in removing particles is affected by contaminations' size [110], so the literature suggests considering the expected type, size, and level of potential contaminants based on the function of indoor spaces to design MV systems.
- A higher flow rate MV system associated with filtration is suggested in clinical areas since higher ACH can remove small particles [110], and filtration can remove remaining contaminants.
- There is the fact that HEPA filters contribute to a pressure drop in the ventilation system and hence higher energy use for fanning, so future studies on the impact of HEPA filters with regards to energy efficiency may lead to solutions for improving ventilation systems considering energy usage and airborne transmission.
- Future studies are recommended to evaluate the ventilation design based on the number of patients and exhausts distance to each patient bed to control pathogen spread.

3.2 Natural Ventilation (NV) & Mixed-Mode Ventilation (MMV)

Kopec [118] introduced NV as a ventilation strategy that refreshes indoor air without mechanical systems and energy usage by using natural forces (wind and buoyancy), which results from pressure and density differences [119, 120]. NV is a standard green alternative to MV systems that contributes to energy saving [121-123] and effectively prevents airborne transmission in indoor areas [124-129]. NV is categorized into two main types: organized and non-organized (infiltration-exfiltration because of the non-steady nature [130]). Organized NV is classified into four strategies: cross, single-sided, stack, and mixed NV [121]. The WHO strongly recommended NV to reduce infection risks after an overview of studies about the influences of NV on reducing infections in indoor spaces [40]. However, although NV has been recognized as a valuable ventilation strategy to remove aerosols [40, 131], it is not commonly applied in clinical and commercial environments, probably because of some disadvantages: inconsistent airflow, concentrations of particles, unstable ventilation rate, and less thermal comfort, particularly in severe climates [71, 132-136]. NV is also not adequate for high occupancy intensity [137]. MMV or a hybrid approach of natural and mechanical ventilation devices can be considered a more reliable strategy to provide stable airflow, dilute contamination, refresh indoor air, and provide thermal comfort, particularly when associated with a control strategy [138, 139]. This section reviews published studies regarding different NV and MMV strategies and design influence on refreshing indoor areas, removing particles, and controlling indoor airborne transmission in clinical and non-clinical environments.

3.2.1 Clinical Environment

Researchers have compared the presence and absence of NV with other ventilation strategies (i.e., MV) to indicate its effectiveness in removing virus-laden respiratory particles in clinical environments. Zia et al. [140] emphasized NV and MMV might not be enough to meet health standards for infection control compared with MV and suggested applying air cleaning technologies associated with NV and MV as a solution to meet IAQ standards for clinical environments, supported by the literature [134, 141, 142]. Wang et al. [143] conducted a 3D Steady-state CFD simulation and compared air distribution patterns, removing respiratory particles, and inhaled pollutions in three different ventilation types: MV (impinging jet) and two MMV: ceiling and side air ventilation in an ICU environment. Numerical simulation results showed that the impinging jet removed more virus-laden respiratory particles and reduced inhaled pollution than the MMV method; hence, it was suggested to be applied in ICU spaces. Somsen et al. [12] analyzed droplet spread from coughs and speech (different sizes and numbers) and travel distance based on ventilation strategies using the Laser Diffraction or Spectroscopy method. This study compared two scenarios in the presence of ventilation (MMV and MV) and one without ventilation, based on the time required to remove small and large droplets. The results showed that droplets number reached zero in the best ventilation strategy, while this period was ten times more in no ventilation. Indeed, the outcomes of this comment article emphasized that populated indoor areas with poor ventilation could quickly spread viruses, supported by [137]. The article recommends healthcare authorities consider ventilation a significant parameter affecting indoor infection risks. Stockwell et al. [134] systematically reviewed studies focused on ventilation impacts on aerosol concentration in clinical environments between 2000 and 2017. This review revealed that the highest bioaerosol concentration was found in the naturally ventilated hospital areas, around ten times more than the highest concentration in mechanically ventilated spaces.

Researchers have recently investigated possible solutions and strategies, including architectural and engineering modifications in clinical environments, to improve NV performance in reducing aerosol spread [140, 144-147]. Escombe et al. [145] conducted a full-scale in-situ experiment and examined the implications of simple modifications like opening and closing windows and doors and creating and opening skylights for Tuberculosis (TB) infection risk using the tracer gas method in waiting and consulting rooms. This study highlighted low-cost and straightforward architectural modifications, such as extra windows to provide cross NV and an open skylight in clinical areas, can improve ACH and noticeably improve NV performance and significantly decrease aerosol transmission risk. A novel strategy named Natural Personalized Ventilation (NPV) has also been presented as an architectural modification to provide clean air for patients in hospital wards [148, 149]. NPV is a buoyancy-driven NV that delivers new outdoor air directly over a patient bed using an elevated duct. Adamu et al. [148] conducted 3D steady-state CFD and dynamic thermal simulation to evaluate the feasibility of using NPV, instead of windows, in a one-bed hospital ward. Simulation results showed that designing ducts, according to Chartered Institution of Building Services Engineers (CIBSE) guides [150], is a potential architectural solution that improves a patient's local breathing zone air quality and removes more aerosol with lower energy usage. This article calculated CRE, Local Air Change Index (LACI) [151], and mean air exchange efficiency indices in case studies with different duct sizes and shapes using CFD simulation. The results revealed that the scenario with larger ducts and direct air delivery to patients had better performance in removing contaminations. Researchers have also considered other architectural ideas; for example, Zhou et al. [152] recommended designing a central corridor for a naturally ventilated hospital ward due to the high aerosol spread from patient rooms. This study suggested using cubicle doors to prevent airborne transmission by cutting off the path. There are also more complex architectural ideas in the literature, such as a semi-enclosed hospital street, to improve NV performance in reducing infection risks [146].

Studies in the literature have examined the impacts of organized NV types (i.e., cross NV) and design features on removing pathogens in indoor spaces [153]. The literature demonstrates that cross NV was frequently employed in the 20th century; for instance, after the influenza pandemic in 1918, large windows were operated in hospital spaces with high ceilings to dilute pathogens with clean air. After the SARS outbreak, researchers have paid more attention to cross NV as an approach to reduce aerosol distribution in clinical spaces [154-156]. Gilkeson et al. [34] compared aerosols movement and infection risks over a full-scale in-situ experiment in a hospital ward (with and without partitions) under cross NV, MV, and without ventilation scenarios using a tracer gas method. Ventilation rates (ACH) and indoor velocity profiles under different ventilation and their impacts on infection risks, Relative Exposure Index (REI) and normalized peak concentration were investigated in this article. This study indicated that NV in an open ward layout led to better dilution and reduction of pathogens. It also highlighted that partitions could reduce the infection risks for patients behind these obstacles, but this phenomenon led to higher contagion risks close to the infected occupant. This study underlined the impacts of NV since shutting the windows, expected in winter and summer and severe climates, led to a significant increase in aerosol concentration. Therefore, this research suggested applying MMV or hybrid ventilation by using fans mounted on windows to extract contamination. Qian et al. [157] supported these findings and revealed higher NV performance through larger openings associated with fans. This study conducted a full-scale in-situ experiment in an AIIR and recommended higher ACH to remove contaminants. It emphasized the possibility of converting the hospital ward to an AIIR if there is enough NV to remove pathogens.

3.2.2 Non-Clinical Environment

After the COVID-19 outbreak declaration, different approaches, such as physical distancing, wearing masks, and using NV, were suggested to reduce the infection risks in public indoors, while these strategies' impacts have not been investigated very well [158]. A commentary article by Morawska and Junji [159] emphasized the fact that physical distancing (e.g. 1.5 m), recommended by WHO [27], might not prevent infections because airflow can spread viruses by tens of meters [160-166]. Sun and Zhai [161] showed that 1.6 to 3m could be safe when considering large droplets, while tiny and nuclei droplets can spread even three times more. They emphasized higher physical distancing is a very effective strategy to reduce infection risks, which may happen by smaller droplets [167]. This study also indicated exposure time, ventilation type, and air distribution impact aerosol movement distances, supported by [162, 163, 168]. The results of a review article by Morawska et al. [20] underlined air distribution as a critical factor in spreading pollution, suggesting supplying clean air instead of recirculation. This article showed proper ventilation strategies and design are crucial to reducing indoor infections. Therefore, various NV and MMV strategies should be associated with an appropriate design to decrease indoor infection risks.

Some studies have compared different ventilation strategies NV, MV, and MMV, in terms of their impacts on IAQ. Irga and Torpy [169] evaluated the effects of different ventilation strategies on the concentration of contamination in several office spaces. This study monitored and compared contamination load and IAQ (i.e., Particulate Matter (PM) 2.5 and PM10, CO_2, and VOCs) in eleven buildings under NV, MV, and MMV in Sydney. This article highlighted a higher contamination concentration in naturally ventilated indoors than buildings under MV and MMV. Mu et al. [170, 171] have investigated the effects of two organized NV types: single-sided and cross on contamination distribution in residential indoors using a small scale experiment (wind tunnel) and a tracer gas method. This study compared gas concentration averages and showed that gaseous pollutants moved in horizontal and vertical directions due to different wind directions in both single-sided and cross NV.

The results indicated that NV performance in reducing contamination spread depends significantly on wind direction and the location of pollutants source. The findings highlighted cross NV has better performance than single-sided if the contamination source was aligned with vertical winds and located leeward or windward. In contrast, cross NV augmented horizontal spread for a sideward source compared to single-sided NV. The importance of wind direction in naturally ventilated indoors has also been emphasized by Li et al. [172]. This study suggested that designers consider indoor airflow patterns when applying wind-driven NV since it significantly affects NV performance in removing contamination. Researchers also emphasized other critical factors, such as occupants' location and seating position, exposure time, and wearing a mask, in addition to NV modes that could affect IAQ and infection probability in indoor areas [173, 174].

The literature points out the airborne transmission possibility between floors through windows and other kinds of openings [175], which is directly relevant to NV modes and particle size [176]. Zhou and Deng [177] numerically investigated the possibility of spreading particles between upper and lower floors under two organized NV, single-sided and cross ventilation. This study highlighted that buoyancy-driven or single-sided NV has critical impacts on vertical contamination spread inter floors, supported by [178]. It also showed that other factors, including window opening strategies and contamination amount, influence IAQ, supported by [179]. The literature indicates previous studies also highlighted single-sided NV and vertical spread of particles. Liu et al. [180] also examined cross-contamination between floors under an organized NV (single-sided) using steady-state and transient CFD simulations. Modellings illustrated a balance between pollutants concentration and mass fractions in upper and lower levels. As a solution to prevent vertical transmission of air pollutants, Wu and Niu [181] suggested using mechanical exhaust tools to remove contaminants and avoid transferring to the upper flat or non-organized NV. This study conducted 3D steady-state CFD simulations to investigate the influence of mechanical exhausts on internal and external flowrate and the indoor airflow pattern through different scenarios: individual and central mechanical exhaust with no mechanical exhaust. The tracer gas results revealed that vertical cross-infection risk between two rooms was reduced when two-way stream (inflow and outflow) airflow was converted to one-way (inflow) by increasing the exhaust rate. The study also indicated the pollutant transmission from the lower to the upper floor was reduced in lower ventilation rates with a mechanical exhaust in both unit floors. This article recommended that residents apply individual mechanical exhaust fans or a central one, which may be a solution for reducing infection risks in hotel quarantine facilities during epidemics.

Similar to clinical spaces, some studies have also investigated architectural modifications, including optimizing opening scales and location in NV and MMV strategies, which can consider changing the NV design to improve the performance in removing contaminants. Opening scale is always viewed as an essential NV design feature that affects both organized and non-organized NV in buildings [182] and other naturally ventilated spaces [183]. Abbas and Dino [184] have suggested refurbishing existing buildings to improve ventilation performance to eliminate contaminants. This study simulated an open office and compared different design scenarios (opening configurations and opening to wall ratio) with the baseline case. Results of 3D steady-state simulations highlighted that the larger scale openings, consequently higher opening to wall ratio, could considerably reduce the contamination concentration and infection risks over time due to better indoor air refreshing. The transient simulation outcomes also showed that increasing the opening to wall ratio could be a more effective strategy than changing the opening location (i.e., opposite to adjacent) in removing aerosols. Pacitto et al. [125] experimentally indicated that larger openings are not always a solution and may lead to more contaminants entering the space. This study compared the impacts of NV and manual airing, as two ventilation strategies, with air purifier influences on the concentration of pollutants in two gyms. The in-situ experiment revealed that although ACH could influence designing NV, using air purifiers, essentially portable filters, could be a game-changer and significantly improve IAQ. Stabile et al. [185] have also emphasized that ACH cannot be the sole indicator for NV design and underlined Event Reproduction Number (ERN) [186], representing the number of the expected infections from an infectious individual. This index may assist in designing ventilation concerning airborne spread, in addition to other critical features such as ACH and IAQ elements [187], which were widely used, particularly since the COVID-19 outbreak [188].

3.2.3 Concluding Remarks

The following points can be concluded from the reviewed literature regarding NV and MMV strategies and design impacts on airborne transmission:

- NV and MMV might not be adequate strategies to meet clinical environment standards for ventilation [12, 140, 143]; thus, some studies strongly recommended applying air purifiers in naturally ventilated clinical spaces [134, 141, 142].
- Low-cost architectural retrofits (i.e., optimizing the number, size, and location of openings) might significantly improve NV performance in removing indoor contaminations [125, 145, 184]. These artificial retrofits may bring outdoor contaminants due to non-organized NV, so these retrofits should be designed based on this constraint.
- Researchers suggested a new NV and MMV by providing individual and central mechanical exhaust fans in medium and high rise buildings to reduce inter-flats airborne transmission [181].
- The literature suggested designing features based on the function of buildings.
- There is a need to legislate new regulations for ventilation concerning airborne spared [159].
- The review highlighted indices, like ERN [186], that could help shift the ventilation paradigm and reduce infection risk by considering ventilation impacts on airborne distribution.
- Although evidence shows that the application of fans affects IAQ by mixing fresh and contaminated indoor air, as well as creating negative pressure and removing contaminants [57, 157], few studies addressed the impact of fans and fanning on indoor airflow patterns and airborne transmission.

3.3 Personalized Ventilation (PV)

PV is a ventilation strategy controlled by an individual to supply clean air directly to breathing zones [189, 190]. PV has been introduced as an effective strategy for reducing airborne transmission, preventing cross-contamination [191-194] and helping to meet thermal comfort by using less energy by reducing clean air demand [195, 196]. PV systems are typically classified in three categories: chair-mounted [197, 198], desk-mounted [199, 200], and partition-based PV [198, 201]. PV can produce vertical airflow with high speed and less turbulence, removing occupants' plumes and easily integrating with existing ventilation without any space-related matters [189]. The literature shows PV performance is comparable to and even better than other typical ventilation strategies [202, 203] if associated with an appropriate design. Melikov [44] listed recommendations to improve PV design; for example, applying personalized airflow with low turbulency and uniform velocity profile, as well as designing PV systems with large air terminal devices in front of occupants are suggested in this article. It is also recommended to create air terminals capable of variating rate and direction while using airflow rate against occupants' faces is highlighted as a preference.

In December 2020, one year after declaring the COVID-19 pandemic, Melikov suggested shifting the ventilation paradigm [29]. He extended his previous recommendation for a ventilation paradigm shift [204] and emphasized bioaerosol spread as a critical hazard after three large-scale epidemics: SARS, MERS, and COVID-19 during the 21st century. This commentary article [29] suggested that ventilation should focus on occupants instead of space, which means providing advanced air distribution using controllable ventilation strategies by occupants could be a solution. PV is one of the best approaches to achieving these objectives.

This section reviews the literature regarding the impacts of different PV strategies on reducing cross-infections and critical design features affecting bioaerosol and contamination spread in clinical and non-clinical environments.

3.3.1 Clinical Environment

PV is introduced as a promising effective ventilation strategy to reduce cross-infection risks [205], associated with existing ventilation strategies in indoor spaces [44, 201, 206]. Despite the fact that PV could be an appropriate ventilation system in a clinical environment, few studies have investigated PV implications for clinical areas. Some studies underlined PV as an excellent strategy compared with other standard ventilation systems, such as sole mixing ventilation, UFAD, and DV [44, 194, 202]. The literature shows while some ventilation strategies, such as DV, might not be the best method for refreshing clinical environments due to pathogen transmission, PV could be a perfect strategy for these spaces [207]. The literature also suggested a need to investigate PV strategies and design not only as a sole system but as an association with other ventilation systems [189]. Melikov et al. [208] developed an advanced PV system, integrated into both sides of patient hospital beds and experimentally compared the application of PV and mixing ventilation with only mixing ventilation in a test chamber, representing a hospital isolation room. The concentration of contaminations and evacuation efficiency in three different points of this chamber (health worker breathing zone, middle of the room, and occupied area) were measured under an identical ACH ($3h^{-1}$) using the tracer gas method. The results approved the effectiveness of this system and highlighted the impacts of applying PV and mixing ventilation in reducing exposure risk, which is also suggested in the literature [44].

Some well-designed PV systems provide an excellent approach to controlling infection risks in clinical environments [202, 209]. Yang et al. [209] suggested using a Personalized Exhaust (PE) or PV-PE system above the occupant's shoulder as a novel method to reduce the aerosol spread to the breathing zone. This study conducted a full-scale experiment in a test chamber representing a health consultation room and compared exposure reduction for infected and healthy occupants in a PV-PE system with other PV designs under two ventilation strategies: mixing ventilation and DV based on infection probability using tracer gas methods. The results emphasized that the introduced PV-PE system has the highest performance when located above the infected occupant's shoulder. A PE above the healthy occupant's shoulder led to the lowest intake fraction. Tham and Pantelic [194, 202] investigated PV performance in reducing the infection risks when associated with three ventilation types: mixing, DV, UFAD, with various ACH rates. The results showed that increasing ACH is not always a good approach, depending on ventilation. Higher ACH led to more infection probability based on the experimental outcomes while increasing ACH under mixing ventilation reached the best results.

3.3.2 Non-Clinical Environment

Most of the articles that addressed PV investigated using PV in non-clinical environments and mainly investigated the PV design features, and few articles examined PV strategies. Different Chair and desk mounted PV strategies have also been presented to control infection risks. Li et al. [201] numerically investigated the performance of two upward chair and desk mounted PV systems with varying ventilation rates in conjunction with mixing ventilation and DV in an office environment. This study compared Intake Faction (IF) index [210], inhaled by an exposed occupant, in different scenarios and revealed almost identical implications of a chair and desk-based PV systems for the indoor environment. It showed PV could primarily deliver higher quality inhaled air when its direction is the same as produced airflow patterns by a DV system. This study suggested a PV associated with DV as an effective strategy for air purification, also recommended in the literature [44, 211]. Performance of a practical PV strategy, a small desk fan associated with a ceiling-mounted PV nozzle (single and co-axial jet PV), in improving IAQ in breathing zone and comfort was numerically and experimentally investigated by Makhoul et al. [212]. This study indicated that a small fan could reduce thermal plum around the occupant, improve the efficiency of a single jet PV nozzle and save energy compared with a co-axial jet, and deliver clean air to the occupant's breathing zone. Habchi et al. [206] also studied the impacts of ceiling plus desk fan when associated with DV and mixing ventilation on cross-infection in an office area. This study used CFD simulation and compared cross-infection, IF, and Deposited Fraction (DFr) [213] indices in different occupants' distance, particle sizes, and HVAC (DV and mixing ventilation) configurations. The simulation results showed that an optimized PV system design could even reduce the infection risk for high-density indoor environments where the distance between occupants is even closer than a fairly typical 2 m physical distance requirement. Mazej and Butala [214] have presented a novel desk-based PV with an air terminal device, including a movable slot diffuser plate. This study used transient CFD simulation and compared personal exposure effectiveness and re-inhaled exposure index [215] to reveal occupants' protection in different scenarios. This study underlined PV operating mode as a crucial parameter influencing inhalation and exhalation air quality in an office area.

PV design features' implications for non-clinical indoor environments were investigated in non-clinical spaces [44]. Wei et al. [216] conducted a full-scale experiment in a test chamber as a workplace and examined the impacts of a personalized air curtain on occupants' heads like a bicycle helmet on workplace infection probability. This study has characterized the design features of this helmet, including ventilation rate and direction, as a respiratory protection factor and underlined a personalized air curtain could be a practical approach to improving Protection Factor (PF): a ratio of particle concentration in the space to the breathing zone. This article offered to apply this helmet in industrial indoor environments with a high concentration of contaminations. Katramiz et al. [217] also inspected PV design effects on breathing air quality and cross-infection risks in an office environment. This study conducted a 3D transient CFD simulation to compare PV with several ventilation flow rates (Lit/Second) and two seating models: tandem (side by side) and face-to-face. This research suggested a low ventilation rate for the tandem and high flow rates for face-to-face seating to protect office mates against cross-contamination. The impacts of occupants' seating model and ventilation rate were also approved in other public environments, such as public transport [218]. Xu et al. [219] indicated efficient PV design could be a high-performance ventilation system. This article investigated the effects of different PV orientations, velocities, and distances to occupants on exposure reduction risk [209, 219] in a test chamber representing a general room. Increasing airflow to the maximum constant rate and shorter air terminal device distance to healthy occupants in all directions could protect them against exposure, also suggested by Melikov et al. [215].

Similar to other ventilation strategies, the location and specifications of the exhaust significantly impact PV performance. Xu et al. [191] have experimentally examined the virus-laden respiratory particles' transmission and infection probability [220] under a novel PV setup, locating nozzles in front of infected and exposed manikins' noses with different ventilation rates in a testing chamber, representing a general room. This study revealed that PV systems would reduce infection risk by efficiently refreshing and cleaning the inhalation zones if these systems were not designed appropriately. This study emphasized that a PV system should be designed based on the human microenvironment, such as inhalation and exhalation zones, to increase PV performance in pathogen transmission, as recommended by [197, 221]. Melikov and Dzhartov [222] also suggested a PV-PE system to reduce cross-infection risk in an aircraft cabin. This article conducted full-scale experiments in a test chamber representing an aircraft cabin and compared the relative concentration of pollutants in passenger exhalation in five scenarios based on turning PV on and off for exposed and healthy passengers in the presence and absence of local exhaust. The measurements showed turning PV on for both infected and exposed occupants with local exhaust significantly reduce exposure risk. This study also indicated the recommended PV-PE arrangement, two exhaust terminals at two sides of the manikins' head, decreased contamination load significantly and did not let polluted air mix and spread in the cabin since the supplied airflow jet pushed back the infected passenger's exhaled air.

3.3.3 Concluding Remarks

Concluding remarks for the reviewed literature are as below:

- PV application in clinical environments is suggested to reduce cross-infections.
- PV design features, such as size and direction of air terminal devices and initial airflow

turbulency and profile [44], location of PV systems and occupants' seating position [217], distance to occupants [191, 206, 219], and ventilation rate [217, 219], are highlighted as being more influential than PV types (i.e., desk, chair, and partition mounted) [201], on improving breathing zone air quality and preventing cross-infections.

- Local exhaust or PV-PE instead of a PV-only design might significantly enhance system efficiency in all environments, particularly when the personal exhaust is located close to the occupants [191, 209, 222].
- Providing clean air directly to the inhalation zone is suggested, so the angle and distance of PV to occupants, as well as airflow rate and direction, play an essential role [191, 216].
- The review recommended applying PV and mixing ventilation instead of mixing ventilation alone [44] and showed that designing PV with regards to existing ventilation strategies, such as DV, can improve whole system performance in removing contaminations [194, 202, 211] and make them suitable for high infection risk spaces, such as hospitals [207].
- PV can be used in high-density and crowded commercial and public areas where it is critical to respect physical distance [206].
- PV as an occupants-based ventilation system is suggested instead of current space-based ventilation to control airborne transmission and shift the ventilation paradigm to safer systems concerning indoor infection risks [29].

3.4 Miscellaneous (Misc.) ventilation types

As mentioned earlier, some articles have not focused on one specific ventilation strategy (i.e., MV, NV, MMV, and PV) and mainly address general ventilation, creating indoor airflow patterns, contamination distribution, and infection risks [223-225]. Indeed, the ventilation effect is the focus of these articles rather than ventilation system design. This part of the literature typically investigated air-conditioning influences on virus-laden respiratory particles transmission and contaminations dispersion in different environments and defined how to control airborne transmission [226-228]. This section examines miscellaneous ventilation impacts on airborne transmission and identifies practical procedures to reduce infection risks in both clinical and non-clinical environments.

3.4.1 Clinical Environment

Few studies investigated airflow impacts on airborne transmission without considering ventilation types. Noakes et al. [229] suggested a new approach to design ventilation in order to achieve a robust system against airborne transmission. The strategy calls for consideration of the whole hospital ward (multiple zones) instead of each room (the typical design approach in hospitals). This article investigated the impacts of ultraviolet devices, such as UVGI, on reducing contagion risks in interconnected spaces. The results revealed ultraviolet tools significantly reduced airborne transmission when these devices were located close to contamination sources in patient rooms rather than connections and corridors. Lim et al. [230] experimentally investigated the stack effect of ventilation on bioaerosol transmission in multi-storey hospitals, a critical issue due to the increasing number of high-rise hospitals. The stack effects on indoor airflow patterns and spreading contaminants from lower to upper floors were measured for different floors. The experiment reveals that there is a high potential of pathogen spread, so it needs to protect occupants against emitted bio-aerosol from patients on lower floors due to the increased chance of spreading contamination, supported by previously published simulation results [181, 231]. There is a need for future studies on mitigating this risk; for example, the idea is to accommodate the most infectious patients on the highest floors, of course with separate elevators, to reduce the infection probability because of the stack effects.

3.4.2 Non-Clinical Environment

The importance of refreshing air by ventilation systems was investigated in public spaces. Harrichandra et al. [225] suggested two strategies, increasing outdoor clean air and wearing masks, as the best strategies to reduce infection risks in nail salons. This study modelled infection probability using the Wells-Riley equation for steady-state conditions, the quanta concentration for non-steady circumstances, and the correlation coefficient for statistical analysis. The results showed infection control strategies, such as wearing masks, physical distancing, and providing more clean air by ventilation systems as approved solutions for opening up businesses. These strategies can be beneficial since it would not be easy to offer simple rules for predicting the necessary ventilation rates to control indoor infections [232]. Dai and Zhao [233] empirically examined the relation between ventilation rates and COVID-19 infection risks inside confined areas (i.e., buses and aircraft). This study investigated how wearing a mask impacts infection probability, widely investigated in the literature [234-236], and revealed that cleaner air and less exposure time significantly affect contagion probability. In addition to the provided clean air, airborne transmission routes have also been considered a critical factor. Gao et al. [237] employed a combination of the Susceptible Exposed Infectious Recovered (SEIR) epidemiological model [238] and the revised Wells–Riley equation to predict infection probability concerning airborne routes. This study underlined that indoor airflow distribution and clean air volume are vital parameters in controlling airborne transmission, causing a delay in respiratory outbreaks.

3.4.3 Concluding Remarks

The following are the concluded points from the literature:

- Clean air volume, air flow pattern, and exposure time are critical factors that affect infection probability [225, 233, 237].
- Wearing a mask and using ultraviolet devices and air cleaners are recommended to reduce contagion risks [92, 229].
- Airborne transmission possibility between floors in high-rise buildings is reported in the literature [230], which could result in significant health impacts [239]. Therefore, it is suggested to consider stack effect and transmission possibility in multi-storey buildings, multi-compartment, and multi-zone environments.

4. Evaluation and Estimation Methods

Applied methods in the literature to evaluate ventilation strategies' effects on indoor airborne transmission are addressed in this section. The purpose is to present statistical information and identify standard devices and techniques. Figure 5. The proportion of utilized evaluation methods

illustrates the most frequent methods to find the impacts of ventilation on aerosol spread through 131 shortlisted documents.

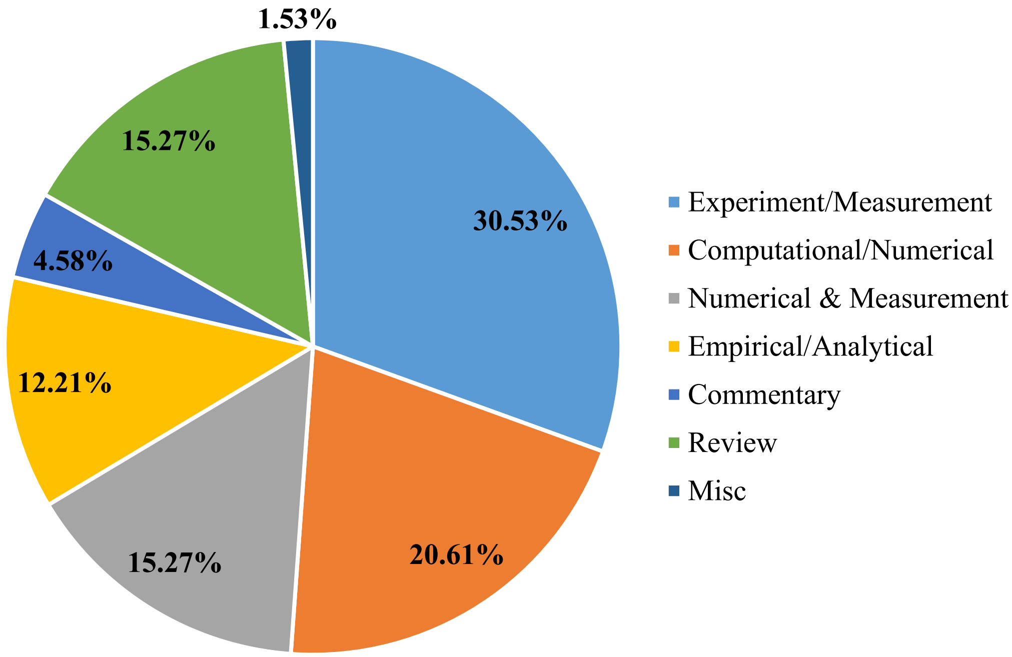

Figure 5. The proportion of utilized evaluation methods

Figure 5. The proportion of utilized evaluation methods
shows that experimental analysis [88, 240], numerical or computational [241], and a mix of numerical and experimental analysis [191] are the principal evaluation approaches applied to investigate ventilation impacts on airborne transmission. Empirical or analytical methods [242] also consist of around 12% of applied techniques in the literature. The Wells–Riley equation is a frequently used analytical method to evaluate airborne transmission and infection risk. The literature indicates that the Wells–Riley equation [243], developed by Wells [244] and Riley [104], was mainly used to evaluate infection risks empirically [245].

The literature review shows that mentioned evaluation methods have mainly been applied to investigate the impacts of different ventilation strategies and designs on three critical parameters: (1) infection risk, (2) particle concentration and removal, and (3) airflow pattern and airborne transmission in indoor environments. Figure 6 illustrates the proportion of articles to 131 shortlisted documents addressing these three factors under different ventilation modes.

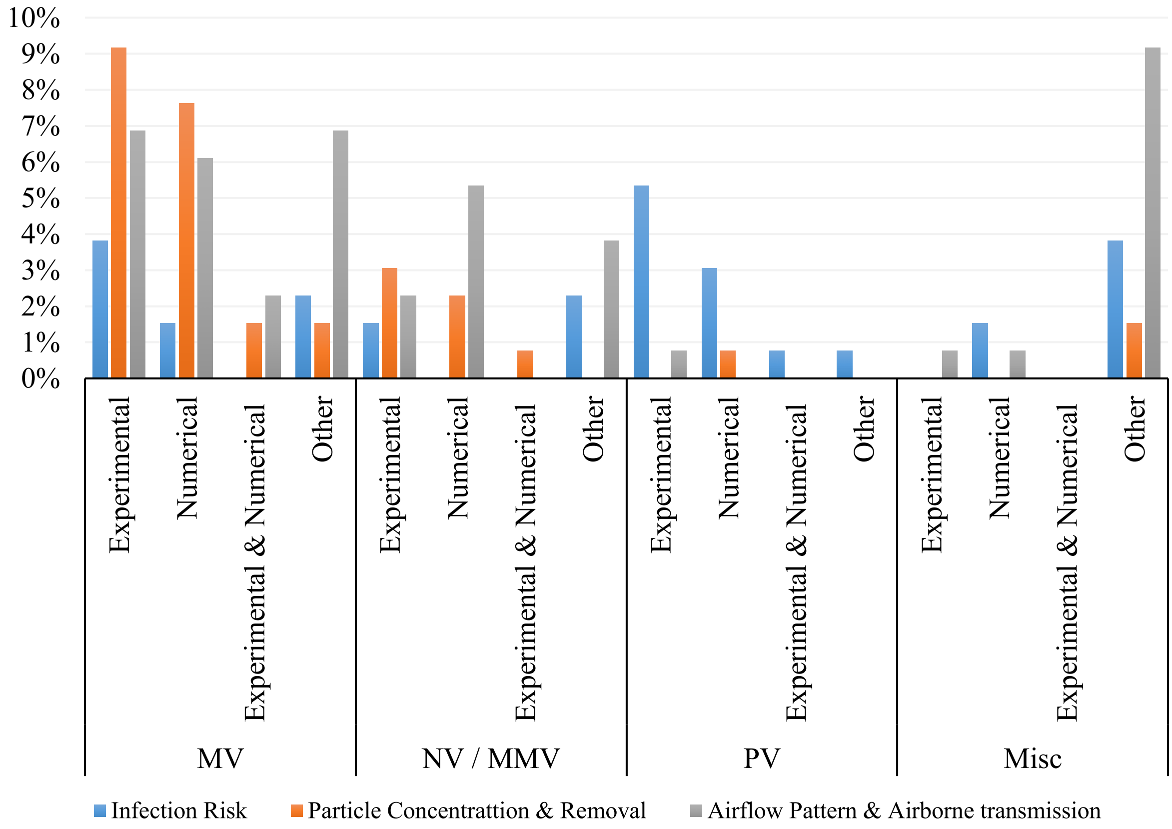

Figure 6. The proportion of utilized evaluation methods

Figure 6 highlights that researchers have widely investigated particle concentration and airborne transmission under MV, NV, and MMV. In contrast, infection risk was the core of the studies on PV systems.

As shown in Figure 5, more than 65% of the shortlisted studies experimentally and/or numerically evaluated ventilation systems' effects on airborne transmission. The details of these experiments and simulations are provided in Table A1 and Table A2, as supplementary material, in Appendix A. Figure 7 illustrates statistical information about the proportion of different experimental setups and methods, as well as simulation solutions and targets.

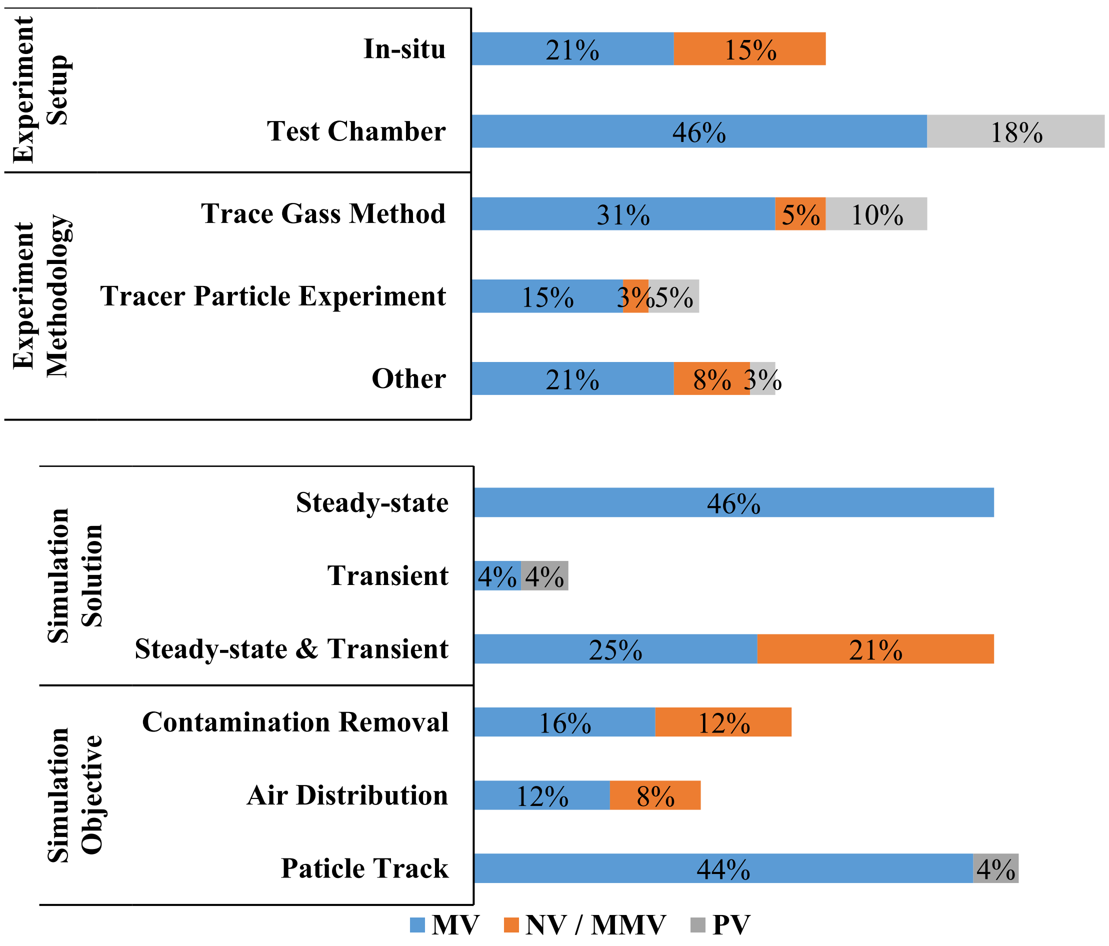

Figure 7. Utilized Experiment and Simulation Details

Figure 7 highlights that 64% of conducted experiments were set up in test chambers. This figure shows there was no study to evaluate the impacts of PV systems in real environments, and these systems have only been investigated in test chambers. So, there is a need to implement PV in practice and study in detail its performance, which the first attempt was conducted in [246]. Figure 7 also underlines tracer gas methods as the most common method utilized to investigate the impacts of ventilation systems. Regarding modellings, although steady-state simulations and a combination of steady-state and transient solutions were applied in 92% of studies, transient simulation was dominant in evaluating PV systems. Figure 7 also indicates that around half of numerical studies were conducted to track indoor particles.

5. Discussion and Future Direction

The present article critically reviewed the literature to examine ventilation impacts on airborne transmission as the most important way of spreading aerosols, which also move larger particles in indoor environments. Utilized ventilation strategies and critical ventilation design features in the literature were explored to investigate how it is possible to control airborne transmission and mitigate infection risks in clinical and non-clinical environments. The review first underlined ventilation systems' significant impacts on spreading aerosols and infection probability. The literature emphasized that all ventilation systems with a proper design with regard to airborne transmission could reduce particle concentration and infection likelihood and improve IAQ.

This manuscript showed that most previous studies addressed MV strategies, particularly for clinical environments. Although the current ventilation standards and guidelines state minimum ventilation rate as the requirements, the literature emphasizes that ACH and ventilation rate cannot be considered the sole indicator for designing a proper ventilation system concerning airborne transmission. The literature review suggested designing ventilation systems by optimizing design parameters, including ACH, ventilation rate, airflow pattern, inlet and exhaust (number and location), particle concentration, and infection risk. Particle level and size can also be another constraint that significantly impacts MV performance in reducing infection risks and controlling airborne transmission. There is also evidence that MV design, particularly selecting proper filter and ventilation rate, can affect ventilation performance based on the expected particle sizes in different building functions.

The literature review underlined inexpensive architectural retrofits, such as changing the exhaust locations, and new strategies like a central duct could significantly increase organized NV and MMV efficiency for removing contaminants, particularly in high-risk environments. The review highlighted the need to enhance the existing guideline for NV and MMV designing parameters and provide more information about minimum requirements for ventilation based on airborne transmission risks in indoor environments. The literature review suggested using air purifiers in naturally ventilated indoor environments can significantly improve performance in removing contaminations. Evidence shows that the stack effect and airborne transmission can transport aerosols between floors (infiltration/exfiltration); hence, new ideas to prevent contagious, like accommodating patients on higher floors, could be helpful.

The review recognized PV as a practical and reliable ventilation strategy to reduce cross-infection risk; however, a few studies investigated PV applications in public environments, particularly clinical spaces (i.e., close to patients' beds), potential environments for using PV facilities. Well-designed PV systems can easily be associated with the current ventilation systems and improve whole ventilation performance in reducing cross-infection even in high-density public areas. The literature review recommended optimizing PV system design based on critical parameters, such as occupants' position (i.e., seats in offices and patients' beds in hospitals), distance to PV facilities, and exhaust location. Some studies suggested more than one exhaust in PV systems and local exhausts. PV-PE system or personalized exhaust for occupants could be an example that showed a higher performance than ordinary PV systems.

The literature recommends applying filters and decontamination devices for ventilation systems to remove particles [247]. Decontamination tools should be associated with different ventilation strategies in zones with higher aerosol concentrations, such as clinical spaces, to make them more efficient in reducing pollution. Selecting filter types and ventilation rates based on the building's function could improve ventilation performance in removing particles. The literature also discovered that ventilation rate should be optimized based on air recirculation, contamination concentration, and indoor infection probability indices, as well as existing particle size, depending on the buildings' location, building functionalities, and types. Regarding evaluation and estimation methods, the review revealed that tracer gas, PIV, and smoke flow visualizations had been the most applied experimental methods to picture airborne transmission and particle concentration to examine different scenarios. Regarding simulations, researchers used Eulerian and Lagrangian DPM to predict airborne transmission, and a combination of steady-state and transient simulation showed an excellent capability to illustrate aerosol spread.

The key areas of further research, as highlighted in this paper, include:

1- Designing MV with several inlets and exhausts and investigating the number, location, and distance to occupants' places (i.e., patients' beds) concerning particles' considerations and infection probability indices.

2- Evaluating the effects of HEPA filters on controlling pathogen spread in clinical spaces with regards to the energy efficiency of MV systems (HEPA filters have adverse implications for pressure drop and cause higher energy use). This study may result in suggesting alternatives to high-efficiency filters.

3- Investigating the impacts of air purifiers and their best locations under NV and MMV based on their performance in removing contaminations and energy usage.

4- Assessing the effects of cooling assist devices, such as ceiling fans, on mixing fresh and contaminated air, as well as spreading contaminants and particles concentration.

5- Conducting research on PV systems' role in shifting the ventilation paradigm from central HVAC systems to occupants-based and reducing respiratory infection [30].

6- Suggesting new amendments to current legislation for ventilation based on building classes (functions and occupants' type and stay), refer to Australian and international codes.

6. Conclusion

The current review paper investigated ventilation effects on airborne transmission in clinical and non-clinical environments and examined the practical and efficient ventilation strategies for controlling the spread. The review showed all ventilation strategies (MV, NV, MMV, and PV) more or less could be efficient for removing contaminations if the essential design features were optimized based on airborne transmission, particle concentration, and infection risks in indoor spaces. This article underlined the exhaust's number and location (distance to the occupants), ventilation rates, and indoor airflow pattern (recirculation) as critical elements for optimising ventilation systems based on the aerosol spread and particle concentration. This article highlighted that innovative ventilation strategies, such as novel PV systems (i.e., PV-PE), could considerably improve occupants' wellbeing in indoor spaces and suggested PV as a practical strategy to shift the ventilation paradigm to safer occupants-based systems concerning airborne transmission. The review also recommended that a combination of ventilation systems and engineering controls, such as decontamination devices and filtration, reduce contamination concentration if these decontamination facilities were selected based on building functionalities and the expected level and size of particles. The study recommends a future direction for researching the possibility of shifting the ventilation paradigm from space-based central systems to occupant-based design to reduce infection risks in indoor spaces. This article can contribute to controlling aerosol transmission, the main route of virus-laden particles spread over ventilation.

Appendix A. Supplementary Material

Specifications of the utilized experimental and computer simulations are summarised in Table A.1 and Table 3. Table A.1 summarizes the experimental studies' details regarding the impacts of ventilation on airborne transmission through the literature.

Table A.1. Specifications of experimental studies

Ref	Ventilation Type	Targeted Parameters & Method	Setup	Equipment
MV (Clinical Environment)				
[65]	MV (HVAC)	Airflow distribution & contamination control under different HVAC scheme & Measurement	Full-scale in-situ in a hospital's OR	1- TSI model PH-731 to measure airflow, 2- Particle counter to count particles in indoor space (OR) & 3- TSI model 9565P to measure temperature & humidity.
[55]	MV (generated jet by air pillars)	Air pillars' performance to confine exhaled contaminants & Tracer gas method	Full-scale in-situ in a hospital's OR simulates a hospital ward)	TSI model APS 3321 spectrometer to measure particles.
[45]	MV (Ultra-Clean Ventilation or UCV)	Surgical contamination distribution & Particle Image Velocimetry (PIV) & Smoke flow visualization	Full-scale (Field chamber as an OR)	1- A scientific digital camera (Hamamatsu) & 2- Laser sheet generator for tracing smoke flow.
[54]	MV (POV)	POV dissatisfaction & impacts on air distribution & Measurement	Full-scale (Field chamber as a single-bed patient ward)	1- TSI VelociCalc 9565-P multi-function ventilation meter & 2- Air velocity by an omnidirectional anemometer.
[115]	MV (POV)	POV impacts on Cross-infection & Tracer gas method	Full-scale (Field chamber represents a patient ward)	1- Two micro-fans (AD0912DX-A76GL, ADDA Corp., Ltd) measured breathing mechanism, 2- NI 9481 & NI 9203 controllers & 3- Lab VIEW version 12.03
[113]	MV (HVAC)	HVAC control impacts on healthcare worker infection & Tracer gas method	Full-scale in-situ (an AIIR)	Multi-gas sampler & photoacoustic multi-gas monitor to measure multi-gas monitor SF6 Tracer gas cylinder to visualize particle spread.

[46]	MV (DV)	DV impacts on contamination removal & thermal comfort & NA	Full-scale (Field chamber represents hospitals' AIIR)	1- TSI Airvelocity Transducer, 2- Thermocouples (Type J) & inner surface temperature by PT100 & 3- Air humidity by HMT100.
[57]	MV	Ventilation effects on airborne transmission & concentration & Tracer aerosol method	Full-scale (Field chamber as a patient room)	1- NUCON SN-10 pneumatic aerosol generator, 2- Polyalphaolefin (PAO) for tracing aerosols & 3- Airborne concentration by optical or laser Lighthouse Handheld 3016.
[68]	MV	ACH impacts on mitigating infection risks & PIV & Tracer decay method	Full-scale (Field chamber as a healthcare room)	1- Grimm1.108 to measure droplet concentration & 2- TSI 9306 six-jet atomizer generated different particle sizes from olive oil.
[114]	MV	MV performance in removing bioaerosol & Particle measurement Verein Deutscher Ing (VDI2167) method	Full-scale (Field chamber simulates hospitals' OR)	1- PALAS AGF 2.0 IP generated particles & 2- a Lighthouse Solair 1100+ particle counter to measure particles.
[50]	MV (DV & Mixing ventilation)	Ventilation impacts on exhalation flow from patients & Tracer gas method	Full-scale (Field chamber simulates hospitals' one-patient ward	1- Omnidirectional anemometers to measure Temperature & Airvelocity connected to Multiple-channel data logger & 2- Two ultrasonic anemometers validated omnidirectional results
[73]	MV	MV design effects on bioaerosol concentration & Tracer gas method	Full-scale (Field chamber simulates hospital ward)	1- Thermocouples (Type K), 2- 14 Dantec 54R10 hot sphere anemometers to measure velocity magnitudes, 3- Fluke Helios Plus 2287A data logger connected thermocouples & 4- Kaye Instruments K170-2C.
[72]	Downward MV	Downward ventilation suitability for hospital wards & Tracer gas method	Full-scale (test room as a two-bed hospital ward)	NA
[116]	MV (DV, mixing & downward ventilation)	MV performance in dispersing exhalation contaminants & Tracer gas method	Full-scale in-situ measurement in a two-bed hospital ward	Thermocouples (Type K) connected to a data logger & 2- Multi-gas monitor (Type 1302) to measure NO_2
MV (Non-Clinical Environment)				
[96]	MV	Impacts of MV & barriers' height on airborne transmission	Full-scale in-situ measurement in an open space office	Thermal anemometer (Testo-405i wireless) for air and temperature measurements.

[112]	MV (downward Fan Filter Units or FFU)	FFU impacts on Particle distribution characteristics	Full-scale (Field chamber represents a clean room)	1- A Hot sphere anemometer, 2- A particle generator (TSI Atomizer 9302) & 3- TSI 9306-V2 for particle concentration measurement
[16]	MV (mixing ventilation)	Aerosol & CO_2 concentration & Tracer particles experiments	Full-scale in-situ (Gym)	1- Two Grimm Aerodynamic Particle Sizer (APS) & 2- Two 110 AQS2020PRO APS to measure particles.
[12]	MV & MMV	MV effects on droplet distribution & Laser diffraction or Spectroscopy	NA	1- A spray droplet measurement system (Malvern Spraytec) & 2- SprayScan laser sheet to measure gas concentration.
[82]	MV (HVAC)	Aerosol & IAQ (CO_2, O_3 & VOCs) & Tracer particles	Full-scale in-situ (Office)	Gas (i.e., CO_2) analyzer & Aerosol instruments for a size range.
[89]	MV (mixing ventilation & DV)	MV effects on airborne transmission, cross-infection & gas concentration & Tracer gas method	Full-scale (Field chamber as a general room)	1- PT100 sensors & Orifice flowmeters to measure air temperature & flow rate, 2- Tracer gas for N_2O, 3- A Fast Concentration Meter (FCM 41) & 4- Sn INNOVA Multi-gas Sampler & Monitor (1312) to measure NO_2 concentration.
[88]	MV (stratum, mixing & displacement air distributions)	MV influences on airborne transmission, Cross-infection & Tracer gas method	Full-scale (Field chamber as a general room)	1- PT100 sensors & Orifice flowmeters to measure air temperature & flow rate, 2- Tracer gas for N_2O, 3- A Fast Concentration Meter (FCM 41) & 4- Sn INNOVA Multi-gas Sampler & Monitor (1312) to measure NO_2 concentration.
[86]	MV (DV)	Indoor temperature & airflow impacts on IAQ & exposure & Tracer gas method	Full-scale (Field chamber as a general room)	1- Omnidirectional thermal anemometer & thermistors to measure air velocity & temperature.
[83]	MV (VAV HVAC)	MV performance in reducing CO_2 & PM concentration	Full-scale (Field chamber as a typical office room)	1- A 24-jet Collison nebulizer (BGI) generated polydisperse particle, 2- Optical particle counter (983, Fluke) recorded particle concentration.
[87]	MV (downward vertical)	Downward ventilation effects on removing contamination & reducing cross-infection & Tracer gas method	Full-scale (Field chamber as a general room)	1- Photoacoustic multigas monitor (type 1412; Innova Air Tech Instruments, 2- two Multipoint Sampler & Doser to measure N_2O concentration.

[90]	MV (DV & Mixing ventilation)	Air distribution effects on infection risk & Tracer gas method	Full-scale (Field chamber as a general room)	Thermocouples & anemometers to measure surface temperature & velocity magnitude & direction.
[84] & [85]	MV	MV system impacts on IAQ, airborne concentration & energy usage	Full-scale in-situ measurement in 422 offices in Hong Kong	1- NDIR analyzer, Electrochemical oxidation & Heated-Metal Oxide Semiconductor (HMOS) sensor to measure CO_2, CO & O_3, 2- Hot-wire anemometer, Polymer capacitor & Thermistor to measure air movements, relative humidity & temperature.
NV & MMV (Clinical Environment)				
[145]	NV	Effect of architectural modification on improving NV performance & reducing transmission risk & CO_2 tracer gas technique	Full-scale in-situ in four waiting & two consulting rooms in a hospital in the subtropical desert climate of Lima	Infra-red gas analyzer (Gas Data Ltd, UK) to measure CO_2 level
[34]	NV (cross-ventilation) & MV	NV impacts on reducing airborne transmission & IAQ & Pulse-injection gas tracer	Full-scale in-situ measurement in a hospital in a temperate Oceanic climate	1- Mobile weather station (Vantage Pro2, Davis Instruments) & Manometer (Testo 512, Testo Ltd) to measure wind (magnitude & direction) & Pressure, 2- Telaire 7001Di monitored CO_2.
[157]	NV & Hybrid (fan + NV)	NV impacts on decreasing cross-infection risk & Tracer gas method	Full-scale in-situ measurement in AN AIIR in the humid subtropical climate of Hong Kong	1- VELOCICAL Plus air velocity meter (8386A) (TSI) to measure air velocity, 2- CH25301 Drager visualized airflow direction, 3- Hood flow rate meter (APM 150, TSI) to measure exhaust rates.
NV & MMV (Non-Clinical Environment)				
[125]	NV	IAQ & Particle concentration	Full-scale in-situ (Gym) in school gyms in the Mediterranean climate of Barcelona (Feb to Apr)	1- Optical Counter (OPC 1.108) to measure droplet concentration, 2- APS 3321 (TSI) spectrometer to measure particles, 3- Nanoscan SMPS 3091 (TSI), 4- AE51 Magee Scientific, 5- Q-TRAK (IAQ 7575) & 6- Thermo Scientific for NO_2.

[136]	NV & Airtight ventilation	IAQ observation in six houses under NV & Airtight ventilations in cold weather	Full-scale in-situ in six residential houses in the dry & cold winter of Shenyang (humid continental climate)	TSI DustTrak & Telaire 7001 for testing particles & measuring CO_2, respectively.
[187]	NV & MMV	A comparison between the impacts of NV, MV & MMV on IAQ & comfort	Full-scale in-situ in three different fitness centers in a tropical climate	Thermo Electron Corporation, Model pDR1200 to measure PM10 & Alnor, TSI, Model CF8585 (thermo-anemometer) was used to measure temperature & relative humidity
PV (Clinical Environment)				
[209]	PV under mixing ventilation & DV	PV effects on personal exposure & gas concentration & Tracer gas & Photoacoustic infrared detection	Full-scale (Field chamber as a healthcare consultation room)	NA
[203]	PV under mixing ventilation & DV	PV's effects on reducing cross-infection risk & bioaerosol concentration & Tracer gas method	Full-scale (Field chamber simulates hospital ward)	NA
PV (Non-Clinical Environment)				
[216]	PV (air curtain)	Impact of PV on respiratory protection & Tracer gas method	Full-scale (Field chamber represents a workplace)	Tracer gas analyzer (INNOVA 1303/1412i) & hot wire anemometer (KIMO VT 115) to measure air velocity
[218]	PV	Infection risks & Tracer particles experiments	Full-scale (Field chamber represents public transport)	NA
[219]	PV	PV implications for airborne transmission & personal exposure & PIV	Full-scale (Field chamber represents general room)	1- A six-jet Collison nebulizer (BGI) & Collison nebulizer (BGI) generated droplets, 2- Optical particle sizer (Model 3330, TSI) & 4- a corresponding diluter (Model 3332, TSI).

[191]	PV	PV impacts on airborne transmission & Cross-infection risks & Tracer particles experiments	Full-scale (Field chamber represents general room)	1- APS 3321 (TSI) spectrometer, 2- Collison nebulizer (BGI) generated droplets, 3- Omnidirectional anemometer (Swema) to measure air velocity, 4- Hotwire anemometer (TSI 9535A) & 5- Thermocouples (Type K).
[222]	PV	PV performance in reducing cross-infection risk & Tracer gas method	Full-scale (Field chamber simulates aircraft cabin)	Temperature & Pressure was regulated in the test room.

The key findings of Table A.1 include the following points:

- Researchers conducted experiments in field chambers to simulate clinical and non-clinical environments, and in-situ measurement was mainly done for NV.
- Indoor environments (temperature, humidity, and air velocity) and IAQ specifications (CO_2, NO_2, VOCs, and PM1, 2.5, and 10) have been widely measured in all spaces.
- A limited number of studies addressed non-clinical environments, except for MV
- Few studies experimented with PV impacts on cross-infection in clinical spaces.

Table A.2 summarizes the details of numerical studies conducted to investigate the ventilation impacts.

Table A.2. Specifications of computer simulations

Ref	Ventilation Type & Setup	Equations & Turbulence model	Discretization Schemes	Software	Comment
MV (Clinical Environment)					
[98]	MV & Partition effects on contamination spread in Classroom	3D Steady-state & Transient RANS & RNG k-ε	First-order for turbulent kinetic energy rate & turbulent dissipation rate	CFD ANSYS Fluent V19.0	Eulerian-Lagrangian Discrete Phase Model (DPM) was employed to track particles' trajectories.

[143]	Compare MV & MMV for removing pathogen in ICU	3D Steady-state & Shear Stress Transmission (SST) k-ω	Semi-Implicit to couple pressure & velocity & 2nd-order upwind scheme	CFD ANSYS Fluent V18.0	Evaluated particle trajectory under different ventilations using Eulerian-Lagrangian DPM. Exhalation was considered a steady phenomenon for simulation.
[70]	Three typical MV systems impact on particles distribution in clinical space	3D Steady-state & Transient RANS & RNG k-ε	Pressure–velocity coupling (PVC) with Semi-Implicit Method for Pressure-Linked (SIMPLE) & 2nd-order upwind scheme	CFD OpenFOAM V1906	Eulerian-Lagrangian DPM simulated particles & 2-Simulation commenced with Steady-state & continued with transient when reached a quasi-steady result.
[69]	MV effects on t particles removal in ICU	3D Steady-state & Transient RANS & Standard k-ε, RNG k-ε, SST-k-ω	NA	CFD ANSYS Fluent V2020 R1	1- RNG k-ε is better to model extreme Reynolds & 2-Lagrangian DPM predicted particles trajectory.
[55]	MV (air curtain) performance in removing particles in hospital wards	3D Steady-state & Transient RANS & RNG k-ε	PVC with SIMPLE & 2nd-order upwind scheme	CFD ANSYS 2016 (Fluent)	DPM was used to model airborne transmission from exhalation.
[54]	MV (POV) influence on infection risks in hospital wards	3D Steady-state RANS & RNG k-ε, Realizable k-ε & SST k-ω	PVC with SIMPLE & 2nd-order upwind scheme	CFD ANSYS Fluent V16.0	SST k-ω showed better agreement to predict temperature & velocity. CFD results can assist in designing efficient POV systems.
[47]	Suitability of DV system for employing in an AIIR	3D Steady-state & Transient (or unsteady) RANS & RNG k-ε	PVC with PISO & 2nd-order upwind scheme	CFD ANSYS Fluent	Contaminants dispersion is a transient phenomenon, so transient simulation is preferred to steady-state.
[113]	MV (HVAC) control to protect healthcare workers in an AIIR	3D Steady-state & RNG k-ε & Standard k-ε	PVC with SIMPLE	CFD STAR-CCM+	Multi-component gas fluid (Air/SF6) was simulated. Changing exhaust airflow rates impacts exposure risks significantly.

[66]	MV (TAF) impacts on airborne concentration in a hospital's OR	3D Steady-state FEM & Realizable k-ε	PVC with PRESTO & 2nd-order upwind scheme	CFD ANSYS Fluent 18.2	Lagrangian DPM predicted bacteria-carrying particles like droplets. TAF can be an energy-efficient alternative to laminar airflow ventilation.
[63]	MV design impacts on mitigating pathogen spread in clinical spaces	3D Steady-state continuity & Momentum equations & Realizable k-ε	NA	CFD STAR-CCM+ (V10)	CFD STAR-CCM+ provides various analysis tools that assist in modelling ventilation systems.
[79]	Impacts of different ventilation configurations on airborne distribution in a mock AIIR	3D Steady-state & Transient Finite Volume Method (FVM) & Realizable k-ε	PVC with SIMPLE & 2nd-order upwind scheme with 2nd-order implicit discretization for temporal terms	CFD ANSYS Fluent V17.0	Lagrangian DPM simulated and tracked bioaerosol (cough aerosols).
[75]	Different airflow diffusion systems (MV) effects on aerosol concentration in an OT	3D Steady-state & Navier–Stokes equations & Realizable k-ε	PVC with PRESTO & 2nd-order upwind scheme	CFD ANSYS Fluent 14.5.7	Eulerian-Lagrangian DPM was used to model continuous gas (Eulerian) & solid dispersed phase (Lagrangian).
[74]	Practical MV design impacts on infection risk in an isolation room	Steady-state, Wells–Riley equation was integrated into CFD & RNG k-ε	PVC with SIMPLE & 2nd-order upwind scheme	CFD	For different diffusers (swirl & square), User-defined Function (UDF) codes were defined to consider surrounding circumstances.
[154]	Safe MV rate in a clinical environment	Transient FVM & Standard k-ε	PVC with SIMPLE	CFD-PHOENICS 3.2 (2000)	CFD & Multi-zone models were carried out to investigate the virus dilutions in different cases.
[72]	Feasibility of using downward ventilation (Misc.) in a hospital ward	3D Steady-state & RNG k-ε	2nd-order upwind scheme	CFD-Fluent	CFD was applied to model airflow patterns and particle spread.

MV (Non-Clinical Environment)					
[96]	MV & Barriers' hight influence on infection risk in an Office	3D Steady-state RANS & Re-Normalization Group (RNG) k-ε	NA	CFD ANSYS Fluent V16.0	1- A User Defined Scaler (UDS) was applied to model contamination spread & 2- Particle concentration simulation is a practical approach to evaluate interior design impacts on airborne transmission.
[37]	MV design impacts on IAQ in workshops	3D Steady-state RANS & Realizable k-ε	PVC with SIMPLE & 2nd-order upwind scheme for pressure interpolation & first-order for turbulent kinetic energy & dissipation rate	CFD ANSYS Fluent	CO, a similar density to air, is selected as a simulation sample. Utilized CFD approach is an appropriate method to evaluate the dilution efficiency of existing ventilation systems.
[117]	Impacts of three mixing ventilation methods on airborne transmission in bus	Steady-state Wells–Riley equation was integrated into CFD & Standard k-ε	PVC with SIMPLE & 1st-order upwind scheme	CFD-Star-CD V4.08	Integrated numerical models can assist in developing control strategies.
NV & MMV (Clinical Environment)					
[149]	Feasibility of using NPV (buoyancy-driven) in hospital wards with multiple beds	3D Steady-state & Dynamic Thermal Simulation (DTS) & RNG k-ε	NA	CFD-Elliptic Numerical Integration Code Series (PHOENICS)	RH was not measured in some points due to PHOENICS limitation.
[148]	Feasibility of using NPV (buoyancy-driven) in one-bed hospital wards	3D Steady-state & DTS & RNG k-ε	NA	CFD (PHOENICS)	Suggested CFD & DTS as two suitable simulation methods to predict indoor environments under buoyancy-driven NV.
NV & MMV (Non-Clinical Environment)					
[184]	NV, changing opening scale impacts on removing contaminants in an Office	3D Steady-state RANS & Reynolds-Averaged Stimulation (RAS) k-ε	NA	CFD using OpenFOAM	Utilized simulation is appropriate to research current building adaption to respiratory outbreaks.

[181]	Mechanical exhaust in NV & MMV on inter-floor spread	3D Steady-state & RNG k-ε	PVC with SIMPLE & 2nd-order upwind scheme	CFD ANSYS Fluent	Suggests aerosol simulation of the generated droplets from occupants to illustrate infection spread under NV.
[172]	Air flow pattern in an atrium under NV (wind-driven)	3D Steady-state RANS & RNG k-ε	PVC with SIMPLE & 2nd-order upwind scheme	CFD software Fluent (version 6.3)	Instability of incident wind made some deviation in validation between experiment & simulation results.
PV (Non-Clinical Environment)					
[217]	PV impacts on cross-infection in an office	3D Transient RANS & RNG k-ε	PRESTO pressure & 2nd-order upwind scheme for mass, momentum, energy, *k*, *ε* & turbulence equations	CFD ANSYS Fluent V17.2	Eulerian-Lagrangian DPM to track cough droplets
Other (Non-Clinical Environment)					
[231]	Ventilation impacts on airflow pattern in a lavatory	3D Steady-state & Shear Stress Transmission (SST) k-ω	PVC with SIMPLE & 2nd-order upwind scheme	CFD ANSYS Fluent V18.0	Lagrangian DPM to track bioaerosol after coughing and flushing

The key findings from Table A.2 are as below:

- CFD is the most popular method to simulate airborne transmission.
- Eulerian-Lagrangian DPM, mostly Lagrangian, was normally employed to investigate aerosols' motion and particle trajectory.
- K-epsilon turbulence models, Realizable, and Renormalization Group (RNG k-ε), were broadly employed as turbulence models to investigate ventilation impacts on airborne transmission. RNG k-ε showed a better performance to predict airflow with extreme Reynolds so that it is suitable for single-sided NV, typically with lower air velocity.
- Steady and unsteady simulations were employed to predict inherently unsteady airborne transmission. Using a combination of steady and then transient reached acceptable results.

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