Building and Environment 247 (2024) 110954

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A systematic review of ventilation solutions for hospital wards: Addressing cross-infection and patient safety

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ARTICLE INFO

Keywords:
Nosocomial cross-infection
Hospital ventilation
Air-cleaning technology
Pathogen removal
Thermal comfort

ABSTRACT

Despite various preventive interventions, nosocomial cross-infection remains a significant challenge in healthcare facilities worldwide. Consequently, prolonged hospitalization, elevated healthcare costs, and mortality rates are major concerns. Proper ventilation has been identified as one of the possible interventions for reducing the risk of cross-infection between patients and healthcare workers in hospital wards by diluting infectious agents and their carrying particles. The use of air cleaners in conjunction with the ventilation system further reduces the concentration of indoor pathogens. This article presents a systematic review of the ventilation solutions employed in hospital wards where pathogen removal performance can be enhanced using air-cleaning techniques while maintaining the thermal comfort of patients and healthcare staff. We provide a comparative analysis of the performance of different ventilation strategies adopted in one-, two-, or multi-bed hospital wards. Additionally, we discuss the parameters that influence the aerosol removal efficiency of ventilation systems and review various air-cleaning technologies that can further complement the ventilation system to reduce contaminant concentrations. Finally, we review and discuss the impact of different ventilation strategies on the perceived thermal comfort of patients and healthcare workers. This study provides insights into the cross-contamination risks associated with various hospital ward setups and the vital role of the ventilation system in reducing the adverse effects of infection risk. The findings of this review will contribute to the development of effective ventilation solutions that ensure improved patient outcomes and the well-being of healthcare workers.

1. Introduction

Indoor pollution has adverse immediate and long-term effects on building occupants' health and well-being. A noticeable share of 4.1% of global deaths in recent decades has been caused by severely poor indoor air quality, especially nosocomial infections [1]. Healthcare facilities are prone to the highest risk of cross-infection since susceptible individuals and vulnerable patients are in close contact indoors. It was proven that patients and attendants are at higher risk of infection compared to the medical staff at the Covid-19 inpatient wards [1]. Dire consequences of nosocomial infections are increased medical expenditure, prolonged hospitalization, and deaths in several cases [2]. Despite strict precautions, such as hygiene measures, personal protective equipment (PPE) like masks, and isolation precautions used to lower cross-infection risk between patients and healthcare workers (HCW), health-acquired infections are still a widespread problem. Pathogenic bioaerosols can be transmitted as airborne particles and lead to the persistence of this problem in spite of several preventive measures, such as avoiding crowded indoor spaces, regular disinfection of surfaces and objects, and using physical barriers like partitions [3]. Contaminated air and hospital ventilation system deficiencies are reported as the major causes of nosocomial infections [2,4,5]. In 2002, approximately 1.7 million healthcare-associated infections (HAI) were reported in the US, of which 99,000 cases led to death [6]. In Sweden, 34% of all injuries (12,456 cases) occurred in hospitals in 2019, and about half of all deaths due to healthcare faults (213 cases) were related to HAI [7].

The indoor environment of healthcare facilities can usually be affected by outdoor sources such as outdoor contamination levels and indoor parameters like human activities and ventilation system

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https://doi.org/10.1016/j.buildenv.2023.110954
Received 21 April 2023; Received in revised form 10 September 2023; Accepted 18 October 2023
Available online 30 October 2023

Nomenclature

ACH	Air exchange per hour
AIIR	Airborne infection isolation room
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
CBNV	Ceiling-based natural ventilation
CDC	Centers for Disease Control and Prevention
CFD	Computational fluid dynamics
HAI	Healthcare-associated infection
HCW	Healthcare workers
HEPA	High-efficiency particulate air filter
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICU	Intensive care unit
IEQ	Indoor environmental quality
TNPI	Temporary negative pressure isolation
MERV	Minimum-efficiency reporting value
OR	Operating room
OT	Operative temperature
POC	Portable air cleaner
POV	Protected occupied zone ventilation
PPD	Percentage of people dissatisfied
SARS	Severe acute respiratory syndrome
SSI	Surgical site infections
TB	Tuberculosis
TNPI	Temporary negative pressure isolation
TVOC	Total volatile organic compounds
UV	Ultraviolet
UVGI	Ultraviolet germicidal irradiation
WHO	World health organization

performance [8]. In recent studies by Gao and Zhang [9] and Li and Tang [10], several design characteristics regarding ward environment were studied, among which ventilation and exposure time were the two dominant parameters in airborne disease infection in hospital wards. Therefore, indoor air pollution in healthcare facilities is higher than outdoors, and controlling the polluting sources and diluting the contaminants are necessary [11,12]. In this regard, the ventilation system plays a key role since they are used as the primary infection control measure in hospitals [13]. However, they may contribute to the transmission of airborne diseases [14]. In order to design efficient ventilation and disinfection systems used in healthcare facilities, both an in-depth and comprehensive understanding of features of the indoor hospital environment affecting patients and HCW health, comfort, and productivity is required [15].

To date, several review studies have been published regarding previous literature to investigate different aspects of healthcare-associated infections. Beggs et al. [16] reviewed the design guidelines for heating, ventilation, and air conditioning (HVAC) systems, specifically ventilation systems for UK and US hospital wards. They intended to evaluate various ventilation strategies for removing airborne pathogens. Shbaklo et al. [17] investigated the infection prevention and control cornerstones in the COVID-19 outbreak and concluded that Guidelines should target modes of transmission while recommending control precautions. Yau et al. [2] studied the state of knowledge of ventilation systems in multiple-bed hospital wards in the tropics based on the available guidelines and practices. They specifically investigated the design, indoor conditions, and engineering controls used in ventilation systems. Khodakarami and Nasrollahi [18] provided a preface of a guideline regarding thermal comfort in hospitals by reviewing the indoor climate in hospitals. Lipinski et al. [19] reviewed the ventilation strategies in high-occupancy buildings such as hospitals to identify the factors affecting air particle properties regarding flow dynamics to reduce indoor infections. Sadrizadeh et al. [20] systematically reviewed the state-of-the-art air quality and infection control in hospital operating rooms (OR). They identified the decisive factors in operating room ventilation performance and indoor contamination level affecting surgical site infections (SSI). They also studied the OR staff's thermal comfort. Similarly, Jangir et al. [21] investigated the adoption of various ventilation systems to prevent bacteria transmission in operating theatres and suggested a temperature control airflow ventilation system as the most efficient for disinfecting contaminants in operating rooms. Zhang et al. [22] studied interventions suggested by previous researchers to decrease respiratory infections in buildings. They categorized all facility management interventions for respiratory virus transmission in buildings into three categories of hard services, such as HVAC and drainage system controls; soft services, such as cleaning and disinfection, and space management, such as space planning and occupancy controls. Another study by Izadyar and Miller [23] highlighted the impact of various ventilation modes and designs on indoor airborne transmission, particle concentration, and indoor air quality in clinical and non-clinical environments. The Chinese HVAC guidelines to tackle pandemic outbreaks are summarized and reported by Ye et al. [24], and the most important differences to guidelines from other countries are discussed. These comparisons revealed the effectiveness of HVAC systems in controlling airborne transmission in buildings during the COVID-19 pandemy. Stockwell et al. [3] summarized the results of 36 studies regarding indoor hospital bioaerosol concentrations. They considered various types of contaminations and ventilation systems used in hospitals and compared the risk of hospital-acquired infections in different parts of hospitals. It was concluded that inpatient facilities were at higher risk of contamination by bioaerosols than restricted or public areas of hospitals. Therefore, a comprehensive literature study revealing the influencing parameters on hospital wards' cross-contamination risk is of utmost importance. These results were in line with Ortiz et al.'s two-year survey conducted in Spain, which suggested that hospital rooms and maternity wards had considerably higher aerobic counts compared to operating theaters [25].

The main focus of the abovementioned previous articles was limited to a few ventilation types or specific hospital wards. To address the need for a comprehensive investigation of various ventilation strategies used in all hospital wards and their ability to reduce the cross-infection risk between patients and healthcare workers, we are motivated to systematically review the existing research evidence on the topic of cross-infection in hospital wards mainly due to airborne transmission. Despite the existence of numerous review studies concerning ventilation strategies and air distribution methods in healthcare facilities, there remains a lack of current information regarding the available and examined techniques for addressing cross-infection within hospital wards. Therefore, this article aims to investigate potential techniques for tackling cross-infection in hospital wards, particularly emphasizing the employed ventilation strategies and supplementary approaches like air purifiers.

2. Review methodology and paper structure

The authors narrate the research findings, provide practice recommendations, and identify potential limitations that can be addressed in future research. To achieve this objective, the authors have adopted a systematic review methodology outlined by Grant [26]. The article's

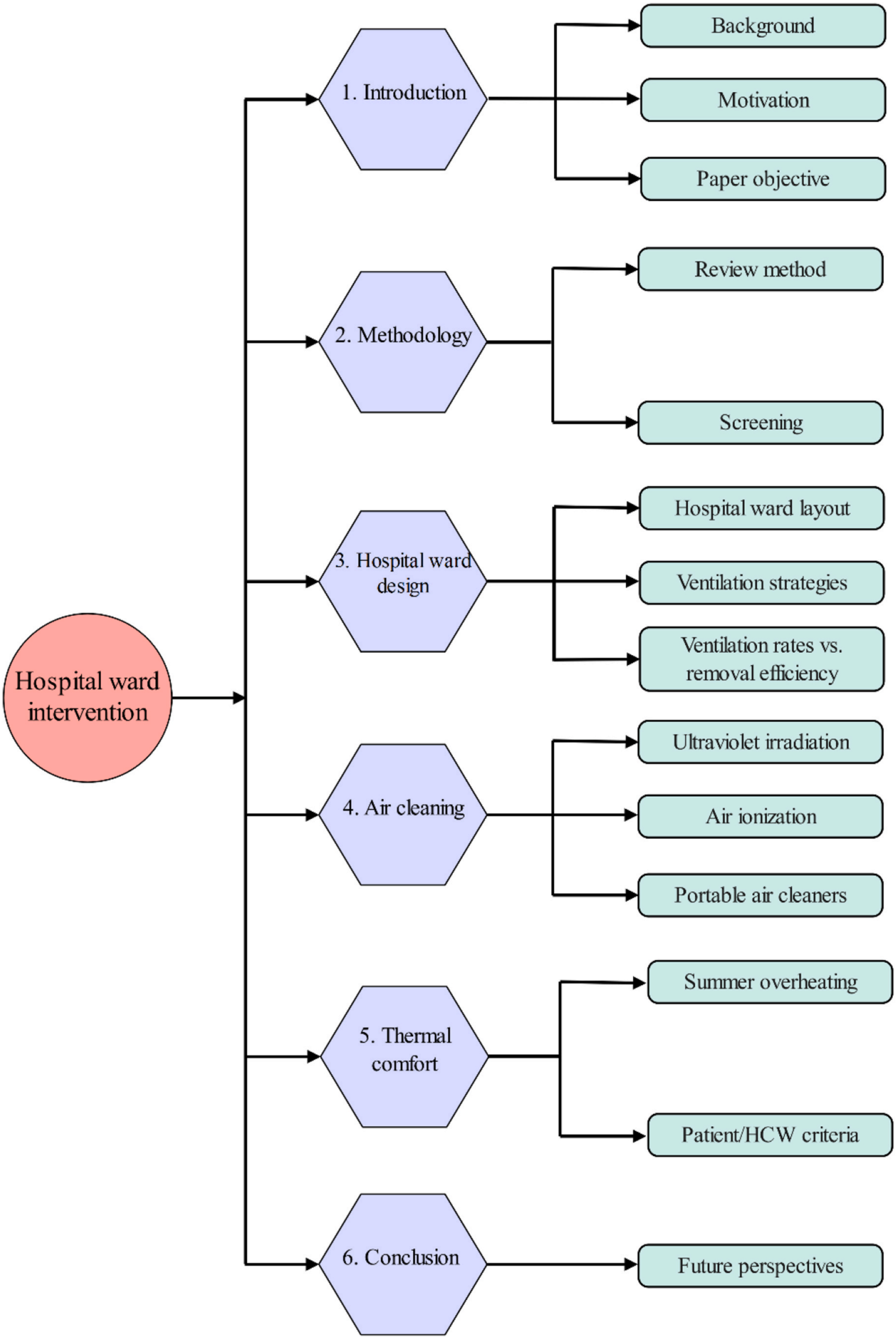

Fig. 1. Overview of the paper structure.

information is structured and presented clearly and concisely, as illustrated in Fig. 1.

The research questions addressed in this review article are.

- How can ventilation reduce cross-contamination in hospital wards?
- What is the role of air filtration and air cleaners in reducing cross-contamination in hospital wards?
- How successful is natural/mechanical ventilation in maintaining thermal comfort and indoor air quality (IAQ) requirements in hospital wards?

2.1. Methodology

Aligned with the research questions and the study's objective, a keyword-based search of published articles, books, and bills was carried out. The sources for these materials were Google Scholar, Scopus, and Web of Science. The keywords used for searching materials were ventilation strategy, indoor pollutants, filtration, infection control, air exchange per hour (ACH), air cleaner, ultraviolet germicidal irradiation (UVGI), thermal comfort, IAQ, and hospital ward. Screening and eligibility of publications were checked by the relevance of the title and the abstract and by the skim reading of their main body. The main inclusion criterion was relevance to the ventilation strategies used in hospital wards, but general buildings and healthcare facilities were also considered. A total of 113 documents were eligible for inclusion in this article. Chapter one, Introduction, briefly describes the overview of available review articles regarding cross-infection in indoor environments, especially in hospitals. Chapter two (Methodology) explains the essential questions that this article aims to answer regarding cross-infection in hospital wards and how the paper is structured.

Various researchers have targeted the aspect of reducing the cross-infection risk in indoor environments, specifically hospital wards. Zhang et al. [22] have categorized the facilities management required to make interventions for respiratory infection transmission in existing buildings into HVAC interventions preventing pathogens transmission via the airborne route, disinfection methods preventing infection transmission via the fomite route, and occupancy management preventing pathogens transmission via the droplet route. Therefore, a chapter entitled "Hospital ward design" reviews the current ventilation strategies used in different types of hospital wards and various methods for reducing cross-contamination. The critical parameters to efficiently achieve this goal have also been investigated. The following chapter, entitled "Use of air cleaners in hospital wards", introduces the role of air cleaners in hospital wards' cross-contamination rate. The effectiveness of ventilation systems when equipped with various air-cleaning technologies is studied and compared. The final chapter titled "Ventilation effect on thermal comfort in hospital wards", investigates thermal comfort in hospital wards and how different ventilation strategies provide a thermally comfortable environment. In chapter six, the conclusions are presented.

3. Hospital ward design

Numerous studies have investigated the design of hospital wards in terms of bed positioning, ventilation system, pollution removal intervention, and thermal comfort. The following studies mentioned in this section highlight the importance of such parameters in hospital wards. Bed positioning, number of beds/patients in a room, supply/exhaust grill position, and the airflow pattern affect the traveling time of pollutants and infectious agents in the air.

A comprehensive study by Jung et al. [27] examined the distribution of various pollutants in different parts of 37 hospitals in Taiwan. Their statistical data showed that the most prevalent pollutants in hospital wards were CO_2, total volatile organic compounds (TVOC), and bacteria. Li et al. [28] reviewed the published literature in major databases up to 2005 and concluded that there was substantial evidence to associate the cross-infection risk and the ventilation in buildings. However, they pointed out the lack of sufficient data to determine the minimum ventilation requirements in hospitals. According to another review study by Zhang et al. [22], a large share of facilities management interventions is composed of HVAC systems in order to reduce the cross-infections of respiratory diseases in existing buildings. Li et al. [29], in their study following the 2003 severe acute respiratory syndrome (SARS) epidemic, introduced the air exchange rate, airflow direction, and airflow pattern as the major factors affecting the performance of ventilation systems installed in hospital wards for SARS patients. Shen et al. [30] suggested that the infection risk can be reduced by 27% by introducing 100% outdoor air in the ventilation system. A high-efficiency particulate air filter (HEPA) filter used for recirculating indoor air can result in the equivalent reduction of infection risk. Hyttinen et al. [31] have pointed out that, previously, mixing-type ventilation was the preferred strategy in airborne infection isolation rooms (AIIR) to meet the US guidelines, and considerable attention was paid to air exchange rates; however, the use of auxiliary devices was also examined. Therefore, important factors affecting the ventilation performance and different types of ventilation strategies commonly used in hospital wards are described and compared in this sections.

3.1. Hospital ward layout

Infection risk is of utmost importance in a multiple-bed hospital ward since airborne nosocomial transmission of infectious pathogens from susceptible individuals is more frequent. Reaching a reduced number of cross-infections between patients in hospital wards secures a lower infection rate between patients and healthcare workers, as well, since patients are more exposed to infection risks than HCWs. Tang et al. [32] have investigated the aerosol transmission of infectious agents and introduced droplets generated during a patient talking, sneezing, and coughing as the transmitting agent, which travels short distances when there is close contact between patients in multi-bed hospital wards. Huang et al. showed that the risk of cross-infection among patients in a multi-bed hospital ward could be diminished by using curtains between adjacent patients [33]. However, the number of trapped particles close to the opposite patient increased. In general hospital wards comprising several beds, ventilated air is usually supplied to the main corridor connecting a number of bed cubicles. In such cases, the air in the supply corridor is cleaner than the rest of the ward and provides safer environments for HCWs who spend more time outside patient rooms. Yam et al. [34] suggested a ducted return strategy to extract the exhaust air from cubicles to an open space outside the hospital. Their computational fluid dynamic (CFD) simulation results revealed that ventilation performance and removal of microbes significantly improved. The airflow direction, in this case, was from a clean area to a less clean area, which is a recommendation by the US Centers for Disease Control and Prevention (CDC) [35]. In general, the quality of air in the proximity of a hospital can be affected by the patients' rehabilitation status, which urges the purification of the indoor air before being discharged.

Many UK hospitals are at risk of overheating, especially in multi-bed wards. Therefore, refurbishment strategies are utilized to address the adverse effects of radiant cooling or overheating. A great deal of previous research focused on using natural and mechanical ventilation and shading systems as refurbishment measures [36]. In addition to these measures, the placement of beds in multi-bed hospital wards can also affect the patients' perceived thermal comfort and potentially influence patients' core body temperature [37]. In general, a multi-bed configuration of patient rooms is proven to promote opportunistic airborne transmission [16]; therefore, there is a move toward single-bed hospital wards in the UK to provide occupants with personalized control over their thermal preferences. This could improve occupants' thermal comfort and hospitals' resilience to climate change [38], but increase the construction and operating costs. Moreover, less cross-infection risk between patients reduces the risk of infection to the HCWs.

3.2. Ventilation strategies

Using ventilation to dilute or remove indoor aerosol pathogens is the primary intervention in many hospital ward designs. The design and operation of ventilation systems in healthcare facilities require extensive attention since their performance directly affects occupants' health. This section reviews various types of ventilation systems installed in hospital wards and discusses the research results regarding their performance. The primary classification of ventilation systems in hospitals is the choice between mechanical and natural ventilation design. The hybrid mode is often the preferred choice to meet the design criteria. Hybrid ventilation refers to a technique employed in buildings to manage indoor airflow by combining natural and mechanical ventilation systems. Its primary objective is to create an indoor environment that is both energy-efficient and comfortable. This is achieved by harnessing the advantages of both natural and mechanical methods to regulate air exchange and temperature. By integrating natural and mechanical ventilation, hybrid systems offer a versatile and adaptable approach to indoor air management. The advantages and disadvantages of these three ventilation designs are summarized in Fig. 2. The information provided in this figure is gathered from Refs. [39–42].

According to the reviewed literature, a more detailed categorization of ventilation strategies in hospital wards is presented in Fig. 3. Here, various mechanical ventilation strategies are presented besides natural ventilation as the major solution for reducing the risk of infection in hospital wards.

3.2.1. Natural ventilation

In a natural ventilation system, the airflow is driven in a building based on natural forces, such as wind or air density differences due to temperature differences. Ilic et al. studied 12 different ventilation strategies and concluded that natural ventilation provides high ventilation rates more economically than mechanical ventilation systems [12], even though its efficiency, in terms of allowing consistent airflow, enabling air filtering and purification, air temperature and humidity control, and mitigating external noise, is not proven superior to mechanical ventilation. The airflow pattern by the natural ventilation system is determined by supply openings, which can be small during the heating season resulting in similar airflow patterns by displacement flow [43]. Effective removal of pathogens by natural ventilation systems is challenging since controlling the ventilation rate is highly influenced by factors such as outdoor air quality, wind speed, interior layout, placement of the inlet-outlet pathways, etc. [22].

Natural ventilation is attractive for maintaining high airflow rates while ventilation energy usage is low. This type of ventilation is mainly used in countries where the outdoor air does not require much

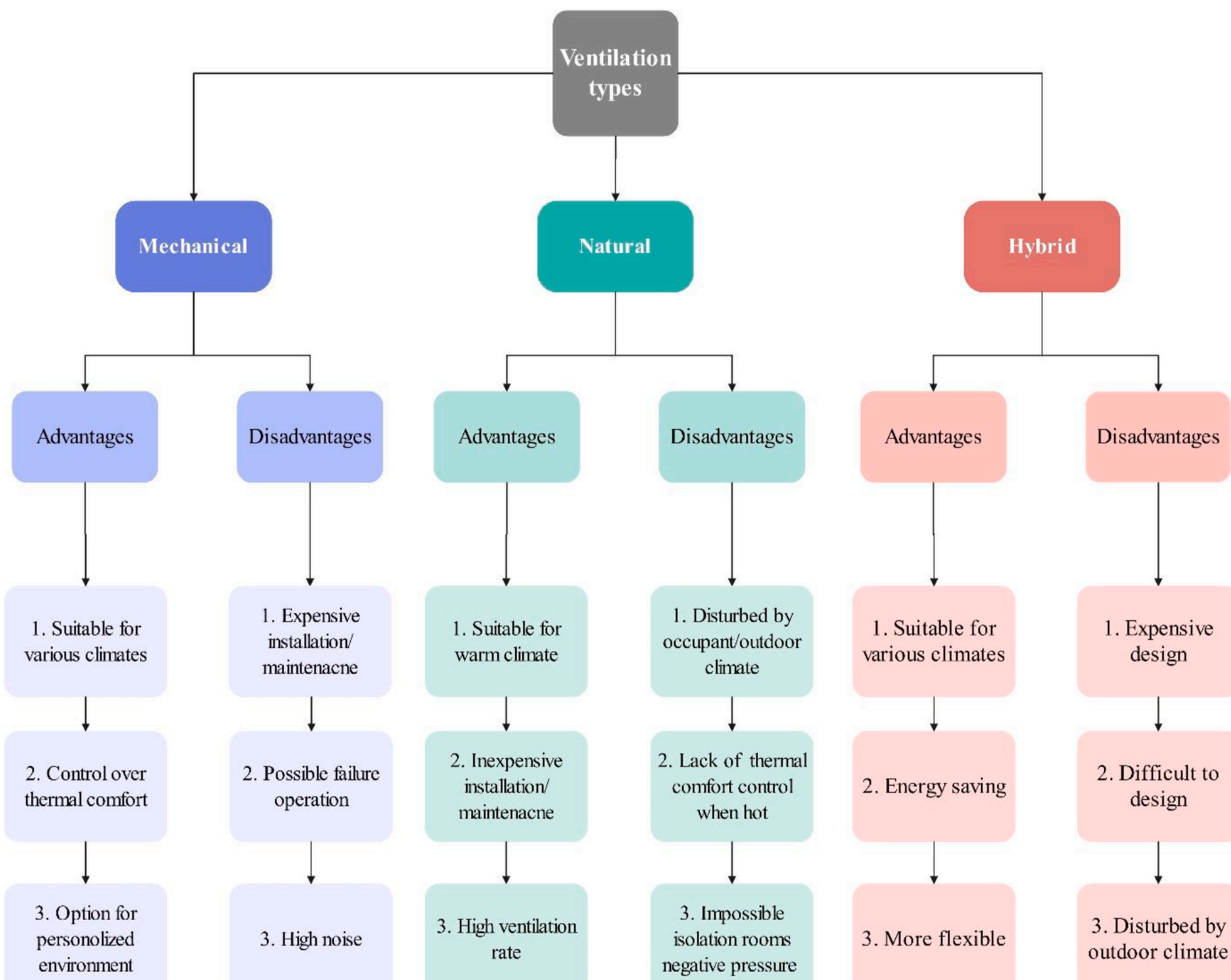

Fig. 2. Advantages and disadvantages of using natural, mechanical, and hybrid ventilation in hospital wards.

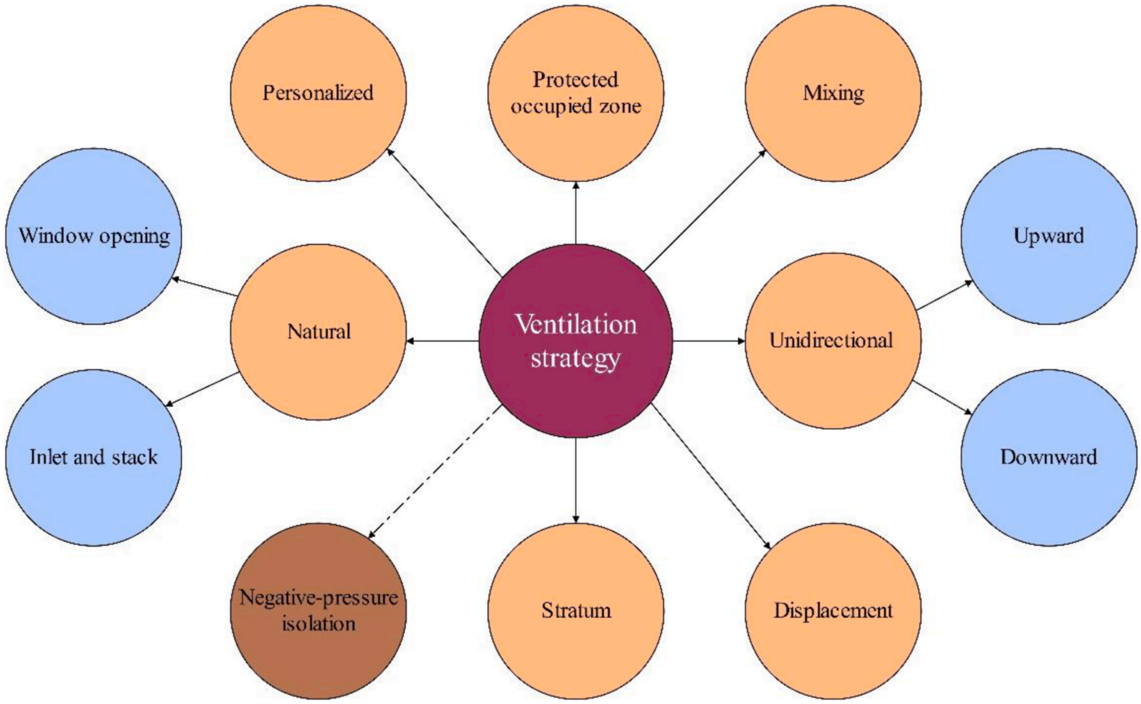

Fig. 3. Ventilation strategies used in hospital wards.

temperature treatment, such as tropical countries [2]. The world health organization (WHO) has recommended a minimum natural ventilation rate of 60 l/s per patient in hospitals' general wards [42]. A drawback of this system is that negative indoor pressure cannot be achieved when benefitting natural ventilation. Adamu et al. [44] evaluated the performance of four types of natural ventilation systems in a single hospital ward. The investigated strategies are single window opening, same-side dual-opening, inlet and stack, and a new concept of ceiling-based natural ventilation (CBNV). They concluded that a 25% fraction of trickle ventilation opening could contribute to achieving acceptable airflow rates and thermal comfort in winter. The CBNV worked similar to personalized ventilation by delivering fresh air to isolated parts of wards over patients.

Rahman et al. [45] investigated the thermal comfort parameters in a naturally ventilated hospital ward in Malaysia using three different methods. They concluded that the prevailing mean temperature in such hot-humid regions was out of range of the set value defined by the ASHRAE-55 Standard [46]. A similar discomfort sensation from the occupants of hospital rds in Singapore was reported by Lan et al. [47]. Additional passive solutions to the available natural ventilation, such as night air purge through automated window dampers, can improve the thermal comfort in the ward in a tropical climate, such as in Singapore. Qian et al. [48] investigated the natural ventilation system's ability to reduce airborne infection in a hospital ward in Hong Kong. High ventilation rates were recorded using natural ventilation, but the airflow pattern and direction were unstable during some measurements. The high ventilation rate reduced the cross-infection of airborne diseases, and by installing mechanical exhaust fans, the existing wards could be converted into temporary isolation rooms. Much like mechanical systems, today's natural ventilation relies on technology for its functionality. In contrast to traditional natural ventilation systems, current methods require state-of-the-art computer control systems, innovative ventilation opening designs, advanced fan designs, etc., to operate effectively.

Gilkeson et al. [49] experimentally investigated the cross-infection rate in a naturally ventilated open hospital ward. Measurements showed that an outdoor air speed of 1–4 m/s resulted in indoor ventilation rates of 3.4–6.5 ACH. The natural cross-ventilation system was effective in open hospital wards with an even distribution of airborne infectious pathogens. Adding physical partitions between beds could increase the protection for neighboring patients; however, a higher concentration of airborne pathogens was expected in the vicinity and downstream of the source. Using extract fans could help offer the best year-round ventilation performance to alleviate the increased infection risk during winter when the windows are closed.

In summary, natural ventilation has advantages in terms of cost-effectiveness and high ventilation rates, but it may not offer the same level of control and consistency as mechanical ventilation. Factors such as building orientation, height, and climate zone, as well as the implementation of appropriate design strategies, are crucial in optimizing natural ventilation systems for specific applications, such as hospitals.

3.2.2. *Negative pressure isolation*

Inducing negative indoor pressure can help remove indoor aerosols, especially during large-scale airborne infectious outbreaks. This can be maintained by a greater exhaust air flow rate than the supply air flow rate. Several researchers and institutions have instructed temporary negative pressure isolation (TNPI). Studies by Miller et al. [50,51] investigated the potential of establishing a negative-pressure isolation ward to meet a hospital's surge capacity during an airborne infectious disease outbreak. The pressure in the test ward was −29 Pa relative to the main hospital hallway; however, there was no pressure reversal at the entrances to the ward. Such a high pressure difference value is recommended in a few countries, such as Australia [52], but there is no sufficient scientific consensus on the pressure difference limit values [31]. Note that the negative-pressure isolation only protects building occupants outside the ward, and the infection risk for the HCWs in a ward is not affected by the induced negative pressure.

The pressure difference should prevent the escape of infectious air from the patient's room. Therefore, a low pressure difference is difficult to maintain, and a high pressure difference might result in elevated air velocities above 0.25 m/s [46]. HCWs are at serious risk of cross-infection in negative-pressure isolation wards since the indoor concentration of aerosols can be high. Wang et al. [53] have investigated the distribution pattern of droplet aerosols both experimentally and numerically. Based on their findings, 10% of aerosols were deposited on the floor under the supply inlets. Thus, exposure of HCWs to the air passing through this region, simultaneous with any cause for resuspension of these aerosols, can create a higher risk of infection.

3.2.3. Mixing ventilation

Complete mixing conditions can be achieved by high-velocity air supplied to the space using mechanical ventilation. Supply jets to the room, which is the most common type of supply, can move the total air volume and mix with the surroundings [43,54]. Mixing ventilation is based on the assumption of a full mixture of the air in the space. This assumption, however, does not consider the detailed local airflow patterns that considerably impact the local infection risk for every individual in that space. Therefore, further investigations on the precise airflow characteristic and distribution are required to correctly define the local infection risk [30] (see Fig. 4).

Bolashikov et al. studied the exposure of a doctor and a second patient to a coughing patient in a two-bed hospital ward [55]. The room was equipped with a mixing ventilation system and ventilated at three air change rates of 3 h^{-1}, 6 h^{-1}, and 12 h^{-1}. The level of exposure for the doctor and the other patient depended on the distance from the infected patient and his coughing posture. Their simulated results showed that the suggested air change rate of 12 h^{-1} by the hospital standards could cause draught discomfort because of higher velocities above 0.5 m/s. Due to complex airflow interaction around the doctor, the elevated ventilation rate (12 h^{-1}) could increase the doctor's exposure to coughed air and the risk of cross-infection compared to the lower air exchange rates (3 h^{-1}, 6 h^{-1}).

Berlanga et al. [56] have compared the performance of four mixing ventilation systems in single hospital rooms based on health workers' exposure to pollutants a patient releases. These mixing ventilation systems differed in supply and exhaust configurations. The supply grilles were in the upper part of a wall or swirl ceiling diffusers, combined with the exhaust grilles located in the opposite wall's upper or lower part. Three air change rates of 6 h^{-1}, 9 h^{-1}, and 12 h^{-1} were also tested. The results showed that the configuration with the swirl ceiling diffuser created adequate mixing and maintained the exposure rate of health workers to pollutants lower than other configurations.

The importance of the inlet vent positioning in a hospital isolation ward has also been investigated by Kumar et al. [57]. They studied the correlation between the height of the inlet vent and the average residence time of bacteria released from a patient. Their results proved that the height of the inlet considerably impacts the draught distribution in the room and the bacteria residence time. Hang et al. [58] conducted CFD analyses of a six-bed isolation ward with nine downward supplies and six ceiling- or floor-level exhausts. They evaluated the flow disturbances by the healthcare workers' motion and the respective airborne transmission. They concluded that HCW motion affected airborne transmission; however, the effect of ventilation design was more important. This was witnessed by better controlling airborne transmission using ceiling-level exhausts than floor-level with the same air change rate of 12.9 ACH. Experimental measurements performed by Cao et al. [59] examined the dynamic interactions between a cough jet and various indoor airflow distributions created by diffusers. The results showed that the downward plane airflow jet prevented the transmission of cough particles from the cough source to the exposed dummy, but the ceiling-attached horizontal jets were not successful in reducing the cross-infection.

3.2.4. Unidirectional airflow ventilation

Unidirectional airflow ventilation is commonly used in protective isolation wards to prevent cross-contamination or infection of microorganisms in severely immunocompromised patients. The restricted areas, including wards in hospitals, are usually equipped with mechanical ventilation systems operating in enhanced mode, including directional airflow ventilation combined with HEPA filters or increased air changes per hour [3]. Chao and Wan [60] investigated the dispersion characteristics of expiratory aerosols for two airflow patterns of ceiling-return and unidirectional downward using a multiphase numerical model. The settling time for small aerosols increased from 20 s in downward airflow to 32–80 s for ceiling-return flow. Lateral dispersion increased from 0.3 m for downward flow to over 2 m in ceiling-return flow, as well. In a downward ventilation hospital ward, Nielsen et al. [61] showed that deposition of particles larger than 10 μm was within 1 m from a horizontal source manikin, and this could be even closer for a vertically upward manikin. This provides higher protection for patients vulnerable to acquiring infection (see Fig. 5).

The interaction between a human body and the uniform flow from various directions was investigated by Lincia et al. [62]. In a similar study, Yang et al. [63] carried out CFD simulations of a protective isolation room equipped with unidirectional airflow ventilation to assess the airflow field in diluting particles from a patient's body. Various supply upward airflow rates induced by thermal plumes were compared. The results showed that the required supply air velocity to control particle dispersion from the patient's body and breathing was at least 0.2–0.25 m/s. Nielsen et al. [64] conducted a full-scale simulation of a two-bed hospital ward equipped with a ceiling-mounted low-impulse semicircular inlet diffuser. Three different return openings placement were tested: an opening at the ceiling, four at the opposite walls to the inlet, and four at the opposing walls with a high location. The system configuration with a high location of the four openings could decrease the cross-infection risk from the exhaled contaminant. They also tested various air exchange rates and discovered that different ACH values did not affect the infection exposure index. At a constant ACH rate, Liu et al. [65] investigated the bioaerosol removal efficiency of unilateral and bilateral downward ventilation systems in a two-bed hospital ward. They concluded that unilateral downward ventilation (inlet grills are

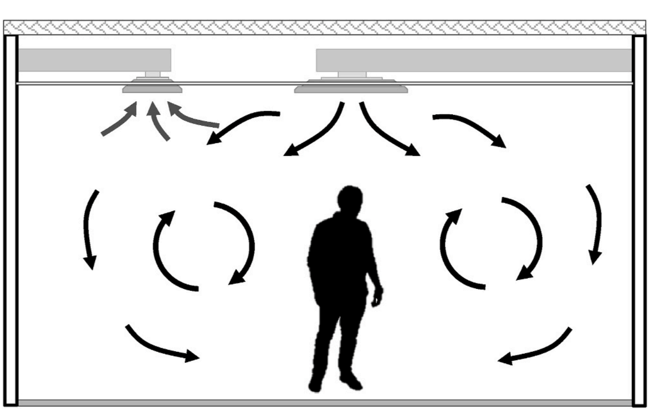

Fig. 4. Schematic of a mixing ventilation system.

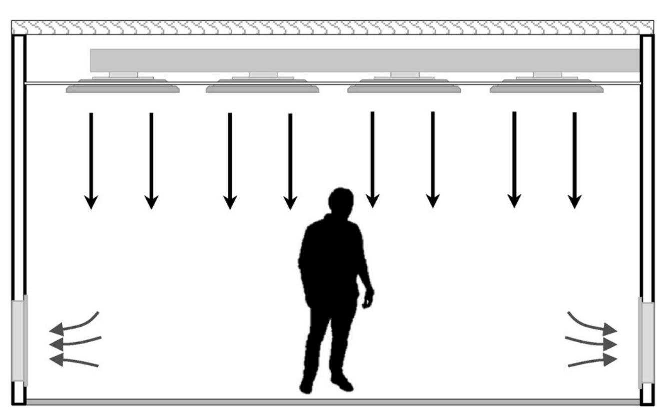

Fig. 5. Schematic of a unidirectional ventilation system.

collectively installed at one place in the ceiling) was 50% more efficient than bilateral downward ventilation (inlet grills are installed at more than one place in the ceiling). Furthermore, the HCW breathing zone concentration of bioaerosols was also lower. This implies the importance of inlet/outlet grill placement in defining air pathways and the potential of the ventilation system to clear the environment from aerosols.

3.2.5. Displacement ventilation

In displacement ventilation, internal heat sources, which create buoyancy forces, govern the flow in the room [54]. In this configuration, low-temperature ventilation air is supplied at the floor level compared to the room mean temperature, and warm air is extracted at the ceiling. This helps remove the excess heat from heat sources in the room and maintain a unidirectional flow close to the supply side [43,54]. This creates a vertical stratification in the room when removing polluted warm air closer to the ceiling, resulting in higher ventilation effectiveness than mixing ventilation [66,67] (see Fig. 6)

Yin et al. [68] investigated the performance of a displacement ventilation system against mixing ventilation installed in a full-scale environmental chamber representing a single-bed patient ward. The displacement ventilation strategy could provide better air quality in the simulated ward, depending on the exhaust location. In cases where the exhaust grill was placed in the upper parts of the wall, displacement ventilation with lower airflow rates (4 ACH) provided an equal level of air quality as mixing ventilation (6 ACH). Displacement ventilation has the potential to reduce the infection risk by 26%, and this could be further improved to 96% by installing partitions between the patients while the hospital ward is equipped with displacement ventilation [30]. However, the results of a single patient room equipped with displacement ventilation show a lockup phenomenon at the height of the HCW where the exhaled contaminants from a lying patient accumulated [69]. This was despite the promising air change efficiency and contaminant removal effectiveness obtained by displacement ventilation.

3.2.6. Stratum ventilation

The focus of stratum ventilation is the breathing zone of occupants; therefore, the thermal comfort and indoor air quality beyond the occupied zone are unimportant. The inlets and outlets are placed on walls in such a way as to ensure a direct supply of fresh air to the breathing zone [70]. Cheng and Lin [71] compared the airflow characteristics of stratum with mixing and displacement ventilation in a multi-occupant room. Due to different flow characteristics, stratum ventilation requires a higher supply air temperature to achieve general thermal comfort and reduce the draft risk. Comparing the measured mean air temperature in the occupied zone proved the high cooling efficiency of stratum ventilation. A comparison between stratum and mixing ventilation was conducted by Oladokun and Lin [72]. A sequential box model for exposure assessment of influenza in a multi-bed hospital ward was developed, and the results showed a similar average concentration for inhalation exposure under both ventilation strategies. However, stratum ventilation was three times less insensitive to the variability in exposure than mixing ventilation (see Fig. 7).

Lu et al. [73] further studied stratum ventilation and suggested that using stratum ventilation in hospital wards could reduce the exposure risk, and HCW could be protected from respiratory infections. They performed CFD simulations of a two-bed hospital ward with two patients and an HCW. The results indicated that at the breathing zone of the HCW (1.3-1-7 m), contaminants diluted more quickly with stratum ventilation compared to mixing, downward, and displacement ventilation cases. In another study, Lu and Lin [74] investigated the coughed droplet dispersion in a hospital two-bed ward equipped with stratum ventilation. The supply diffusers were placed on the wall opposite the patients at a height of 1.5 m, and the exhaust grills were at the floor level. Compared to mixing and displacement ventilation strategies, stratum ventilation resulted in reduced patient exposure risk. This was due to an intense deposition of droplets at the initial dispersion stage and the dilution of droplet concentration at the breathing zone by the horizontal air jet.

3.2.7. Personalized ventilation system

In contrast to the traditional mixing or displacement ventilation systems which provide clean air to the entire space, a personalized ventilation system delivers clean air in the proximity of each individual's breathing zone [43]. A personalized ventilation system is a new development in the field of HVAC that has the capability to enhance occupant comfort and mitigate the potential transmission of contagions among occupants compared to total volume ventilation. The individualized air is conditioned through an air-handling unit, which adjusts the airflow rate based on occupancy while also regulating the temperature and humidity of the air supplied to the occupants' breathing zone. This system delivers clean, refreshing, and precisely controlled air to the breathing spaces or occupied areas, primarily focusing on regulating the air within the microenvironment adjacent to the occupants [113]. Nozzles located nearby the occupants supply fresh air in addition to a background general air distribution. Despite providing adequate fresh air and energy efficiency, personalized ventilation is often expensive, and connecting ducts to every section of indoor spaces is challenging.

Health hazards regarding the hospital indoor environments and their possible impacts on health workers and patients were summarized and categorized by Dovjak et al. [75]. They presented three types of hazards, namely, biological, chemical, and physical (related to thermal comfort), that the HVAC system can influence. It was revealed that there was a lack of technology to provide optimal thermal conditions for individual occupants. Therefore, they designed and tested an integral control of physical hazards that enabled control over personalized thermal comfort parameters to satisfy the requirements of each occupant in the same room. This system provided optimal conditions for burnt patients and healthcare workers in the hospital ward and, simultaneously, thermally neutral zones for other potential users.

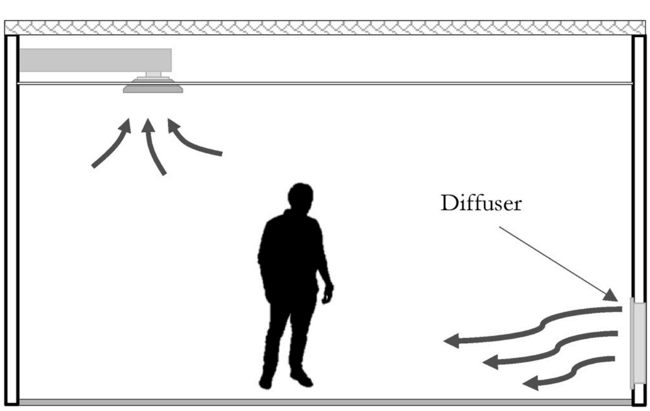

Fig. 6. Schematic of a displacement ventilation system.

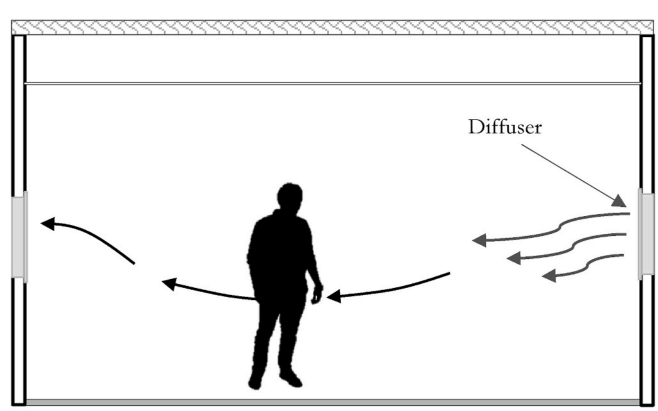

Fig. 7. Schematic of stratum ventilation.

3.2.8. Protected occupied zone ventilation

A relatively novel air distribution system called the protected occupied zone ventilation (POV) system prevents the transmission of contaminated air from a polluted zone to a protected area using a downward plane jet [76]. Cao et al. [59,77] showed that the POV decreased the risk of cross-contamination between two people by separating the protected zone from the polluted one by up to 2800 ppm. Aganovic et al. [78] evaluated the percentage of people dissatisfied (PPD) in a hospital single-bed patient room due to draught. Even though the supply air velocities to the room did not exceed the suggested comfort criterion, the draught risk at ankle level when the patient was sitting, exceeded the maximum allowed value.

A summary of the studied ventilation strategies indicates their crucial role in hospital ward designs to mitigate the transmission of airborne pathogens. The primary classifications include mechanical and natural ventilation, with hybrid ventilation often preferred. Natural ventilation utilizes natural forces but may struggle to provide consistent airflow and control air quality. Conversely, mechanical ventilation offers better regulation but can result in draught discomfort and increased cross-infection risk. Mixing ventilation achieves complete air mixing, but precise airflow characteristics and local infection risks require further investigation. Unidirectional airflow ventilation is commonly used in protective isolation wards, providing higher protection for vulnerable patients but posing risks to healthcare workers. Displacement ventilation removes excess heat and maintains a unidirectional flow, demonstrating potential in reducing infection risk, yet challenges persist regarding draught distribution and contaminant accumulation. Stratum ventilation focuses on occupants' breathing zones, requiring higher supply air temperatures and showing promising air quality and reduced exposure risks. Personalized ventilation systems deliver clean air to individuals but face implementation challenges and higher costs. Protected Occupied Zone Ventilation (POV) utilizes a downward plane jet to prevent cross-contamination, separating polluted and protected areas, but draught risks and comfort criteria must be carefully addressed.

While ventilation strategies in hospital ward designs offer numerous benefits, several research gaps and challenges remain. Understanding and improving natural ventilation control and addressing the influence of outdoor air quality, wind speed, and interior layout are crucial. Maintaining proper negative pressure isolation and airflow control during airborne outbreaks requires further investigation. The precise airflow characteristics and distribution patterns of different ventilation strategies, along with their impact on local infection risks, need to be studied more comprehensively. Issues such as draught discomfort, air velocity, and the risk of cross-infection in mixing ventilation should be carefully assessed. Furthermore, challenges exist in implementing personalized ventilation systems due to cost and complex ducting requirements. Finally, addressing thermal comfort, avoiding draught risks, and optimizing the design of protected occupied zone ventilation systems are essential considerations. Further research, innovative technologies, and effective strategies are needed to optimize ventilation in hospital ward designs, ensuring patients' and healthcare workers' safety and well-being.

3.3. Ventilation rates versus removal efficiency

Various guidelines have addressed specific issues such as tuberculosis (TB), nosocomial infections, and surgical site infections. Filtration of the supply air and the air exchanger rates are mainly based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommendations. However, there are no explicit requirements for the filtration of supply air to patient rooms and hospital wards. Kowalski [79] has shown the effect of filtered outdoor air on the initial level of airborne microbial contamination compared with the impact of HEPA filtration on recirculated air. In general, higher ventilation rate results in reducing the risk of cross-infection in hospitals [80].

By increasing the ACH to 4 h^{-1}, 6 h^{-1}, and 12 h^{-1}, the indoor concentration of colony-forming units per cubic meter falls below 10^{-6} CFU/m^3 within 2 h and less than 1 h, respectively. Typically, patient rooms and intensive care units (ICU) are supplied with an ACH of 4–6 h^{-1} with 2 h^{-1} ACH of fresh outdoor air. Dai and Zhao [81] have investigated the association between ventilation rates and infection probability by a coronavirus in a simulated hospital room. Their results indicated the importance of adequate ventilation rates in reducing the infection risk in confined places. They suggested that to keep the infection probability below 1%, ventilation rates of 100–350 m^3/h and 1200–1400 m^3/h per infector for an exposure time of 0.25 and 3 h were required, respectively. However, wearing a mask could reduce the required ventilation rates to a quarter, which are achievable by standard ventilation systems installed in buildings.

Memarzadeh and Manning [82] studied the effectiveness of a patient room ventilation system using CFD simulations. They suggested a ventilation rate of 4 ACH to maintain adequate conditions and the possibility of reaching an optimum ventilation system performance by increasing the ventilation rate to 5–6 ACH. They also suggested low-level exhausts provided better mixing conditions than ceiling-level for extreme winter situations at low ACH. Memarzadeh and Xu [83] hypothetically illustrated an optimized ventilation system design to reduce cross-contamination risk in a hospital ward by risk assessment without necessarily increasing the ventilation airflow rate. They concluded that even though increasing the air changes per hour dilutes the concentration of infectious agents, it does not increase ventilation effectiveness. They identified the path between the contaminant source and exhaust as the dominant factor in controlling the transmission of contaminants. Therefore, maintaining the uninterrupted path by an air stream is a more important factor than increasing the ventilation flow rate. This is in line with the results provided by other studies [84,85], which also found that increasing the ventilation rate to 12 ACH did not assuredly reduce the cross-infection risk in hospital wards. Mousavi and Grosskopf [86] have also investigated the dominance of pathways between pathogenic sources and exhaust over the air change rate in a general hospital ward. They found that increasing the ventilation rate from 2.5 h^{-1} to 5.5 h^{-1} reduced indoor aerosol concentration by 30%, while the particle concentration increased by more than 40% in pathways between the patient (source) and the exhaust. Similar results reported by Li et al. [26] indicated that doubling the total supply airflow rate resulted in a 37% reduction in the infection risk. Therefore, a higher ventilation rate was not proven to reduce the aerosol concentration proportionately. Kim et al. [87] investigated the concentration of virus-like particles in a nursing room during the Covid-19 outbreak. They found that such particles might spread over long distances by the indoor airflow in the absence of mechanical ventilation and small openings in the awing-type windows. The extended floating time of these particles results in a prolonged exposure time for occupants. This could be disturbed by utilizing mechanical ventilation and air cleaners to dilute particles in a shorter time.

The study by Correia et al. [14] showed that ACH had a minor influence on health workers' exposure to contaminants when swirl ceiling supply diffusers were installed in a mixing ventilation strategy. Other combinations of supply and exhaust grill locations resulted in different distances between the inlet and exhaust air, which could be affected differently with ACH. The exposure rate could be even less when displacement ventilation is used instead of a mixing strategy for lower values of ACH. CFD simulation results by Guo et al. [88] highlighted the impact of ACH on infection risk in a negative-pressure hospital ward from airborne exposure. In contrast, a minor effect of ACH on infection risk from surface exposure was reported. Wang et al. [89] studied ten air distribution proposals in a hospital ward and concluded that cross-infection could be reduced by 95% by optimization, while ACH was constant in all cases. Therefore, not only should ACH be considered an influential parameter on cross-infection, but other factors such as air distribution, flow pattern, and inlet/outlet openings play a crucial role [90].

4. Use of air cleaners in hospital wards

Source control solutions, in addition to other measures such as adequate ventilation, can considerably reduce the infectious aerosols in the air of hospital wards. In practical cases, infectious aerosols dispersed from patients have complex movements due to exhaust grill location, the thermal plume from the patient's body, and air movements because of the presence of medical personnel. In such situations, the ventilation system hardly achieves a capturing velocity while maintaining acceptable indoor air quality. Therefore, capturing the infectious aerosols close to their sources is recommended before they are dispersed in the room [31]. The Centers for Disease Control and Prevention suggested using HEPA filters at the discharge of exhaust ducts [35]. ASHRAE design manual for hospitals and clinics suggests using two-stage filters for treatment rooms and ICUs, a minimum-efficiency reporting value (MERV) 7 filter for the first stage and a MERV 13 or 14 filter for the second stage [91]. Below, three principal approaches mentioned in the literature for eliminating pathogens in hospital wards are reviewed and discussed. The major limitations of each method are shown in Fig. 8 (see Figs. 9 and 10)

4.1. Ultraviolet irradiation

Ultraviolet (UV) and negative air ionization are effective measures against the transmission of infectious aerosols. There is a risk of human exposure to irradiation that can be eliminated by installing UV lamps in the upper part of rooms, directing radiation upwards to ceilings, or inside exhaust ducts in case of recirculating air handling units [31]. Adding shields to the lamps can provide more safety to the occupants but reduce the effectiveness of UVGI systems, which is defined by an equivalent ventilation rate. The size of particles carrying microbes and air humidity can also affect the effectiveness of UVGI systems [92]. Various researchers have investigated the relation between the ventilation rate and efficiency of UVGI systems since higher ventilation rates reduce the exposure time of infectious pathogens to UV irradiation. Wojciech et al. [93] studied the use of UVGI with increased ventilation rates. They concluded that particles deposited and ventilated out were more significant in number compared to the airborne bacteria that UV killed. UVGI prevented 70% of TB infections and more than half of TB diseases in an investigation by Escombe et al. [94]. Therefore, they recommended UVGI systems for hospital spaces and the emergency ward. Hospital field trials of UVGI systems reported by Kowalski [79] show a significant reduction in infection cases in nine hospitals across the US. After installing two UVGI types, overhead and upper air systems, the average infection reduction was 78% and 65%, respectively. CDC recommended ventilation rates of 6–12 h^{-1} ACH for hospital wards, including TB patients, and UVGI as a complimentary disinfection system. But the UVGI system's efficiency depends on the ventilation

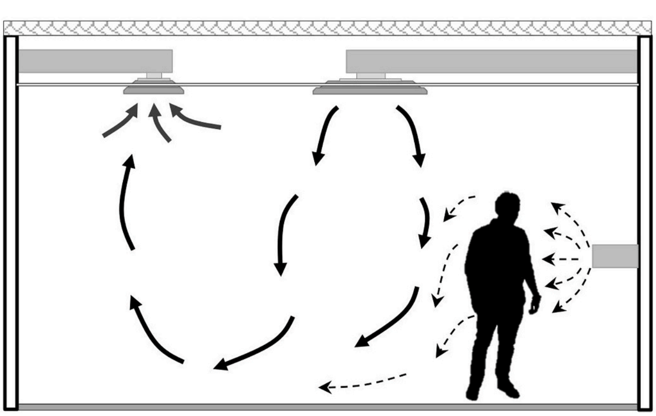

Fig. 8. Schematic of personalized ventilation.

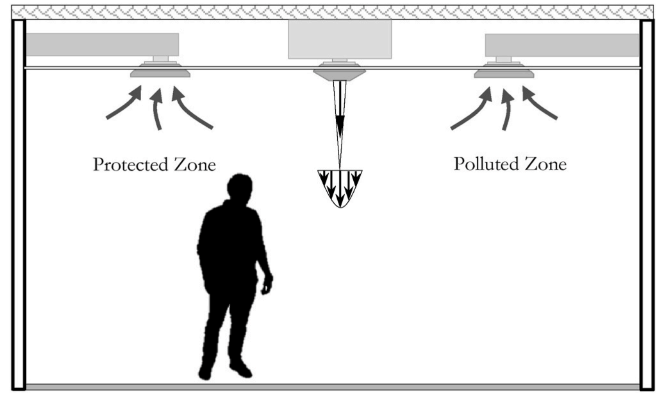

Fig. 9. Schematic of protected occupied zone ventilation.

system's design. Shen et al. [30] suggested an average infection risk reduction of 59% for the upper-room UVGI system in hospital wards. Noakes et al. [95] have investigated the analytical modeling of UVGI systems utilized with different ventilation systems. They suggested that high-level air supply and extraction are less suitable for upper room UVGI performance since the cleaned air is mostly extracted before being used by the occupants. Barnewall et al. [96] investigated the efficacy of an air purifier combining UV-C light and a HEPA filter in a controlled environment where Covid-19 was the test organism. The air purification system using this combination successfully removed the virus from the air.

4.2. Air ionization

A technique used to remove respirable airborne particles and microbial agents is the air ionization of airborne particles and microorganisms in indoor environments, even though it is not recommended as an efficient air-cleaning solution by many studies [31,97,98]. Air ionization results in the deposition of airborne particles on walls and charged surfaces, and this is due to negatively charged repellent particles in the air [99]. Aerosol concentration reduction induced by ionizers can be disturbed by particle depletion characteristics, particle size and concentration, and especially external ventilation. Grinshpun et al. [100] investigated the effectiveness of unipolar air ionization as an indoor air pollution control. Their measurements compared the concentration decay due to ionic emission and natural decay of mainly bacterial particle size range of 0.5–2 μm. The obtained results proved that human exposure to indoor air pollutants was significantly reduced by the ion-driven decrease in the aerosol concentration together with the bactericidal effect. Some studies showed that the ionization of particles resulted in inconsistent beneficial biological effects and, therefore, is not a reliable method that can be used for different sizes of particles and the inactivation of viable microorganisms [31,98]. However, in a comprehensive study by Escombe et al. [94], negative air ionization, both solely and combined with upper-room UV lights, effectively prevented airborne TB transmission. On the other hand, a reported drawback of negative air ionization was the accumulation of potentially infectious particles onto the grounded surfaces of the ionizer.

4.3. Portable air cleaners

In general, 90–95% of bacteria in hospital environments can be confined using efficient filters, and for viruses whose size is less than 1 μm, HEPA filters are recommended in healthcare facilities [2]. Buising et al. [101] investigated the cross-infection risk in a single hospital ward equipped with two portable air cleaners compared to the commonly used ventilation system alone. This study was conducted in one of the patient rooms at the Royal Melbourne Hospital during the Covid-19 outbreak. The ventilation system, which provided 12 ACH air changes

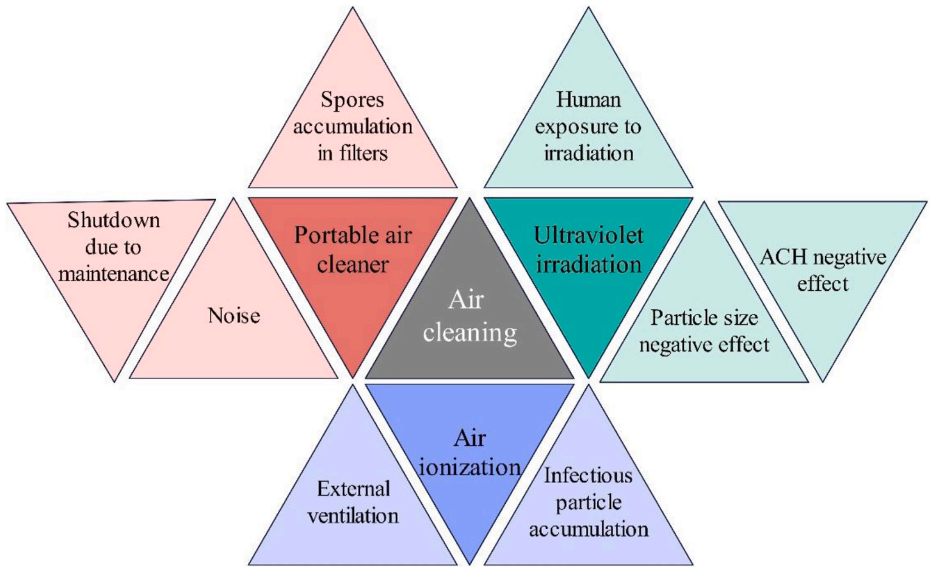

Fig. 10. Drawbacks and limitations of air cleaning approaches used in hospital wards.

per hour, could dilute the aerosols in the patient room within approximately 17 min. After running two portable air cleaners with HEPA filters, the released aerosols in the patient room were diluted after 5.5 min (almost a 67% reduction compared with the case without air cleaners). They also concluded that depending on the location of the return air duct, aerosol dispersal could be boosted beyond the patient room. Therefore, low-cost portable air cleaners could reduce aerosol concentration dramatically. The protection provided by air cleaners was equivalent to more than 30 air exchanges per hour for the staff in the ward common areas. In a similar study by Huang et al. [33], the transmission of Covid-19 in isolation wards of a hospital in Hong Kong was investigated numerically and experimentally. The calculation of accumulated exhaled particles shows the concentration in the upper of the room. Therefore, using ceiling-mounted air cleaners was an effective intervention measure for reducing the cross-infection of Covid-19 in isolation wards. When combined with natural ventilation systems, portable air cleaners can considerably increase the entire system's effectiveness to reduce the spatial concentration of particles and aerosol pathogens in hospital wards [13].

If the ventilation system cannot secure adequate air exchange, recirculated HEPA-filtered air is an alternative. The efficiency of such recirculation systems is expressed as an equivalent ventilation rate to achieve the same dilution rate of pathogens [102]. In large hospital wards where centralized ventilation systems may not adequately provide dilution of the pathogens in the air, portable air purifiers with HEPA filters are an effective measure to mitigate the concentration of virus and bacteria-carrying particles [103]. Phu et al. [104] have designed and evaluated a portable negative pressure hood equipped with HEPA filtration that could be used in hospital wards where patients suffering from transmissible respiratory infections were treated. Their results suggested that enclosing patients in a negative pressure environment supported by HEPA filters decreased the cross-infection risk between patients and provided additional protection for healthcare workers. This also reduced the need for wearing masks by HCWs since the protection provided by HEPA filtration (transmission of 3 out of 10, 000 particles allowed) is much better than N95 masks (transmission of 1 out of 20 particles allowed) [105]. Kim et al. [87] conducted various experiments in a nursing room based on field interviews during the Covid-19 outbreak in Korea. Their experiments visualized particle behavior and the long-distance transmission of aerosol-sized particles. In an unoccupied zone, the virus-like particles remained floating in the room for 15 h, indicating the need to eliminate or flush out these aerosols to prevent possible long-distance exposure in daycare centers. The concentration of such particles dropped by approximately 27% and 86% in weak and strong working modes of an air purifier, respectively, compared to the case without it. Filter bypass in ventilation systems is a source of fungal contamination in ventilated hospital areas. Since the ventilation rates in hospital environments are high, filters accumulate a lot of spores. Therefore, regular maintenance procedures require system shutdown or bypass, which might result in spores entering the ventilation system [79].

Table 1 provides an overview of the investigated infection control interventions in the literature. It is evident that ventilation is the foremost approach to controlling cross-infection in a hospital environment, although other techniques can effectively contribute to lowering the infection rate.

5. Ventilation effect on thermal comfort in hospital wards

Several researchers have devoted their investigations to identifying indoor environmental quality (IEQ) indicators in hospitals [106]. The essential indicators reported by many of these studies are indoor air quality, lighting, thermal comfort, and acoustics. Strict requirements of indoor air quality and the necessity for low contamination levels in hospital environments, especially hospital wards and patient rooms, impose priority on the perceived thermal comfort of the medical staff and patients. Although both physiological and psychological factors affect the perceived thermal comfort of the occupants in hospital wards, the latter is not mainly covered in such studies since it they are not mainly influenced by ventilation. Various studies have evaluated the performance of ventilation strategies to secure clean indoor air in hospital wards; however, their performance concerning the thermal comfort criterion needs to be clarified. Therefore, this section of the article revolves around thermal comfort in hospital wards.

Yau et al. [2] gathered and reviewed the suggested indoor conditions for multiple-bed hospital wards and how the ventilation systems could meet these requirements. A criterion used in the UK allowed 3% of working hours to exceed an operative temperature (OT) of 27 °C. Specifically for hospitals, a range of 18–28 °C for single and general wards with supply-only ventilation was considered where mechanical cooling systems ensure summertime internal temperatures in patient rooms not exceeding 28 °C for more than 0.6% of the occupied hours [107]. Other guidelines regarding overheating criteria are given by Fifield et al. [108]. However, nighttime thermal comfort in hospitals differs from the

Table 1
A summary of the reviewed literature on interventions used for infection control in hospitals.

Year	Reference	Setting	Infection control intervention			
			Ventilation	UVGI	Air ionization	Filtration
2022	[1]	Inpatient room	×			
2006	[4]	General ward	×			
2002	[6]	Entire hospital				
2022	[8]	Isolation ward, ICU	×			×
2021	[9]	General ward	×			
2021	[10]	Outpatient building	×			
2022	[13]	General ward	×			×
2022	[14]	Entire hospital	×			
2015	[27]	Entire hospital	×			×
2008	[29]	Isolation ward	×			×
2021	[30]		×			×
2006	[32]	Entire hospital	×			×
2022	[33]	General ward	×			×
2011	[34]	General ward	×			
2009	[42]	Entire hospital	×			
2012	[44]	General ward	×			
2010	[48]	Entire hospital	×			
2013	[49]	General ward	×			
2017	[50]	Isolation ward	×	×		×
2021	[51]	Nursing room	×	×		×
2022	[53]	Isolation ward	×			
2012	[55]	Patient room	×			
2018	[56]	Patient room	×			
2008	[57]	Isolation room	×			
2014	[58]	Isolation room	×			
2015	[59]	Experimental chamber	×			×
2006	[60]	Experimental chamber	×			
2009	[61]	General ward	×			
2015	[62]		×			
2015	[63]	Isolation room	×			×
2010	[64]	General ward	×			
2020	[65]	General ward	×			×
2020	[66]	Entire hospital	×			
2019	[67]	General ward	×			
2019	[68]	General ward	×			
2019	[69]	Patient room	×			
2020	[71]	General ward	×			
2019	[72]	General ward	×	×		×
2022	[73]	General ward	×			
2014	[77]		×			
2019	[78]	General ward	×			
2015	[79]	Entire hospital	×	×	×	×
2020	[81]		×	×		×
2000	[82]	Patient room	×	×		
2012	[83]	Patient room	×			
2010	[84]	Patient room	×			
2012	[85]	Patient room	×			
2014	[86]	Patient room	×			
2022	[88]	General ward	×			
2021	[89]	General ward	×			
2017	[90]	Patient room	×			
2000	[92]	Entire hospital	×	×		×
2000	[93]	Isolation room	×	×		
2009	[94]	General ward	×	×	×	
2004	[95]	Patient room	×	×		
2021	[96]			×		×
1976	[97]				×	
2007	[98]		×	×	×	×
2004	[99]		×		×	
2004	[100]				×	×
2021	[101]	General ward	×			×
2021	[103]	Entire hospital	×			×
2020	[104]	General ward	×			×
2018	[108]	General ward	×			

requirements proposed by studies of healthy individuals in typical environments. This is due to both the impact of illness/medication on sleep quality and how thermal comfort during sleep is framed (rate of heat loss, sleep patterns, skin temperature, etc.) compared to conventional satisfaction of mind with the thermal environment. Lomas and Giridharan [38] investigated the performance of a UK hospital ward's hybrid ventilation system after refurbishing the entire system to comply with the increased energy use due to climate change. This study aimed at indoor overheating during summertime with a critical overview regarding the thermal comfort standards at the study time. In the monitored nursing stations, occupants had no mechanism for controlling the local temperatures, which led to dissatisfaction. The lack of operable windows and thermostats controlling the radiant ceiling could help reduce the temperature. Fans were suggested to be an effective and low-cost retrofit option to improve the thermal resilience of existing wards.

Derks et al. [109] have also investigated the responses from nurses and the measured indoor thermal condition of a hospital ward. Their results suggested that the existing thermal conditions (temperature between 20 and 25 °C) imposed a slightly warm sensation on the hospital workers. Their suggestion for improving the thermal comfort condition was to divide the hospital ward into smaller separate thermal zones. This would enable different set-points for patients and care professionals. A similar conclusion was drawn from a literature study by Khodakarami and Nasrollahi [18]. They reviewed related studies on thermal comfort in hospital wards and highlighted the need for solutions reconciling various thermal comfort conditions for different occupants.

Khodakarami and Nasrollahi [18], in their review article, mentioned the lack of simultaneous study of a ventilation system regarding its capability to reduce cross-infection risk and maintain thermal comfort requirements for patients and staff. Indoor air velocity of 0.1 m/s was sufficient in patient rooms, which generally corresponds to 6 ACH. However, this could be reduced to 4 ACH in rooms with supplementary heating/cooling systems. Therefore, different thermal zones based on set temperatures and air velocities can meet personalized thermal comfort requirements for each patient. Moreover, different occupancy categories in hospital buildings impose various requirements for thermal comfort. For instance, the perception and satisfaction of patients differ from hospital staff, and this should be noted. Skoog et al. [110] investigated the thermal comfort requirements of the two groups occupying Swedish hospital environments: staff and patients. They collected data during summer and winter to identify the possible seasonal variations. They found that the perception of the indoor air temperature for staff and patients differ more during winter than summer. This was contrary to physical measurements, which suggested similar temperatures in both seasons. Indoor relative humidity of hospital wards was measured in Sweden and Taiwan during winter and summer, and the perceived relative humidity by staff and patients was low [111,112]. High indoor temperature or particle concentration in hospital wards results in low perceived air humidity. This highlights the need for air humidifiers in hospital wards.

6. Conclusions

This systematic review aimed to explore the role of ventilation systems in controlling cross-infection risk in hospital wards and to investigate alternative measures such as air-cleaning devices. The findings from the reviewed articles provide several key messages for consideration in hospital ward design and improving indoor air quality.

- Firstly, maintaining low infection risk in a naturally ventilated hospital ward depends mainly on several design parameters, and natural ventilation alone is not recommended for hospital wards. If the airflow direction between zones deviates from the intended patterns and creates a situation where contamination increases, introducing a slight positive pressure in critical areas can prevent the intrusion of contaminated air.
- Secondly, filter bypass and maintenance are major problems that can lead to air contamination, and increased air exchange rates can decrease cross-infection risk, but defining ventilation effectiveness depends on the travel path and time between the pollutant source and exhaust.
- Thirdly, using air cleaners in combination with centralized ventilation systems and real-time monitoring of the critical parameters using sensors is an effective measure to mitigate the risk of cross-infection in hospital wards by reducing the concentration of aerosols. However, hospital wards equipped with portable air cleaners are susceptible to high levels of background noise, which should be taken into consideration.
- Finally, overheating is a significant problem in hospital wards, which can be resolved through simple solutions such as natural ventilation or fans. Division of multi-bed wards into smaller thermal zones enables different set-point temperatures in each zone according to the patient or healthcare worker's preference.

Given several complexities and challenges, it is crucial to approach ventilation design in healthcare settings with a multidisciplinary and evidence-based perspective. Various situations where the final design of ventilation strategies in a healthcare setting may not fulfill the design goals or represent the optimal solution can be, for instance, complex indoor environmental factors, uncertainty in pathogen behavior, human behavior and compliance with protocols, and insufficient or outdated data. In such cases, suboptimal designs may not adequately address the specific needs of the healthcare settings.

In conclusion, this review highlights the importance of selecting appropriate ventilation systems and alternative measures to ensure good indoor air quality in hospital wards. Implementing the findings discussed in this review can significantly reduce the risk of cross-infection and improve patient outcomes. Therefore, it serves as a foundation for future research and projects to create highly effective ventilation strategies for hospital wards and visualize the transmission routes of airborne pathogens in specific cases. Doing so can pave the way for the development of intelligent monitoring and alert systems that constantly monitor the air quality, temperature, and humidity levels in hospital wards. These systems would be capable of generating real-time alerts whenever these parameters deviate from the optimal range, ensuring timely corrective actions to maintain a healthy environment. Additionally, envisioning future hospital ward designs, it is conceivable that personalized climate control systems will be integrated, catering to the individual needs of patients and healthcare workers. These systems would enable them to personally adjust the temperature and airflow in their immediate surroundings, enhancing their overall comfort and well-being. Such advancements hold great potential in optimizing infection control measures and promoting a safer and more comfortable healthcare environment.

CRediT authorship contribution statement

Behrouz Nourozi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Aneta Wierzbicka:** Writing – review & editing, Conceptualization. **Runming Yao:** Writing – review & editing, Conceptualization. **Sasan Sadrizadeh:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

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

Acknowledgment

This research study was financially supported by Formas, the Swedish research council [Grant No: 2021-01422]. The authors are also grateful for the input from the Building Post Corona research group and [Grant No: 2021-02382].

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