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How Different Ventilation System's Designs Affected Their Applications in Healthcare Facilities: A Comprehensive Review

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ABSTRACT

Effective indoor ventilation systems are crucial in reducing airborne viruses in healthcare facilities which include significant sections such as OR, isolation room and emergency department. Infection control through indoor ventilation system can be done by manipulating the concentration of infectious particles to reduce airborne infections. This review article highlighted different types of indoor ventilation strategies including mechanical ventilation system, natural ventilation system and hybrid ventilation system that have been integrated into different healthcare facilities. The overview, advantages, and limitations of each strategy were discussed in detail. The utilization of mechanical was deemed more suitable for better air quality control, while a vertical (ceiling-mounted) airflow ventilation system was found to promote higher air cleanliness in the desired zone in healthcare facilities. However, many ventilation systems face limitations when attempting to maintain both thermal comfort, indoor air quality, and energy efficiency simultaneously. The findings of this review are useful for the researchers who design appropriate ventilation strategies in healthcare facilities to ensure good indoor air quality meanwhile reduce the risk of disease dissemination.

Keywords:

Ventilation strategies; healthcare facilities; airborne virus infection; COVID-19

1. Introduction

Airborne particles, defined as sub-micron particles, are invisible to human eyes in the atmosphere. Due to their low-density characteristics, they can remain airborne and are highly susceptible to turbulent airflow. Airborne particles are affiliated with particulates, also referred to as atmospheric aerosol particles, atmospheric particulate matter, particulate matter (PM), or suspended particulate matter (SPM) [1]. Particulates are described as microscopic solid or liquid

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particles suspended in the air. A cleanroom employs air filtration to remove them from the air supply, as airborne particulates can harm delicate operations.

Airborne fiber particles have recently been identified as a contaminant of concern in the ambient air [12]. They are directly emitted from synthetic fiber-based materials, or produced by the disintegration of bigger fibers. In 2020, research was conducted in Beijing by collecting fibre particles in the near surface air, building materials and surface deposited dust [3]. The particles were classified as organic fibres comprised of natural organic fibre particles and micro plastic, and inorganic fibres, which were mainly calcium sulphate, metal fibre particles, man-made mineral fibres (MMMFs) and asbestos respectively. It was suggested that the particles were mainly derives from surface and were re-suspended, as the concentration of the particles was about 16.7 x 10^{-3} fibres/ml at 1.5 m above the ground [3]. Additionally, other concentration value recorded was 14.1 x 10^{-3} fibres/ml at 18 m. 80 percent of the airborne fibre particles were identified to be less than 20μm in diameter.

Bacteria-carrying particles (BCPs) are airborne particles associated with viruses or bacteria. Respiratory issues may arise from the production of BCPs during surgical procedures [4]. For instance, in the operating room (OR), most of the BCPs come from the skin scales that fall off from the medical staff which result in surgical site infections (SSI) [5]. BCPs can spread in poorly ventilated and, or congested interior environments where people prefer to spend more time. This is due to the fact that aerosols remain suspended in the air or travel over long-range distances (more than one meter). Most patients in hospitals or healthcare facilities have a weakened immune system, making them vulnerable to infections [6]. Factors that may spark the infections are airborne bacteria, viruses, and mold spores, direct contact with personnel, infected surgical equipment, or medical devices.

A particular highly spread airborne virus, SARS-CoV-2, or mostly referred to as COVID-19, was first outbreak in Wuhan, China. The first official case of COVID-19 was reported by the World Health Organization (WHO) on December 31st, 2019. Since then, COVID-19 has become a global pandemic and has struck almost every country worldwide. As of the end of January 2023, the global tally of cases has surpassed 750 million, with the cumulative death toll reaching 6.8 million according to World Health Organization (WHO). Figure 1 shows a COVID-19 particles.

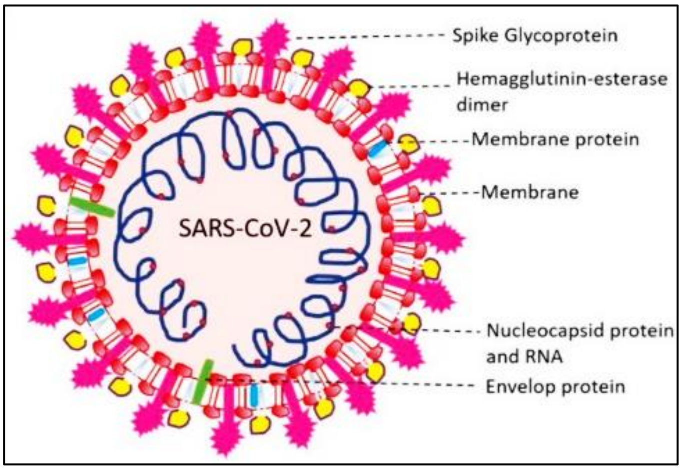

Fig. 1. An electron micrograph of a COVID-19 particle [7]

In the early stage of the pandemic, very limited information was reported on the size distribution of COVID-19. Thus, a detailed study of COVID-19 characteristics was conducted using an air sampling approach in a healthcare workplace [8]. The onsite measurement was performed by simultaneously collecting the air samples in three different size fractions at over 30 hospitals. The analysis also examines the size distribution of SARS-CoV-2 in airborne particles in three distinct size fractions. With concentrations ranging from 3 to 25 particles/m^3, it was found that 65% of the samples tested positive for COVID-19's ribonucleic acid (RNA). The obtained experimental data is tabulated in Table 1.

Out of the 13 positive samples, five samples were placed at the hospital entrance gates, and eight samples were located indoors. Referring to Table 1, positive samples were also identified in other indoor environments, including in ambient-pressure ICUs (two positive samples) and symptomatic patients' rooms with multiple and single beds (six positive samples). Larger particles were found in samples taken from symptomatic patient rooms, which may be related to patients not being forced to wear masks within their rooms at all times. On the other hand, larger particles were not found in samples recorded at ICUs and TQFs probably due to air filtration of high efficiency particulate air (HEPA) filter which can continuously consistently remove infectious SARS-CoV-2 from the air [9].

Table 1
Number of positive samples detected in each location category by size fraction [8]

	≤ 2.5 µm	2.5-10 µm	≥ 10 µm	Total
ICU-ambient pressure	1	1	0	2
ICU-negative pressure	0	0	0	0
Symptomatic patient rooms	0	3	3	6
Asymptomatic patient rooms	0	0	0	0
Nurse's stations	0	0	0	0
Nurse's locker rooms	0	0	0	0
Observation rooms	0	0	0	0
Staff bathrooms	0	0	0	0
Hospital lobby	0	0	0	0
Outside hospital main entrance gates	2	3	0	5
$\mathbf{TQF^a}$-outside main gate	0	0	0	0
TQF-swab exit	0	0	0	0
TQF-swab waiting area	0	0	0	0
TQF-reception waiting area	0	0	0	0
TQF-patient area hallway	0	0	0	0
Total	3	7	3	13

***TQF = Temporary Quarantine Facility*

Symptomatic patient rooms were occupied by patients who were affected by a condition and were showing the related symptoms for that particular condition [8]. In contrast, asymptomatic patient rooms were occupied by patients who were affected with the same condition but did not show any related symptoms. There are two categories of ICUs with ambient pressure and negative pressure. A negative pressure isolation ward is specifically allocated for patients confirmed positive for airborne diseases, aiming to mitigate the risk of pathogen exposure to individuals outside the designated room [10]. It was concluded that fine-size particles (≤ 2.5 µm) were detected in rooms with intubated patients and outside the hospital entrance gates. Coarse virus-laden particles (2.5 to 10 µm) were present in all locations with positive samples, while large particles (≥ 10 µm) with the virus were found in symptomatic patient rooms (Figure 2).

In eliminating airborne pathogenic particles in healthcare facilities, especially in an operating room (OR) or an isolation ward, ventilation systems can be considered the primary solution [11]. One of the most essential aspects of infection control in hospitals is controlling the concentration of infectious particles in patient rooms, which aims to reduce airborne infection. Ventilation strategy is identified as one of the most effective solutions [12].

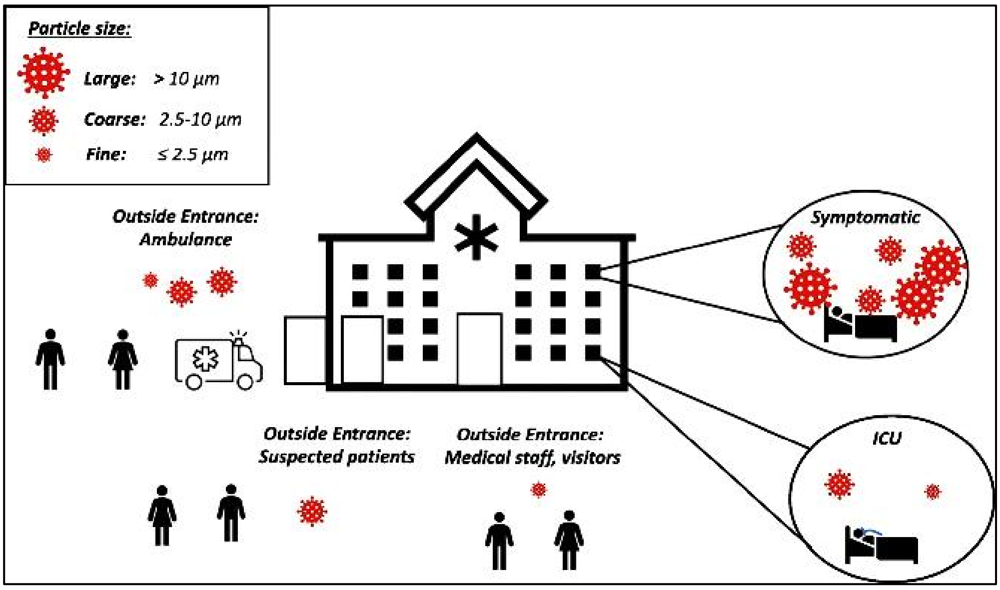

Fig. 2. The size distribution of airborne SARS-CoV-2 in different hospital locations [8]

Healthcare facility ventilation system design is a challenging endeavour that necessitates careful consideration of many different elements. One of the main challenges include the ventilation type and air motion structure. Some of the most common indoor ventilation approaches used in medical facilities are mechanical ventilation and natural ventilation. Furthermore, a few other types of ventilation systems were deemed suitable and were suggested for the indoor environment of healthcare facilities [11]. Those suggestions were turbulent mixing airflow ventilation system, vertical (ceiling) airflow system, horizontal and mobile laminar airflow (LAF) ventilation system, and hybrid ventilation system. Ventilation systems fall into one of two categories when it comes to air motion: mixing or displacement. The goal of mixing ventilation is to provide a consistent, low-concentration of contaminated air that can be removed. Air density variations are used in displacement ventilation to propel the airflow. In actuality, the majority of systems combine the two mechanisms [13].

Moreover, designing an indoor ventilation system for healthcare facilities involves ventilation rates and pressure relationships. Healthcare institutions must maintain precise pressure relationships and ventilation rates in their various regions. For instance, negative pressure should be used in isolation rooms for airborne infections to stop pollutants from spreading to other locations. A minimum of five air changes per hour (ACH) is advised by the CDC to lower the risk of exposure to airborne pollutants [14].

Last but not least, cost and energy considerations. It might be expensive to implement ventilation upgrades in healthcare facilities that are already in place. The choice of breathing techniques is influenced by variables such as rates of community infection and the implementation of other measures. Certain treatments, like opening windows, do not cost anything up front, but they use more energy. Others, such as moving HVAC dampers, do not cost anything up front but need constant upkeep and energy [14].

To the best of authors' knowledge, the review on the types of ventilation system in healthcare facilities are rarely reported. Therefore, this article outlines the advantages and limitations of various indoor ventilation systems that integrated in the healthcare facilities. Also, the application of each ventilation system was also highlighted and critically discussed, for the ease of possible future application by engineers and researchers.

2. Methodology

The present paper retrieved the published articles from the established scientific databases, i.e., Web of Science (WoS) and Scopus. The literature search was done in September 2023, with the criteria that the articles were published in English. Any research providing findings on the definition, benefit, and drawback aspects of indoor ventilation strategies for healthcare facilities were included by combining the keywords “indoor”, “ventilation system” and “healthcare facilities”. From the result through keywords searching, the references were pre-screened through abstract reading to retrieve only related content. Through a systematic review process, final list of reference was obtained being identified as relevant to the scope of this study. Additionally, searches of the retrieved publications' references were done to identify relevant research. The articles selection process is depicted in Figure 3.

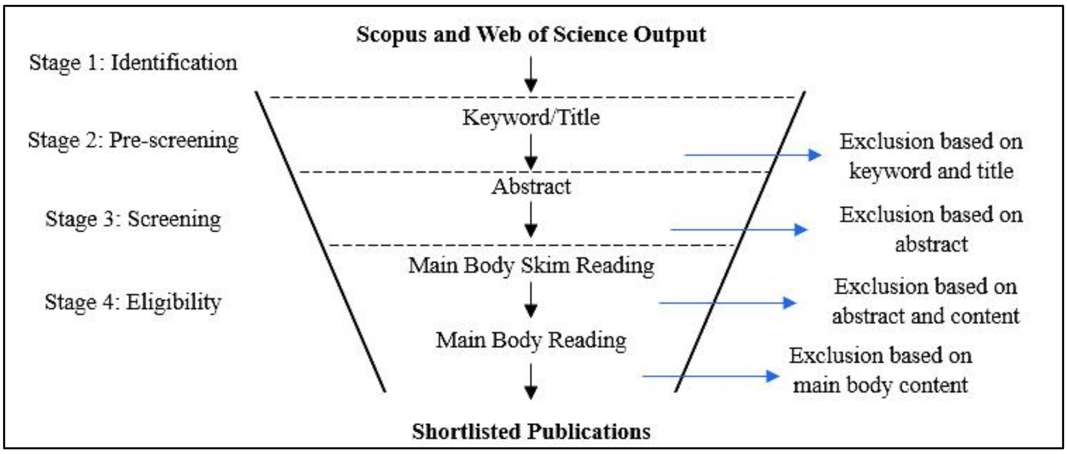

Fig. 3. The applied approach for shortlisting relevant articles

3. Types of Indoor Ventilation Strategies for Healthcare Facilities

To reduce airborne diseases in healthcare facilities, ventilation strategies are essential [15]. The primary function of ventilation systems is to reduce disease transmission through the air by supplying clean air and eliminating stale air from indoor environment [16]. Ventilation systems renew indoor air by bringing in fresh outdoor air through one or more inlets and expelling "used" or stagnant air through exhausts. The quantity and positioning of inlet and outlet can have a notable impact on the effectiveness of ventilation in removing contaminants [17]. Different surgical tools, different room sizes, different personnel counts, varied types of gear utilized, different surgery types and durations, drugs, and patient circumstances can all make such systems complicated. Infection specialists, design engineers, and ventilation experts continue to argue and disagree despite years of study and many papers. There is still little or no consensus on what sort of ventilation systems should be utilized, what clothing style should be worn, and what are the important aspects impacting ventilation performance and its efficiency [11].

3.1 Mechanical Ventilation System

By eliminating and reducing pollutants, such as water vapour, engineers agree on mechanical ventilation's function in maintaining the indoor air quality (IAQ) and controlling moisture in indoor environment. It involves the utilization of mechanical ventilation systems, occupant behaviour, and uncontrolled airflow through the building exterior [18]. Typically measured in litres per second or cubic meters per hour, mechanical ventilation systems move particular volumes of air per unit time. Components such as supply inlets, ducting, fans, air-to-air heat exchangers, and control systems make up these systems.

The efficiency of ventilation systems in healthcare institutions is greatly influenced by architectural design, particularly when it comes to infection control and patient comfort. Healthcare facility design should take into account elements such as overhangs, wind walls, roof design, and internal space distribution to maximize natural ventilation possibilities and avoid drafts [19]. Figure 4 shows and example indoor mechanical ventilation system architectural design. Mechanical ventilation system is supposed to bring in fresh air from the outside, in order to replace the contaminated indoor air that can lead to discomfort, health problems, or even damage to building components. In terms of architectural design specification, indoor mechanical ventilation extract system is as equally as important. Mechanical ventilation extract system's function is to remove air from the building and discharge it to the outside. The mechanical ventilation extract systems are commonly categorized as two types, which are: high flow rate localized extraction (Figure 5) and general extract system (Figure 6).

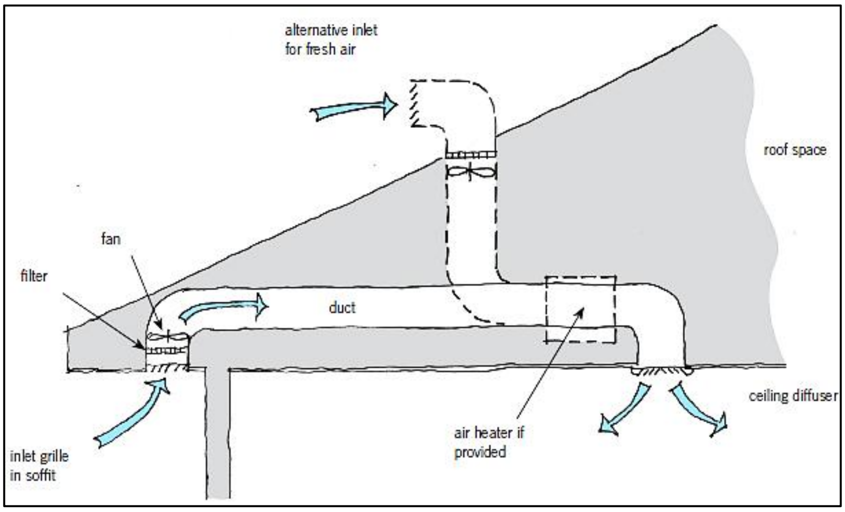

Fig. 4. General architectural design of a mechanical ventilation system supply-only system [18]

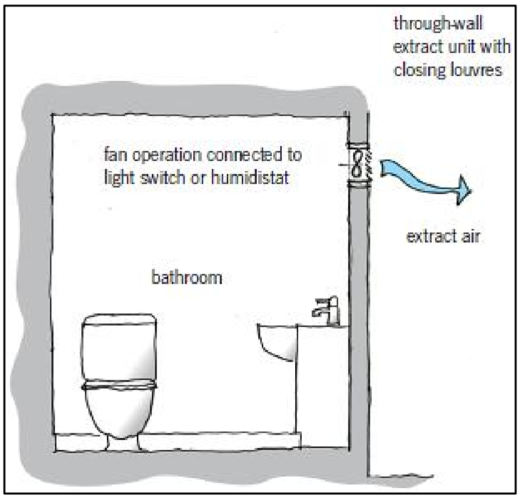

Fig. 5. High flow rate localized mechanical ventilation extract system [18]

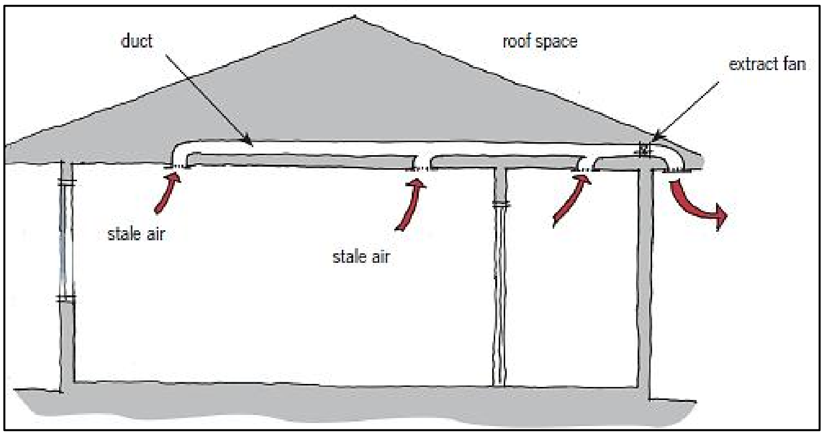

Fig. 6. Indoor mechanical ventilation general extract system [18]

The arrangement of the rooms inside the structure is also crucial, taking into account things like placing "dirty" areas on the leeward side to stop contaminated air from recirculating and making sure that windward sections have big windows to increase the amount of incoming air flow. To further stop warm air from accessing upper floors, stairwells and shafts should be included in the construction of multi-storey structures as exhaust ventilation systems [19]. Achieving safe and efficient natural ventilation in healthcare environments requires the implementation of strategies such as operable window integration, analysis of ventilation regulations, and consideration of passive and active ventilation systems. Social distance and airflow patterns are crucial components of architectural design techniques for infection prevention and control in hospital environments. In order to prevent touch transmission and provide safer conditions for patients and staff, waiting areas and hallways should be designed with sufficient distance to promote social separation [20].

Healthcare facilities, however, have their own standards and regulations in designing the ventilation system compared to other multi-purpose buildings, which cover all areas in healthcare facilities such as reception area, isolation wards and rooms, operating room (OR) and intensive care unit (ICU). As example, isolation rooms in Malaysia include three main lines of defense in infection control, which are contact protocol, segregation of the patients, and ventilation strategy [21]. Additionally, "indoor mechanical ventilation" itself is described as the use of mechanical equipment, such as fans and air conditioners, to move and purify the air in enclosed areas [15]. Figure 7 shows another example of a simple indoor mechanical ventilation system design in a healthcare facility.

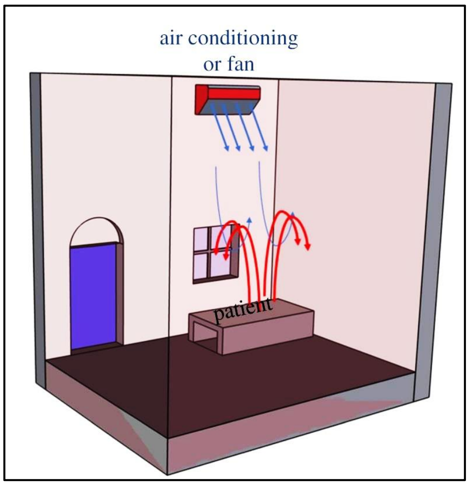

Fig. 7. Small-scale indoor mechanical ventilation system [22]

In crowded indoor events, mechanical indoor ventilation is crucial for comfort and lowering the risk of disease transmission [23]. International organizations such as WHO, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) suggest mechanical ventilation systems as a key method of reducing indoor air pollution. In indoor settings, the concentration of airborne pathogens, such as viruses and bacteria, can be decreased with the aid of mechanical ventilation [15]. The risk of respiratory infections can be decreased, and indoor air quality can be improved with an adequate mechanical ventilation system [24]. Another advantage of mechanical ventilation is that it can assist in regulating indoor temperature and humidity levels, enhancing comfort and lowering the danger of mold formation [25]. Conventional mechanical ventilation systems exhibit greater efficacy in eliminating smaller particles such as viruses (<20 µm) compared to larger elements (D > 40 µm), as larger particles tend to settle on surfaces [26].

Mechanical ventilation has the downside of potentially increasing the danger of indoor air pollution and the transmission of airborne diseases if it is built improperly or poorly maintained [24]. Installation and maintenance costs for indoor mechanical ventilation in a hospital can be excessive, and the system may also consume a lot of energy [15]. Moreover, to stop the transmission of airborne diseases in healthcare institutions, mechanical ventilation systems may need to be turned off during specific procedures.

3.1.1 Turbulent mixing airflow ventilation system

A type of mixing ventilation system known as turbulent mixing airflow ventilation introduces clean air to the surroundings through ceiling or vertical diffusers, where it mixes with the ambient air to produce a turbulent flow [11]. Figure 8 shows the schematic illustration of an indoor mixing ventilation system in an operating room. It is shown that air is supplied through mixed ventilation along the space's perimeter, and it is afterward withdrawn by the perimeter outlets. Changes in temperature and momentum flow from the output diffusers generate the air movement. However, throughout the years, operation theatre (OT), or also known as operating room (OR) has experienced changes in the application of ventilation systems. Figure 9 below shows the trend of ventilation system applied in operating room (OR).

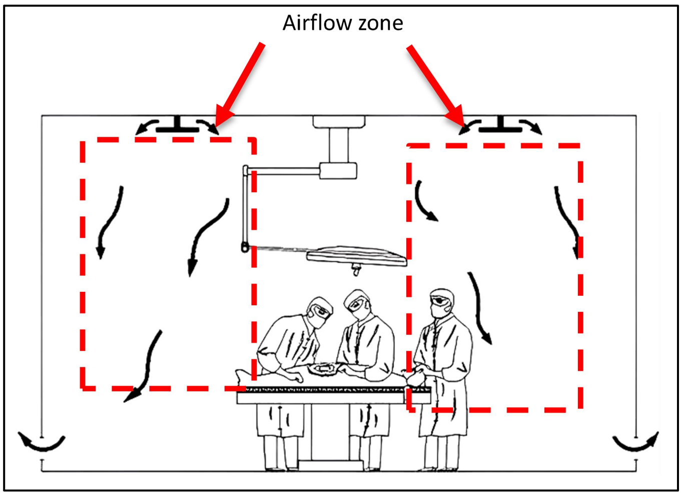

Fig. 8. Illustration of mixing ventilation system practiced in hospital operating room [27]

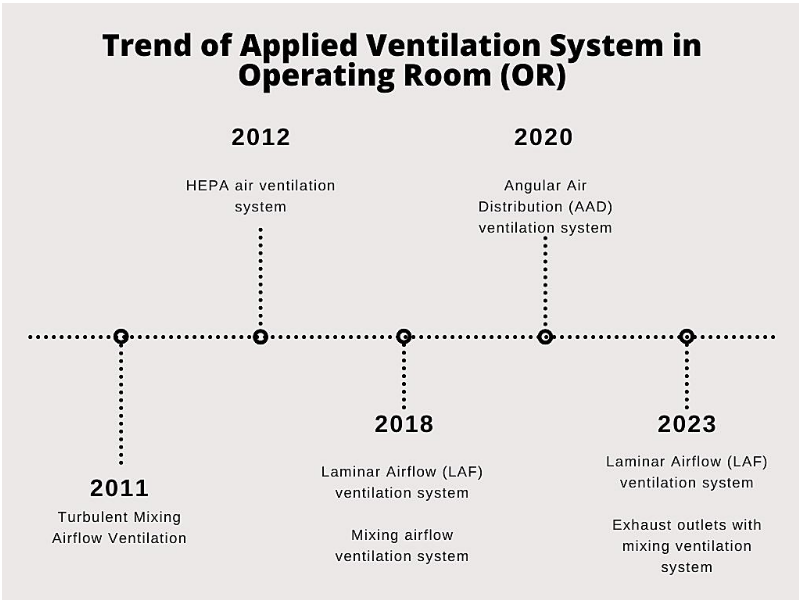

Fig. 9. Trend of applied ventilation system in operating room (OR) throughout the years

From previous example in Figure 8, it is determined that OR used the turbulent mixing airflow system [27]. In 2012, An experiment was conducted in OR with the aim to apply new technology along with the HEPA air system in order to reduce cost, save energy and prevent the prevalence of hospital-acquired infection [28]. This experiment marked the start of changes in applied ventilation system in OR. Moreover, an experiment was conducted in 2018 to compare the effects between laminar airflow (LAF) ventilation and the conventional mixing ventilation in the OR [29]. The results show the positive impact of ventilation system on the air cleanliness in operating theatres with the new proposed ventilation strategy, LAF ventilation system proved to create cleaner air than commonly used mixing system at that time. Since then, LAF ventilation system was adapted to the OR in the most healthcare facilities up until now.

Additionally, a ventilation system named Angular Air Distribution (AAD) was proposed to the applied in 2020 with the aim to study and visualize the airflow distribution in OT [30]. The performance of the AAD system with varying inlet diffuser angle, constant 0.4 m/s inlet velocity and air flow pattern were investigated with the of numerical simulation and experimental set up of prototype OT model. However, the complex design and high costs of the system have yet made AAD unable to completely overtake LAF ventilation system in OR.

In the present, LAF ventilation system are still widely practiced in most of healthcare facilities' operating room (OR). Under ideal situation, the LAF system recommended by ASHRAE 170-2017 transports handled air from the top inlets through a unidirectional airflow diffuser [31]. However, in the future, engineers have identified a new ventilation system that combined the effect of exhaust airflows with mixing ventilation as a better alternative to current LAF [32]. Figure 10 illustrates another installation of a mixing ventilation system in healthcare facilities. Warm air rises to the ceiling as a result of mixed ventilation, and the interior temperature generally stays constant outside of the areas around the ventilation inlets and pressure outlets [28]. This type of ventilation system could be installed in the corridor walkway or waiting zone in the hospital.

There are a few benefits associated with turbulent mixing airflow ventilation systems. In healthcare facilities, turbulent mixing airflow ventilation can reduce airborne diseases [15]. A ventilation system utilizing turbulent mixing airflow is simple to program, numerically reliable, and roughly accurate [27]. One of the most widely used principles for ventilation system design in healthcare institutions is mixing ventilation. However, a ventilation system with turbulent mixing flows can produce a turbulent flow that might not be appropriate for some healthcare facilities [11]. Overall, turbulent mixing airflow ventilation is a prominent ventilation technology that can reduce the risk of respiratory diseases in medical facilities. There are also restrictions on its effectiveness, and not all medical facilities may be suitable to utilize it.

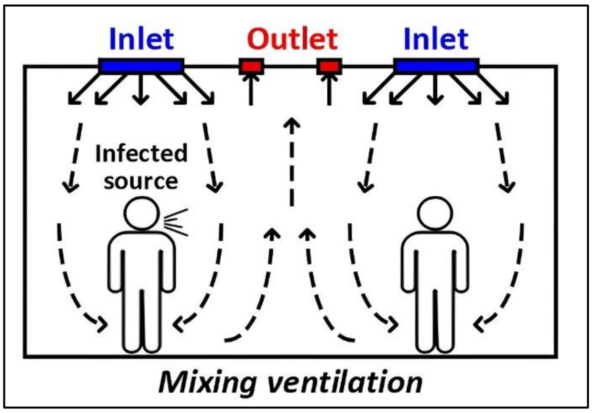

Fig. 10. Mixing ventilation system that is possible to be installed in the hospital's corridor walkway or waiting zone [33]

3.1.2 Vertical (ceiling) airflow ventilation system

An indoor ventilation system known as vertical (ceiling) airflow ventilation draws air from the floor and supplies it through grilles in the ceiling [34]. By providing a substantial volume of air from the ceiling to the floor at a comparatively slow speed (0.2-0.3m/s), vertical (ceiling) ventilation systems allow the "washing" effect to remove airborne pathogens from the surgical zone to the exhaust grill [11]. Moreover, various other studies also stated the values between 0.35m/s to 0.55m/s as acceptable airflow speeds from the ceiling to the floor [35-37]. The setup of vertical airflow ventilation is shown in Figure 11.

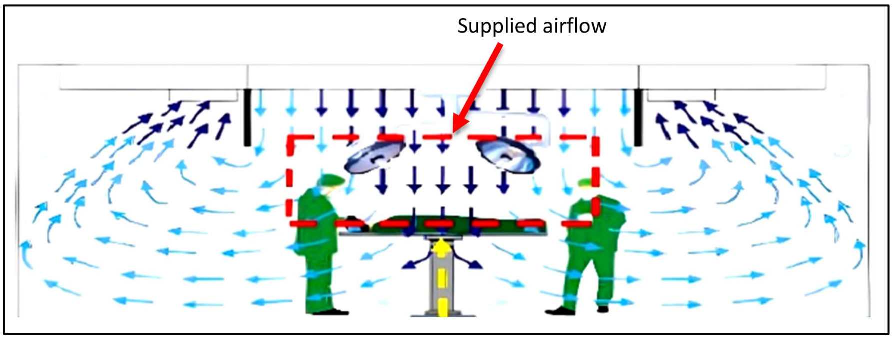

Fig. 11. Airflow distribution of a vertical (ceiling) airflow ventilation system installed in an OR [11]

Installing this type of ventilation system in a healthcare facility can reduce the risk of patients contracting airborne infections. This occurrence is due to the supplied clean air removing the airborne contaminants from the surgical zone, and the airborne contaminants are subsequently being removed via exhaust grilles [15]. The vertical (ceiling) airflow ventilation system also promotes better indoor air quality (IAQ) in hospital buildings by introducing a sufficient air change rate [27]. A past study also disclosed that the vertical (ceiling) airflow ventilation system helps reduce indoor odors in healthcare facilities [34].

Some of the drawbacks of installing the vertical (ceiling) airflow ventilation system in a hospital building is the cost, as the system’s installation and regular maintenance can be very expensive. Furthermore, with this method of ventilation, it can be challenging to generate uniform airflow throughout the location, which might result in areas in which the air is stagnant [34]. Additionally, in healthcare institutions where patients need a peaceful environment, the potential for noise from this technology may be an issue.

3.1.3 Horizontal and mobile laminar airflow (LAF) ventilation system

To reduce the risk of airborne infections in healthcare facilities, two different ventilation systems can be used: horizontal laminar airflow (LAF) ventilation and mobile laminar airflow (LAF) ventilation [15]. Clean air is delivered by a diffuser at the head of the patient's bed, travels horizontally across the patient, and exits through a low-level exhaust during horizontal LAF ventilation. On the other hand, using portable high-efficiency particulate air (HEPA)-filtered equipment, a mobile LAF ventilation system surrounds the patient with a clean air environment. Figure 12 shows the application of mobile LAF units in a hospital.

By creating a clean air environment surrounding the patient, horizontal LAF ventilation can help lower the risk of airborne infection transmission in healthcare settings. However, because it can be costly to install and operate, horizontal LAF ventilation may not be appropriate several healthcare environments. Meanwhile, a wider range of healthcare facilities can adopt a mobile LAF ventilation system, which is often more affordable than the horizontal LAF ventilation system. In reducing the likelihood of transmitting airborne infections, a mobile LAF ventilation system is unlikely to be as effective as a horizontal LAF ventilation system and might not be appropriate in all patient care situations.

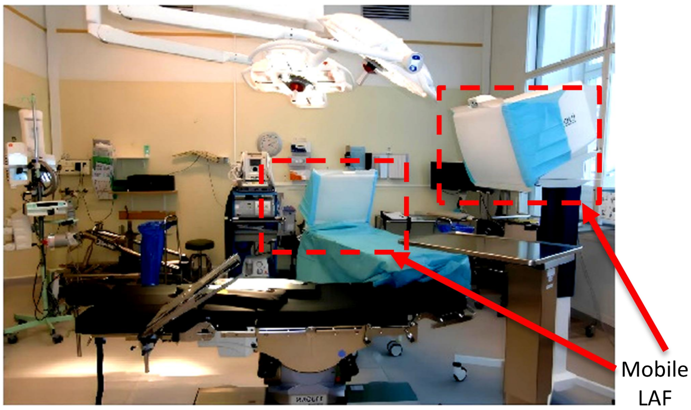

Fig. 12. Integrating the mobile LAF units in an OR in South Hospital (Södersjukhuset), Stockholm [38]

It is important to note that researchers remain divided on the beneficial effects of the LAF ventilation system in lowering the risk of airborne diseases spread in healthcare facilities [11, 39, 40]. According to some research, there is not a significant distinction in the rate of surgical site infections between ORs using LAF ventilation and those with traditional turbulent ventilation [40]. This claim was further proven by meta-analyses conducted by Ouyang *et al.,* [41]. However, others have discovered that LAF ventilation can be useful in reducing the risk of airborne disease transmission [11, 39].

3.2 Natural Ventilation System

The process of delivering and removing air from a room inside without the use of mechanical equipment is known as natural ventilation [19]. Outdoor air is forced through purpose – designed buildings in the building envelope by natural forces, such as winds and thermal buoyancy force, resulting from differences in indoor and outdoor air densities. Windows, doors, solar chimneys, wind towers, and trickling ventilators are examples of purpose-built buildings. Climate, building design, and human behavior all affect a building's natural ventilation system. The natural ventilation system also varies in designs and arrangements, as shown in Figure 13.

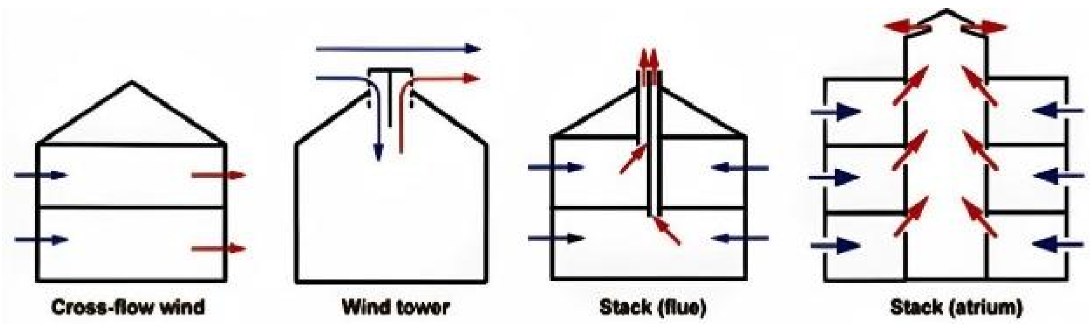

Fig. 13. Different indoor natural ventilation system designs for healthcare buildings [19]

Suitable ventilation rates can be provided in airborne prevention rooms or well-built naturally ventilated hospitals. With a simple system, natural ventilation can deliver a high air-change rate at a low cost [19]. Modern natural ventilation systems that are properly installed and maintained can substantially exceed the minimum ventilation requirements in buildings by achieving very high air-change rates. Another advantage of natural ventilation is that it can lower the possibility of airborne infection in hospitals and isolation rooms [42]. In addition to using regular isolation rooms during infectious outbreaks, natural ventilation can also be useful for building temporary isolation rooms.

However, natural ventilation has significant difficulties, primarily in metropolitan areas, due to outdoor air pollution [7]. Moreover, the natural ventilation system's measured airflow pattern might not be sufficient, and the needed air change rate might not be met [42]. Its infrequent application in clinical and commercial settings may be attributed to certain drawbacks, including irregular airflow, particle concentration, fluctuating ventilation rates, and diminished thermal comfort, especially in extreme climates [43]. The naturally ventilated sections of the hospital exhibited the highest concentration of bioaerosols, approximately ten times greater than the maximum concentration observed in spaces with mechanical ventilation [44].

In appropriate hospital wards, natural ventilation has been recommended for infection management [42]. In locations with limited resources, multiple healthcare facilities utilize natural ventilation [45]. According to a study, implementing small, inexpensive modifications to existing infrastructure can significantly enhance natural ventilation in healthcare facilities [19]. Numerous researches and works have been produced involving natural ventilation in hospitals or other types of healthcare facilities, with one of them being published by Zhou *et al.,* [46] in 2021. The experiment was performed in four hospitals with applied natural ventilation and disinfection practices in Wuhan, China. Another published study that utilized natural ventilation was conducted in Lima, Peru [47]. Experiments were performed to improve natural ventilation and reduce modelled tuberculosis (TB) transmission risk.

Natural ventilation is commonly used in general wards in hospitals [45]. It is a low-cost alternative, especially promoted in the UK and widely used in other tropical nations [27]. Apart from the general wards, other areas in a healthcare facility that employ natural ventilation include the waiting rooms, consulting rooms, non-clinical areas, and single-bed wards [19, 47, 48]. As natural ventilation is not restricted by cost to just high–risk areas, it can be applied to various areas [49].

Natural ventilation is one type of ventilation system that is utilized in hospitals in Malaysia [27]. With ventilation rates of 18 and 24 ACH (air changes per hour), natural ventilation was effective in lowering the chance of airborne illness cross-infection. To achieve the necessary ventilation rates, prevent potential heat discomfort, and stop the spread of infections, natural ventilation systems must be carefully planned and built. Poor construction quality and inefficient air conditioning system performance can result in problems like mold contamination, as experienced by a 700-bed hospital in Malaysia that failed to replicate the same ventilation system used in Hong Kong [27].

Natural ventilation techniques have also been investigated by hospitals in other tropical nations. Several design elements, such as space proportions, building envelope design, and ventilation system design, have an influence on indoor air quality, according to a study of the literature on naturally ventilated public hospital wards in tropical regions. When it comes to interior air quality, hospitals with advanced mechanical ventilation systems often do better than those that only use natural ventilation [50]. But according to a Malaysian public hospital ward's thermal comfort study, natural ventilation is insufficient to keep interior temperatures tolerable [51]. The naturally ventilated ward's inhabitants reported warm to hot temperatures, according to simulations, measurements, and questionnaires. Understanding the local climate and the interior thermal environment is crucial for the design of efficient natural ventilation systems in healthcare facilities [52].

3.3 Hybrid Ventilation System

Mechanical and natural forces are merged in a two-mode system in a hybrid ventilation system, and the operation mode changes depending on the season and outside environment [19]. This ventilation system makes use of the environment at any given time. Unlike the natural ventilation, the use of MMV (Mixed-Mode Ventilation) or a combination of natural and mechanical ventilation devices may be regarded as a more dependable approach for maintaining consistent airflow, reducing contamination, refreshing indoor air, and ensuring thermal comfort, especially when implemented alongside a control strategy [53, 54]. Figure 14 shows the schematic concept of an indoor hybrid ventilation system.

By supplying a blend of clean outdoor air and filtered air from mechanical systems, the hybrid ventilation system can enhance the IAQ. Moreover, through the use of natural ventilation. In comparison to fully mechanical ventilation-hybrid systems can use less energy when the outside circumstances are good. Hybrid ventilation improves indoor temperature and humidity control of the medical facilities, making the environment more comfortable for the medical staff and also the patients. Additionally, a hybrid ventilation system's ability to save energy may enable medical institutions to operate at reduced costs.

However, several drawbacks come from the hybrid ventilation system. One of the negative aspects of the respective ventilation strategy is its design complexity. A hybrid ventilation system needs to be carefully planned, considering building layout, climate, and control systems. The initial design and installation expenses could rise due to these complexities. Hybrid ventilation systems may need regular maintenance and monitoring to ensure peak performance and avoid problems like air leakage or broken mechanical parts. Thirdly, in cases of extreme weather, the hybrid ventilation system has limited control. Hybrid ventilation systems may not be able to adequately provide indoor comfort in certain extreme weather situations, such as extremely hot or cold temperatures, without relying heavily on mechanical air circulation. Furthermore, natural and hybrid ventilation system might not be adequate strategies to meet clinical environment standards for ventilation.

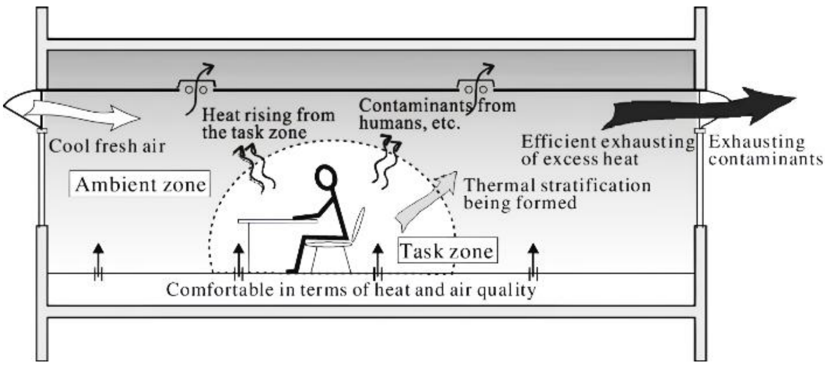

Fig. 14. Concept of natural and mechanical hybrid ventilation [45]

4. Discussion

To ensure patients' and staff's safety and well-being, healthcare facilities are complex buildings that require careful planning and design. The OR, isolation room, and emergency department are only just a few of the most significant sections of a healthcare facility, each having specific needs [55]. The hospital's OR, where surgeries take place, is a crucial area. To reduce the danger of infection, traffic and activity in the surrounding area must be strictly regulated. Specific rooms should be set aside for performing surgical procedures, processing instruments, and other goods. The reception area should be the most polluted section of the operating unit, followed by the ORs.

To prevent and control the spread of diseases, adequate ventilation and filtration systems are also required [56].

Next, another important part of a healthcare facility is the isolation wards or isolation rooms. An isolation ward is created to control the airflow in the room. To ensure the cross-infection of other people within a healthcare facility is highly unlikely, the number of airborne infectious particles is reduced in isolation wards. Generally, this feat is achieved by maintaining different air pressures between adjacent areas, diluting infectious particles with larger air volumes, controlling the quantity and quality of intake or exhaust air, and designing airflow patterns for specific clinical procedures.

Specifically, isolation rooms are classified into four categories: Class S, Class P, Class N, and Class Q, with both Class N and Class Q, respectively, being the negative pressure isolation rooms [57]. Class N rooms' purpose is to protect outsiders from any infectious airborne particles from the inside, while Class Q rooms are the type of negative pressure rooms with additional infection control measures, such as anteroom. Anterooms are commonly utilized for quarantine purposes. In comparison, Class N rooms are typically not equipped with anteroom feature. The recommended minimum differential pressure between the isolation room and adjacent spaces should be 15 Pa if the room is not provided with an anteroom [58]. Table 2 lists the recommended pressure gradients for each class of isolation room.

Table 2
Recommended pressure gradients for different classes of isolation room [58]

Type of pressurization	Isolation room
Class S	NA
Class N	-30 Pa
Class P	+30 Pa
Class Q	+15 Pa

From Table 2, Class S, which refers to the standard pressure isolation, has no recommended pressure gradients. This is because this class is not equipped with an anteroom. For the negative pressure isolation room (Class N), the recommended pressure gradient value is -30 Pa, while for Class P, the positive pressure room is recommended +30 Pa pressure gradient between the isolation room and its adjacent space. Additionally, for Class Q, which means quarantine isolation room or Class P with negative pressure anteroom, the recommended pressure gradient is +15 Pa.

Negative pressure rooms are so termed because the air pressure inside the room is lower than the air pressure outside. This implies that, possibly polluted air, or other hazardous particles from the room will not escape into non-contaminated areas as the door is opened. On the other hand, non-contaminated filtered air will supply into the negative pressure room. Contaminated air is sucked out of the room by an exhaust system. The process involves filtering the clean air before it flows outside and away from the healthcare facility.

Positive pressure isolation room (Class P), also known as "protective environment room (PE room)" or "protective isolation units", is used to isolate immune-compromised patients [58]. An example of immune-compromised patients are oncology and some transplant patients. Contrary to Class N (negative pressure), positive pressure isolation room protects its patients from potentially dangerous particles outside the room [57].

A positive pressure isolation room also does not require an anteroom, compared to a negative pressure room, but does require a self-closing door, an ensuite, and a clinical hand wash basin with "hands free" operation. The positive pressure in the isolation room is supplied by an air ventilation system, which provides positive pressure greater than the surrounding environment [59]. This approach is used to avoid pathogen transfer from outside surroundings to individuals with severely impaired immune systems.

Apart from OR and isolation rooms, emergency rooms are also regarded as important areas in a healthcare facility. The purpose of the emergency department is to stabilize the patient, treat them, and move them to the proper area of the hospital for additional care. Patients with severe injuries or diseases are given rapid medical attention in the emergency room. Clear signage and sufficient space are needed for visiting families to have easy access. Utilizing single-bed rooms within healthcare facilities can improve patient safety and foster healing environments [60].

Qi *et al.,* [61] used an actual negative pressure isolation ward in Beijing to study the poor air distribution and ventilation strategy which contributed to the bad indoor air quality situation. The outcome revealed that the ventilation system is adequate. When the patient breathes quietly, the supply air distributor is put in one side of the ceiling opposite the patient's bed-head. In 2021, Weng and Kau [62] proposed a full-outer-air-intake natural air-conditioning system with the aim to greatly improve the air-exchange rate in negative pressure isolation wards. Miller *et al.,* [63] conducted a study to increase hospital surge capacity by setting up temporary negative pressure isolation wards a fully functioning hospital. By adjusting the ventilation system and continuously measured differential pressure at 22 different locations, results showed that the pressure on the test ward relative to the main hospital was -29 Pa on average.

Different ventilation strategies were applied for every section of a healthcare facility to accommodate their purposes. For example, in their publication, Tysiąc-Miśta *et al.,* [64] performed an air disinfection procedure in an OR by using a turbulent mixing airflow ventilation system. Xu *et al.,* [65] also applied turbulent mixing airflow ventilation in their experiment. Table 3 summarises different types of indoor ventilation systems used by scholars in various healthcare facility areas.

Table 3
Types of indoor ventilation systems for different healthcare facility area

Type of indoor	Types of ventilation	Details	Reference
OR	Turbulent mixing airflow ventilation	Room dimension: 8.60 m x 7.50 m x 3.20 m Airflow rate: 2 m^3/s Inlet air velocity: 1.4 m/s Inlet air temperature: 24.85 °C Inlet turbulent intensity: Not provided Room pressure: 5 Pa	[64]
	Vertical (ceiling) airflow ventilation	Room dimension: 6.00 m × 5.50 m × 3.00 m Airflow rate: Not provided Inlet air velocity: 0.43 m/s Inlet air temperature: 19 °C Inlet turbulent intensity: 5 % Room pressure: Not provided	[66]
		Room dimension: 6.00 m × 5.50 m × 3.00 m Airflow rate: Not provided Inlet air velocity: Range from 0.1 m/s to 0.6 m/s (6 case studies) Inlet air temperature: 19 °C Inlet turbulent intensity: 5 % Room pressure: Positive pressure (Assumption)	[67]
		Room dimension: 6.00 m × 5.50 m × 3.00 m Airflow rate: 1.86 m^3/s (Present), 2.45 m^3/s (SLD1),	[68]

		6.85 m^3/s (SLD2) Inlet air velocity: 0.45 m/s Inlet air temperature: 19 °C Inlet turbulent intensity: 5 % Room pressure: Not provided	
		Room dimension: 6.00 m × 6.90 m × 3.00 m Airflow rate: Not provided Inlet air velocity: 0.43 m/s Inlet air temperature: 19 °C Inlet turbulent intensity: 5 % Room pressure: Not provided	[69]
		Room dimension: Not provided Airflow rate: Not provided Inlet air velocity: 0.32 m/s Inlet air temperature: 18.85 °C Inlet turbulent intensity: 20 % Room pressure: Not provided	[70]
		Room dimension: Volume = 64.3 m^3 Airflow rate: 0.35 m^3/s Inlet air velocity: Not provided Inlet air temperature: Range from 18.3 °C to 19.5ºC Inlet turbulent intensity: Not provided Room pressure: Not provided	[71]
		Room dimension: Volume = 105 m^3 Airflow rate: Not provided Inlet air velocity: Not provided Inlet air temperature: Not provided Inlet turbulent intensity: Not provided Room pressure: Not provided	[72]

Table 3. Continued

Types of indoor ventilation systems for different healthcare facility area

Type of indoor	Types of ventilation	Details	Reference
Isolation Room	Turbulent mixing airflow ventilation	Room dimension: Not provided Airflow rate: 160 L/s Inlet air velocity: 0.1 m/s – 0.3 m/s Inlet air temperature: 10 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[65]
		Room dimension: 8.00 m x 5.30 m x 2.90 m Airflow rate: 0.35 m^3/s Inlet air velocity: Not provided Inlet air temperature: Not provided Inlet turbulent intensity: Not provided Room pressure: 5 Pa	[73]
	Vertical (ceiling) airflow ventilation	Room dimension: 4.00 m x 2.50 m x 2.65 m Airflow rate: Not provided Inlet air velocity: 0.75 m/s Inlet air temperature: 19 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[74]

		Room dimension: 6.00 m x 4.20 m x 3.00 m Airflow rate: Not provided Inlet air velocity: 0.77 m/s Inlet air temperature: Not provided Inlet turbulent intensity: 10 % Room pressure: Not provided	[75]
		Room dimension: 6.00 m x 4.20 m x 3.00 m Airflow rate: Not provided Inlet air velocity: 0.77 m/s Inlet air temperature: 16.55 °C Inlet turbulent intensity: 10 % Room pressure: Not provided	[76]
	Horizontal laminar airflow ventilation system	Room dimension: 4.00 m x 4.25 m x 2.75 m Airflow rate: Not provided Inlet air velocity: 0.3 m/s Inlet air temperature: 19 °C Inlet turbulent intensity: 10 % Room pressure: Not provided	[77]
		Room dimension: 6.00 m x 3.00 m x 3.00 m Airflow rate: Not provided Inlet air velocity: 1.0, 3.9, 5.5 m/s Inlet air temperature: 27 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[78]
Emergency Room	Mechanical ventilation	Room dimension: 3.65 m x 4.25 m x 2.75 m Airflow rate: 11,500 m^3/h Inlet air velocity: 2.97 m/s Inlet air temperature: 22 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[79]

Table 3. Continued
Types of indoor ventilation systems for different healthcare facility area

Type of indoor	Types of ventilation	Details	Reference
Intensive Care Unit (ICU)	Vertical (ceiling) airflow ventilation	Room dimension: 7.00 m x 6.30 m x 2.50 m Airflow rate: Not provided Inlet air velocity: 0.57 m/s Inlet air temperature: 17 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[80]
		Room dimension: 9.14 m x 6.10 m x 3.6 m Airflow rate: Not provided Inlet air velocity: 0.3 m/s Inlet air temperature: 22 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[81]
	Horizontal laminar airflow ventilation system	Room dimension: 9.14 m x 6.10 m x 3.6 m Airflow rate: Not provided Inlet air velocity: 0.3 m/s Inlet air temperature: 22 °C Inlet turbulent intensity: Not provided Room pressure: Not provided	[81]

Based on the findings of scholars listed in Table 3, it is shown that vertical (ceiling) airflow ventilation is the most common ventilation system being applied at healthcare facilities especially at isolation room or intensive care unit. It is probably due to its effectiveness on removing contaminated airborne particles hence reducing the risk of infections to the patients who need better healthcare protection.

5. Limitations of the Existing Literature

In crowded indoor events, indoor ventilation systems are crucial for maintaining indoor environmental quality and lowering the risk of disease transmission [23]. Nevertheless, most ventilation systems have constraints when simultaneously preserving thermal comfort, indoor environment quality, and energy balance [7]. Listed as follows are some of the limitations of literature reviews about different types of indoor ventilation systems for healthcare facilities. Firstly, the lack of standardization. Lack of consistency in ventilation system design, management, and maintenance may result in unpredictable indoor air quality and cross-infection issues [82]. Secondly, the complex aspects of diverse ventilation strategies. Indoor ventilation systems are intricate and involve many different elements, including temperature regulation, air filtering, and circulation. Therefore, comparing the efficiency of multiple ventilation systems in reducing the risk of disease transmission might be difficult [7]. Last but not least is the limited applicability aspect when comparing different types of indoor ventilation systems for healthcare facilities. Some research has focused on specific kinds of ventilation systems or particular indoor locations, limiting their findings' application to other settings [83].

6. Conclusions

Overall, the literature evaluation indicates that indoor ventilation systems are essential for ensuring good indoor air quality, minimizing the risk of disease transmission, and supplying thermal comfort in medical facilities. To maintain the safety and well-being of patients and healthcare professionals, it is crucial to consider the design, interior environment, and engineering of ventilation systems in healthcare facilities. The example given would be the systematic review performed by Li *et al.,* [23, 84], as they found that in a variety of indoor environments, including hospitals, offices, classrooms, and homes, natural ventilation or a combination of mechanical and natural ventilation was very successful in reducing the airborne transmission of COVID-19. International organizations, including WHO, ASHRAE, and REHVA, have suggested increased ventilation rates at respective workplaces to ensure a low level of airborne viruses and bacteria in healthcare facilities. An in-depth study on the appropriate ventilation system is required, whether hybrid ventilation, mechanical ventilation, or natural ventilation shall be used in different healthcare to ensure human safety [84].

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