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Review

Viral infection transmission and indoor air quality: A systematic review

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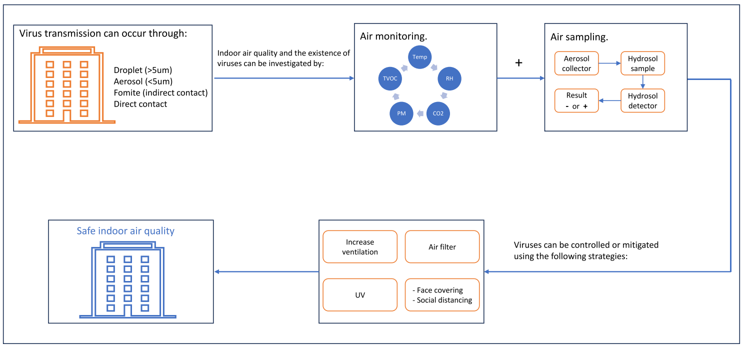
HIGHLIGHTS

- Viral transmission can occur through aerosols, droplets, fomite, and direct contact.
- To investigate viral transmission, air sampling and air monitoring are used to determine whether the virus exists in the sampling area and to assess if the air quality is good and safe for occupants.
- The most important parameters affecting indoor air quality are temperature, relative humidity, particulate matter, and CO2.
- many strategies can be used to control and limit infection risk. Some of them are non-engineering strategies such as face covering and social distancing. In contrast, some control strategies include engineering measures like ventilation, air filtration, and ultraviolet radiation.

GRAPHICAL ABSTRACT



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ABSTRACT

Respiratory disease transmission in indoor environments presents persistent challenges for health authorities, as exemplified by the recent COVID-19 pandemic. This underscores the urgent necessity to investigate the dynamics of viral infection transmission within indoor environments. This systematic review delves into the methodologies of respiratory infection transmission in indoor settings and explores how the quality of indoor air (IAQ) can be controlled to alleviate this risk while considering the imperative of sustainability. Among the 2722 articles reviewed, 178 were retained based on their focus on respiratory viral infection transmission and IAQ. Fifty eight articles delved into SARS-CoV-2 transmission, 21 papers evaluated IAQ in contexts of other pandemics, 53 papers assessed IAQ during the SARS-CoV-2 pandemic, and 46 papers examined control strategies to mitigate infectious transmission. Furthermore, of the 46 papers investigating control strategies, only nine considered energy consumption. These findings highlight clear gaps in current research, such as analyzing indoor air and surface samples for specific indoor environments, oversight of indoor and outdoor parameters (e.g., temperature, relative humidity (RH), and building orientation), neglect of occupancy schedules, and the absence of considerations for energy consumption while enhancing IAQ. This study distinctly identifies the indoor environmental conditions conducive to the thriving of each respiratory virus, offering IAQ trade-offs to mitigate the risk of dominant viruses at any given time. This study argues that future research should involve digital twins in conjunction with

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machine learning (ML) techniques. This approach aims to enhance IAQ by analyzing the transmission patterns of various respiratory viruses while considering energy consumption.

1. Introduction

Individuals spend approximately 90 % of their time inside buildings, making indoor air quality (IAQ) a crucial factor influencing health, comfort, and productivity (Megahed and Ghoneim, 2021). This paper addresses the multifaceted aspects of IAQ, considering the concentration of air pollutants and the need for precautions against airborne viruses. Precautions such as reducing shared space capacity, increasing ventilation rates, employing natural ventilation, avoiding air recirculation, and minimizing direct airflow exposure are important (Qian and Zheng, 2018). Additionally, the adoption of lockdowns and face masks have been identified as significant in reducing infection numbers (Zhang et al., 2020). While these precautions effectively prevent the spread of infections, various parameters such as temperature, relative humidity (RH), and evaporation can influence SARS-CoV-2 transmissions (Yao et al., 2020). To enhance IAQ and prevent airborne infections, basic strategies, including adequate ventilation, air filtration, humidity regulation, and temperature control, have been recommended by (Sloan Brittain et al., 2021). The importance of ventilation in controlling indoor airborne transmission has been emphasized in some studies (Y. Li et al., 2020; H. Li et al., 2020; Setti et al., 2020). It is crucial to consider room air patterns and ventilation airflow rates to optimize indoor air distribution (Pantelic and Tham, 2013; Li et al., 2007). During pandemics recommendations from international organizations, such as ASHRAE, REHVA, and CAR, advise increasing outdoor air ventilation during pandemics (Pang et al., 2021). However, managing ventilation carefully is essential to avoid potential contamination or infection (Tham, 2016). In the context of contamination risk, incoming outdoor air can be filtered using appropriately sized high-efficiency particulate air (HEPA) filters to remove viral particles and pollutants known to enhance COVID-19 transmission (Y. Li et al., 2020; H. Li et al., 2020). Moreover, monitoring co_2 levels for infection risk assessment, considering respiratory activities as a primary source, is essential, as proposed by Pang et al. (2021). The examination of how SARS-CoV-2 spreads in indoor environments has been a focal point of IAQ studies, focusing on airborne transmission pathways, as (Azuma et al., 2020) have discussed. The virus can stay viable on surfaces for days and in aerosols for hours (Van Doremalen et al., 2020). Understanding these transmission routes is crucial for implementing effective preventive measures. The integration of digitalisation technologies, such as Digital Twins, and the widespread use of IoT devices contribute to the management of indoor environments and the resolution of IAQ concerns (Boschert and Rosen, 2016; Tao et al., 2018; Gandomi and Haider, 2015; Feroz et al., 2021). These technologies offer virtual planning, real-time monitoring, and predictive maintenance capabilities. Additionally, the analysis of unstructured Big data generated by IoT devices, when integrated with AI techniques like machine learning algorithms, offers valuable insights for informed decision-making, a concept explored by (Gandomi and Haider, 2015; Feroz et al., 2021). In exploring aerosols and airborne transmission, various methods, including experimental and computational fluid dynamics (CFD) analyses, have been used to investigate aerosols and airborne transmission (Ai and Melikov, 2018; Shen et al., 2020). CFD serves as a robust tool to analyze real-world fluid flow problems, and models such as the Wells-Railey equation have been used to predict the risk of airborne infections (Dai and Zhao, 2020).

This paper seeks to explore three primary objectives:

(a) understanding the dynamics of respiratory disease transmission in indoor environments, particularly in relation to the transmission of COVID-19; (b) identifying effective measures for assessing Indoor Air Quality (IAQ); and (c) proposing strategies to enhance IAQ, thereby reducing the transmission of respiratory diseases such as COVID-19. The overarching goal is to ensure the healthy air quality of occupants within enclosed spaces while simultaneously addressing energy consumption considerations. To achieve these objectives, the following research questions are formulated:

State-of-the-art Interventions
- What are the current state-of-the-art interventions employed to mitigate the risk of indoor respiratory infections, with a specific focus on SARS-CoV-2, while concurrently improving IAQ?

Gaps and Limitations
- What are the existing gaps and limitations in current research endeavours aimed at designing measures to mitigate the risk of indoor respiratory infections?

Future Research Directions
- What potential future research directions should be pursued to sustain consistently safe indoor environments and proactively prevent the risk of respiratory viral infections?

By addressing these research questions, this study aspires to contribute valuable insights into the intricate relationship between indoor air quality, respiratory disease transmission, and the specific challenges posed by COVID-.

19. The findings will shed light on current practices and limitations and guide future research efforts toward creating safer indoor environments. The structure of this paper reflects the research questions. Following this introduction, an overview of the methodology that supports this review is provided in section two. Section three investigates the transmission of respiratory viruses in indoor environments with a focus on SARS-CoV-2 and interventions that are employed to mitigate the risk of indoor respiratory infections. Section four discusses existing gaps and limitations, followed by future research directions in Section five. Section six provides concluding remarks.

2. Research approach

This systematic review was conducted to identify current areas of research that have investigated IAQ in relation to the risk of indoor respiratory disease infections. Multiple approaches are necessary to understand how infections spread and indoor air quality comprehensively. These include the use of epidemiological and microbiological methods, as well as computational fluid dynamics simulations. Integrating digital technologies, such as Digital Twins and IoT devices, is essential in managing indoor environments and resolving IAQ concerns. These technologies provide virtual planning, real-time monitoring, and predictive maintenance capabilities. Furthermore, analyzing unstructured Big data generated by IoT devices, coupled with AI techniques like machine learning algorithms, can provide valuable insights for informed decision-making. It is also crucial to consider engineering and protective theories, behavioural theories, or a combination of these to gain a well-rounded understanding of the issue. Using this combination of techniques, we can gain insights into indoor infection risks' physical, behavioural, and protective aspects. Table 1 summarizes the various proportions of studies dedicated to each approach. The current research focuses on the transmission of respiratory viruses in indoor environments, particularly emphasizing the transmission of SARS-CoV-2 and its air-borne surveillance, engineering and non-engineering control strategies, computational fluid dynamics modelling, and energy consumption related to indoor air quality. It is important to note that many other methods are available to investigate infection transmission and indoor air quality. The research focuses on SARS-CoV-2 due to its global significance as a public health concern and the need to address the unique

Table 1
The percentage of publications in each category.

Category	Percentage	Notes
Epidemiological modes	29.78 %	Computational fluid dynamics simulations were the focus of 10.67 % of the total reviewed publications.
Microbiological methods	44.38 %	Machine learning techniques were utilized in 5.06 % of the microbiological methods studies.
Engineering and protective theories	25.84 %	Energy consumption considerations were integral to 19.57 % of the engineering and protective measures studies.

challenges posed by this infectious agent.

(Fig. 1) explains the relevant documents were gathered from IEEE, Scopus, Web of Science and ScienceDirect using the following keywords: [Indoor OR confined OR enclosed] AND [air quality OR ventilation OR co$_2$] AND [SARS-CoV-2 OR COVID-19 OR SARS OR respiratory viruses]. Initially, these keywords led to the identification of 2722 documents, including journal articles, review papers, and conference papers.

To carry out this systematic review, three main steps were carried out:

1. Utilizing established search engines to identify current authoritative research papers.
2. Examining and retaining relevant publications.
3. Extract relevant studies using COVID-19 and other respiratory viruses transmission in indoor environments to study IAQ.

In Fig. 2, a noticeable surge in research related to Indoor Air Quality

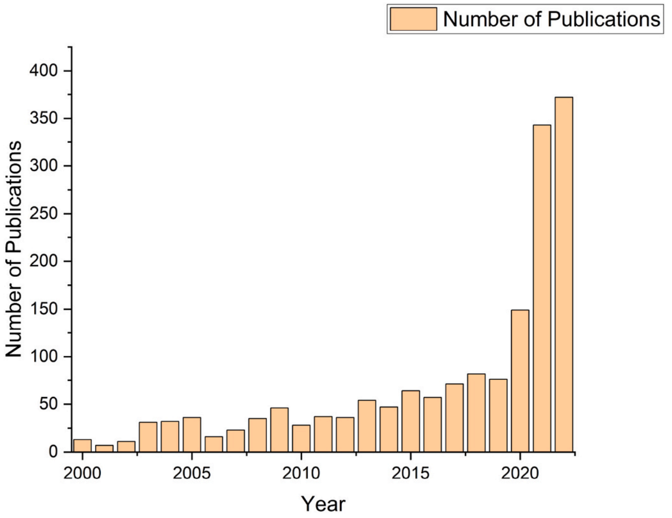

Fig. 2. Number of IAQ documents based on the year of publication.

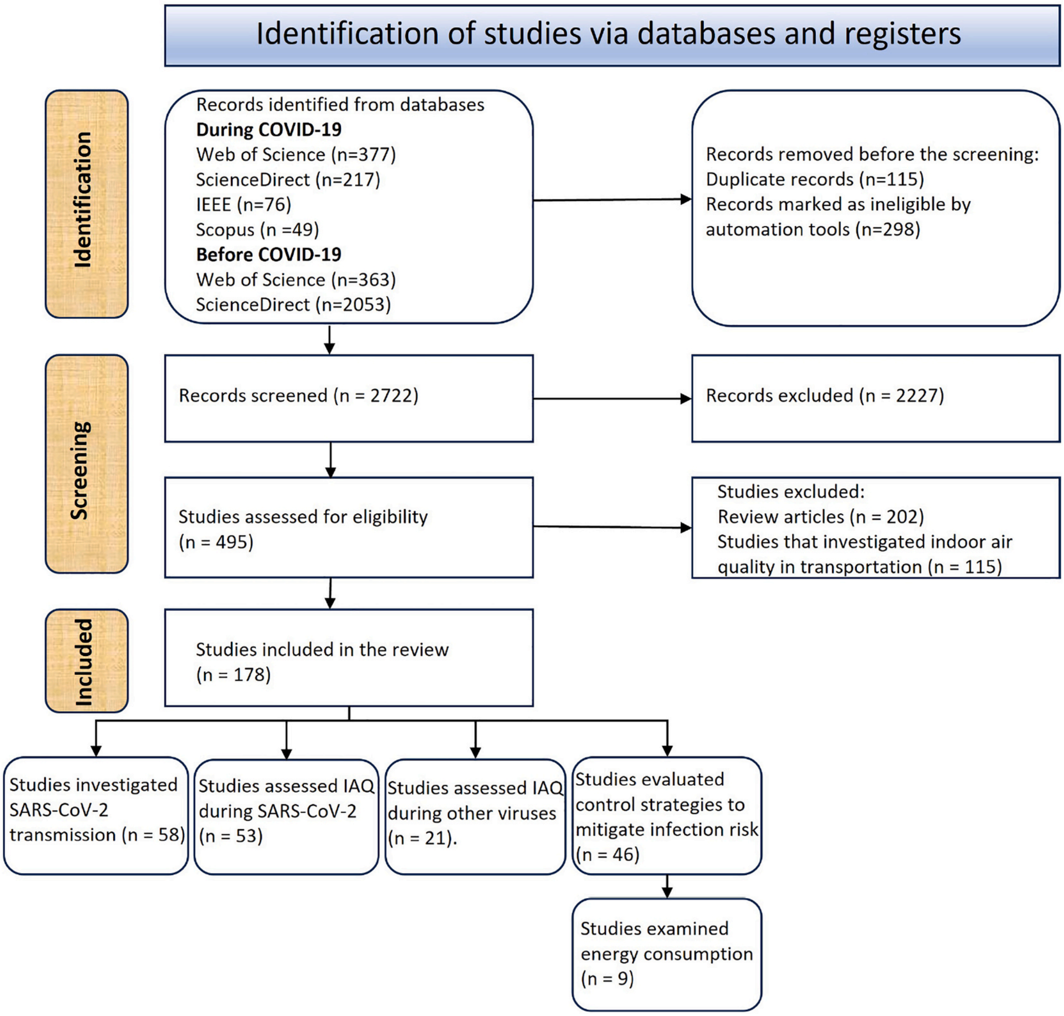

Fig. 1. PRISMA flow diagram for systematic review.

(IAQ) is evident, particularly in the years following the onset of the COVID-19 pandemic. Additionally, Fig. 3 illustrates that most publications fall into the realms of environmental sciences, engineering, and public environmental occupational health, among others. Studies from preceding years were incorporated into the analysis, with a specific focus on their relevance to COVID-19. Initially and before the selection of titles and topics, 115 duplicate articles and 298 publications which marked as ineligible by automation tools were excluded. Then, the screening was completed by scanning the titles and reading the topics. That allowed the reduction of the list of documents from 2722 to 495 papers. After the screening was completed, the list of 495 documents was assessed for eligibility. Therefore, 202 review papers and 115 papers that investigated IAQ in transportation were excluded, and the list of documents became 178 papers.

Within the updated collection of articles, four distinct and pivotal themes have emerged. The first theme revolves around investigating the transmission of various viruses that occurred in indoor settings before COVID-19. The second theme involves investigating SARS-CoV-2 transmission in indoor settings. The third theme focuses on evaluating indoor air quality. The final theme delves into control strategies that can help mitigate infection risks in indoor environments. This thematic categorization provides a structured overview of the diverse areas covered in the literature, offering valuable insights into the multifaceted dimensions of IAQ research in the context of different pandemics.

A framework was developed to systematically explore each subject in depth. The framework should help highlight current research trends and indicate conclusions that may be applied to relatable scenarios. The following information was gathered for each study:

1. Scale: This reveals information about what kind of indoor environment is involved in the study.
2. Application field: Studies are categorized based on the field of study.
3. Scope: This offers a summary of the overall purpose of the study.
4. The type of method utilized: This determines the method used to validate the study.
5. Using IAQ measurements: Does the study use sensors to measure IAQ?
6. Conclusions: A brief description of the results of the study.
7. Study limitations: The reasons why the study was limited include not measuring other factors or providing unreliable results.
8. Future directions: Some tips and suggestions for future research to improve IAQ and prevent viral transmission in indoor environments.

3. Transmission of respiratory viruses in indoor environments

Respiratory viruses, such as influenza virus, parainfluenza virus, respiratory syncytial virus (RSV), severe acute respiratory syndrome coronavirus (SARS-CoV), rhinovirus, and adenovirus, are important human pathogens primarily affecting the upper respiratory tract. The potential for pandemics, as indicated by (Kohlmeier and Woodland, 2009), has heightened public awareness and concern about these viruses. Typically, these infections follow four primary transmission routes, as illustrated in Fig. 4. These routes are direct contact (e.g., handshakes), indirect contact via fomites, respiratory droplets (larger particles >5um), and aerosols (smaller particles <5um) as described by (Leung, 2021; Kutter et al., 2018; Klompas et al., 2020). In this section, as detailed in Table 2 we will review various studies investigating the transmission of respiratory viruses in indoor environments.

The first virus is a severe acute respiratory syndrome (SARS), which emerged in China in the early 2000s and led to a global outbreak (Hung, 2003). Numerous studies have examined its transmission in indoor environments. For instance, (Li et al., 2005) investigated the transmission between apartments in high-rise buildings, revealing challenges in controlling air leakage due to airflow influenced by airtightness and pressure differences. Furthermore, (Chen et al., 2006) explored the effectiveness of isolation and contact tracing in containing the SARS epidemic. Additionally, Niu and Tung (2007) provided insights into vertical transmission in high-rise buildings, showing how exhaust air can move between floors. Subsequently, Jiang et al. (2009) highlighted the importance of safe ventilation rates in infection control, a finding echoed by Yu et al. (2017) in their CFD studies on virus dispersion in hospital wards.

The second virus is Influenza, a fast-spreading virus that can impact humans and animals, announced as an outbreak by (Organization et al., 2009) in 2009. Various studies have delved into the dynamics of influenza transmission, providing insights into potential control measures and environmental factors influencing its spread. For instance, Chen et al. (2006); Chen and Liao (2008); Koep et al. (2013) investigated the impact of engineering controls and public health interventions on influenza spread. Pantelic et al. (2009) demonstrated a reduction in infection risk with personalized ventilation. In the context of

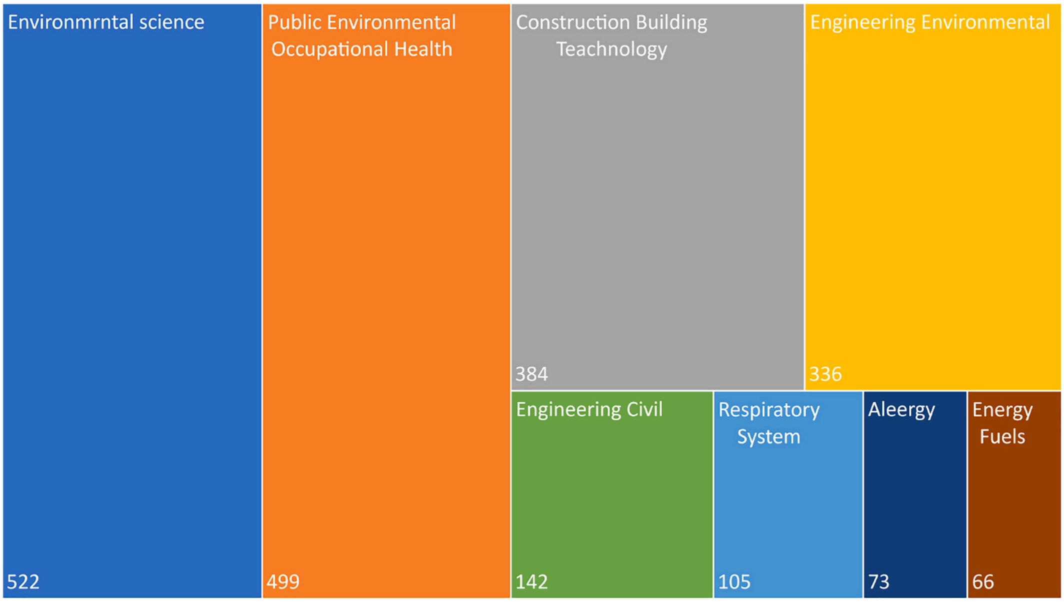

Fig. 3. Publications categories.

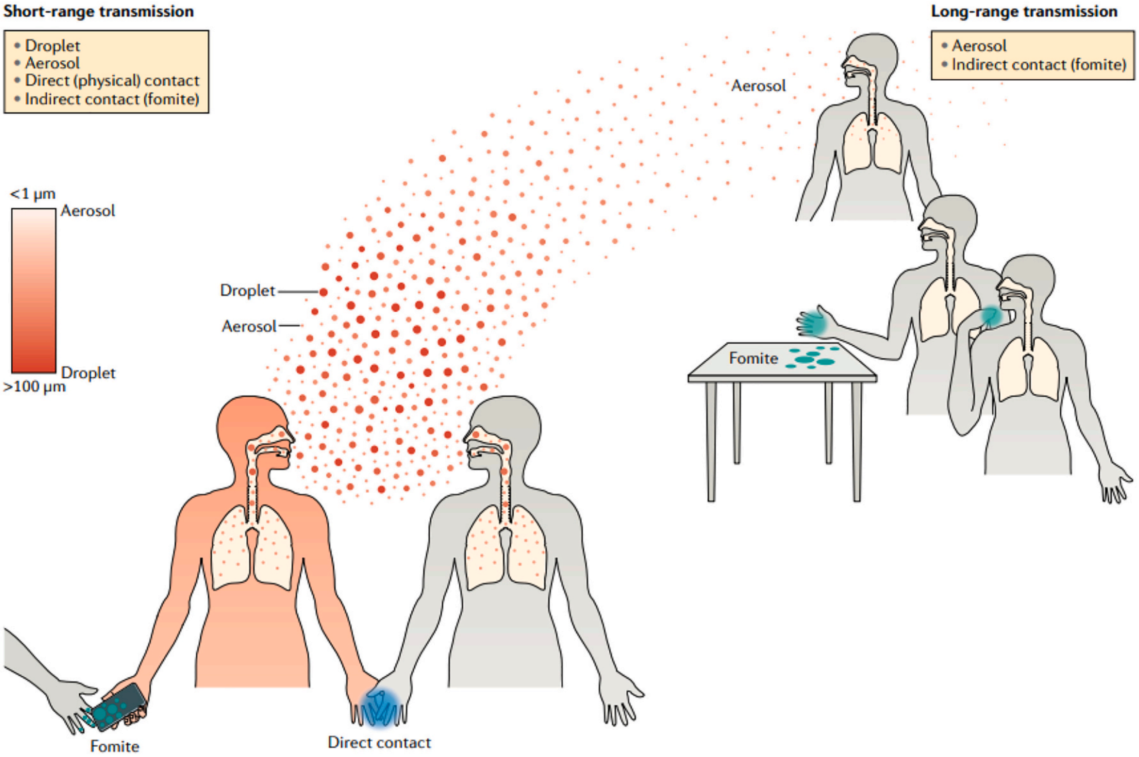

Fig. 4. Major routes of respiratory viruses transmission (Leung, 2021).

environmental controls in hospitals, (Beggs et al., 2010; Wan et al., 2016) provided valuable insights. Moreover, Koep et al. (2013); Myatt et al. (2010); Noti et al. (2013) reported that maintaining indoor air at RH >40 % could reduce influenza virus survival and transmission, while Azimi and Stephens (2013) found that HVAC filtration effectively reduced infection risk.

Thirdly, the Middle East respiratory syndrome (MERS) virus is another coronavirus that emerged in 2012 in Saudi Arabia. It is similar to the SARS-CoV-1 virus (Giannis et al., 2020). Several studies have investigated the transmission dynamics of MERS in different indoor environments, shedding light on potential risk factors and mitigation strategies. Yu et al. (2017); Sung et al. (2018); Jo et al. used CFD and tracer gas experiments to study MERS transmission in hospitals, emphasizing the role of indoor and outdoor airflow in infection control.

In addition, the transmission dynamics of diseases like tuberculosis, measles, and adenovirus in indoor environments have also been the subject of significant research. Studies by Chen et al. (2006); Pantelic et al. (2009); Beggs et al. (2010); Wan et al. (2016) highlight the importance of environmental controls and personal protective measures.

Lastly, the SARS-CoV-2 virus, which originated in Wuhan, China, in 2019, has spread rapidly worldwide, prompting the World Health Organization (WHO) to declare it a global pandemic. The next section will discuss the modes of SARS-CoV-2 transmission. The virus's persistence in aerosols and on surfaces necessitated reevaluating indoor air quality measures, with studies like those by (Morawska et al., 2020) emphasizing the need for improved ventilation and air filtration. The effectiveness of masks and social distancing in reducing transmission was highlighted by (Coyle et al., 2021), while environmental factors like temperature and humidity were also found to influence viral spread (da Silva et al., 2021).

3.1. *Transmission vectors of SARS-CoV-2*

SARS-CoV-2 modes of transmission, akin to other respiratory viruses such as influenza, severe acute respiratory syndrome (SARS), and Middle East respiratory syndrome coronavirus (MERS-CoV), include direct or indirect contact, aerosol, and droplets.

Aerosol transmission is particularly prevalent in indoor environments characterized by inadequate fresh air ventilation and a high density of individuals relative to the confined space. This phenomenon has been extensively studied across various indoor settings, including classrooms and educational buildings (Zemouri et al., 2020; Farouk et al., 2021; Jones et al., 2021; Li et al., 2021a, 2021b; Vouriot et al., 2021; Mikszewski et al., 2021; Dacunto et al., 2022; Singer et al., 2022), healthcare facilities (Garbey et al., 2020; Polednik, 2021; Zhou and Ji, 2021; Li et al., 2022; Crawford et al., 2021; Grimalt et al., 2022; Beaussier et al., 2022; Burgos-Ramos et al., 2022), offices (Augenbraun et al., 2020; Burridge et al., 2022; Cammarata and Cammarata, 2021; Y.-F. Ren et al., 2021; C. Ren et al., 2021; Riediker et al., 2021; Shrestha et al., 2021; Jahromi et al., 2022; Shang et al., 2022), nail salons (Harrichandra et al., 2020), historic building (Alaidroos et al., 2021), rooms (Bathula et al., 2021; Hussein et al., 2021; Muthusamy et al., 2021), gym (Blocken et al., 2021), residential building (Hwang et al., 2021), stores (Jiang et al., 2021; Zhang et al., 2022), chamber (Kappelt et al., 2021), Skagit Valley Chorale event (Miller et al., 2021), lift (Peng et al., 2021; Dbouk and Drikakis, 2021), concert halls (Schade et al., 2021), restrooms (Schreck et al., 2021), courtroom (Vernez et al., 2021), restaurants (Yu et al., 2021; Auvinen et al., 2022), terrace (Rivas et al., 2022), indoor arena (Moritz et al., 2021) and courtyard (Leng et al., 2020).

On the other hand, fomite transmission refers to the spread of infectious agents, such as viruses or bacteria, through contact with contaminated surfaces or objects. Numerous studies have explored fomite transmission by conducting surface or object sampling in indoor spaces, aiming to ascertain the presence of COVID-19, as outlined in Table 3. While Wang et al. (2020); Viegas et al. (2021) reported negative results for SARS-CoV-2 on surfaces, attributed to routine cleaning and disinfection, several other studies have identified the presence of COVID-19 in various indoor environments, including hospitals. (Nissen et al., 2020; Krambrich et al., 2021; Horve et al., 2021; Razzini et al.,

Table 2
Publications investigating indoor air quality before COVID-19.

Ref	Building type	Type of respiratory virus	Result
(Li et al., 2005)	Flat	SARS 2003	It is difficult to completely prevent the movement of air between the apartments in a high-rise building using only natural ventilation.
(Niu and Tung, 2007)	Flat	SARS 2003	Windows in high-rise buildings can be a significant pathway for the vertical spread of pathogen-containing aerosols.
(Myatt et al., 2010)	House	Influenza	Increasing the RH level decreases influenza survival.
(Chen et al., 2006)	Hospital, elementary school	Influenza, chickenpox, measles, SARS 2003	Engineering control measures combined with public health interventions can effectively mitigate the spread of respiratory infections.
(Jiang et al., 2009)	Hospital	SARS 2003	To minimize the risk of airborne viral infection, it is recommended to reduce air from a SARS patient by a factor of 10,000 by the introduction of clean air for safe ventilation.
(Beggs et al., 2010)	Hospital	Influenza, tuberculosis, measles	To mitigate the infection risk spread in a waiting area, and before using expensive technological solutions, it is important to first minimize waiting times and the number of susceptible individuals present.
(Wan et al., 2016)	Hospital	Enterovirus, RSV, influenza A virus, adenovirus, M pneumoniae	All respiratory viruses except enterovirus were detected in the air and objects.
(Yu et al., 2017)	Hospital	MERS, SARS, and Influenza (H1N1)	The location of a virus-infected patient may affect the infection risk for others. In addition, increasing the air change rate can help reduce the risk of infection.
(Sung et al., 2018)	Hospital	MERS	Infectious aerosols may be spread indoors via airflow influenced by outdoor winds.
(Jo et al., 2019)	Hospital	MERS	The outdoor wind could spread infectious aerosols indoors through the airflow.
(Koep et al., 2013)	School	Influenza	Increasing relative humidity (RH) by up to 60 % and increase absolute humidity (AH) may reduce influenza virus survival and transmission.
(Chen and Liao, 2008)	School	Measles, SARS 2003	The mathematical model used in this paper can offer an initiative applicable to a real elementary school to predict the optimal control measures and to protect susceptible students from infection by infected students.
(Azimi and Stephens, 2013)	Office	Influenza	Filtration reduces the infection risk of the influenza virus with lower costs than the option of increasing ventilation.
(Noti et al., 2013)	Chamber	Influenza	Keeping RH above 40 % in indoor environments helps reduce the spread of the influenza virus.
(Pantelic et al., 2009)	Chamber	Influenza, tuberculosis	The use of PV (personal ventilation) can reduce the infection risk of airborne transmissible disease.

Table 3
Information from publications on the SARS-COV-2 transmission through indoor surfaces in different indoor environments.

Ref	Building type	Sample size	Result reported in study
(Wang et al., 2020)	Hospital	45 samples	None of SARS-Cov-2 RNA was detected among these samples.
(Razzini et al., 2020)	Hospital	37 samples	Nine out of 37 samples tested positive for SARS-CoV-2.
(Nissen et al., 2020)	Hospital	19 samples	SARS-CoV-2 was detected in the filters of the air filtration systems of COVID-19 wards.
(Krambrich et al., 2021)	Hospital	200 samples	50 samples out of 200 samples were positive for SARS-CoV-2.
(Horve et al., 2021)	Hospital	56 samples	25 % of the samples tested positive for SARS-CoV-2.
(Rodríguez et al., 2021)	Households	13 samples	All air samples and 75 % of the surface samples tested positive for SARS-CoV-2.
(Viegas et al., 2021)	Educational building	106 samples	All the samples for SARS-CoV-2 were negative.
(Shankar et al., 2022)	Residential building	7 samples	SARS-CoV-2 was detected in an air sample from volunteer A and in various air and surface samples from volunteer B.

2020), households (Rodríguez et al., 2021), and residential rooms (Shankar et al., 2022). The next section will investigate the presence of SARS-CoV-2 in indoor environments by examining different techniques.

3.2. Airborne surveillance of SARS-CoV-2

To detect viruses and evaluate indoor air quality, it is imperative to employ diverse techniques such as air sampling and air monitoring.

Air sampling, a method employed to identify airborne pollutants in an environment, has been extensively utilized in numerous studies, as illustrated in Table 4. These investigations focus on various indoor settings, employing air sampling to ascertain the presence of COVID-19. Masoumbeigi et al. (2020); Faridi et al. (2020); Vosoughi et al. (2021) reported negative results for SARS-CoV-2 in their air samples. In contrast, multiple investigations have confirmed the presence of SARS-CoV-2 in the air across diverse indoor settings, such as hospitals (Kenarkoohi et al., 2020; Baboli et al., 2021; Ghaffari et al., 2021; Hemati et al., 2021; Habibi et al., 2021; Passos et al., 2021; Bazzazpour et al., 2021), household (Rodríguez et al., 2021), public building (Gehrke et al., 2021), and residential building (Shankar et al., 2022). On the other hand, indoor air monitoring involves a variety of essential measurements in the indoor environment that are used to assess Indoor Air Quality (IAQ) as depicted in Fig. 5. While some studies focus on one

Table 4
Information from publications on the SARS-COV-2 transmission through indoor air in different indoor environments.

Ref	Building type	Sample size	Result reported in study
(Masoumbeigi et al., 2020)	Hospital	31 samples	All the samples tested negative for SARS-Cov-2.
(Faridi et al., 2020)	Hospital	10 samples	All the samples tested negative for SARS-Cov-2.
(Vosoughi et al., 2021)	Hospital	33 samples	The results illustrated that air samples taken 2 to 5 m away from the patient's beds were negative for SARS-COV-2.
(Kenarkoohi et al., 2020)	Hospital	14 samples	Two out of fourteen air samples tested positive.
(Baboli et al., 2021)	Hospital	51 samples	Six of the fifty-one samples collected from the COVID-19 ward tested positive for SARS-CoV-2, four cases were in patient rooms, and 2 cases were in the hallway.
(Ghaffari et al., 2021)	Hospital	16 samples	All samples from the toilets and hallway were negative, but two samples collected from the intensive care unit (ICU) were positive.
(Hemati et al., 2021)	Hospital	107 samples	Six out of 107 air samples tested positive.
(Habibi et al., 2021)	Hospital	13 samples	Five of the 13 air samples collected from three major hospitals in Kuwait tested positive for SARS-CoV-2.
(Passos et al., 2021)	Hospital	52 samples	Five out of 52 air samples collected from hospitals in Brazil tested positive for SARS-CoV-2.
(Bazzazpour et al., 2021)	Hospital	36 samples	Thirteen of the thirty-sex cases tested positive for SARS-CoV-2.
(Rodríguez et al., 2021)	Households	16 samples	All air samples and 75 % of the surface samples tested positive for SARS-CoV-2.
(Gehrke et al., 2021)	public buildings	12 samples	Six out of 12 aerosol samples were detected for SARS-CoV-2.
(Shankar et al., 2022)	Residential building	7 samples	SARS-CoV-2 was detected in an air sample from volunteer A and in various air and surface samples from volunteer B.

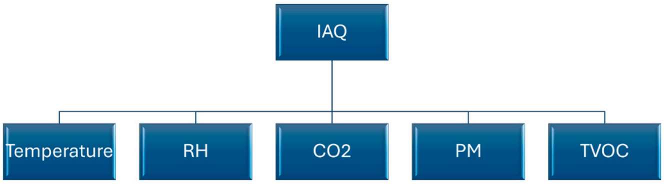

Fig. 5. Indoor air quality measurements.

or two measurements, others encompass a comprehensive set of metrics, as detailed in Table 5. One key indicator for evaluating IAQ is particulate matter (PM2.5). Consequently, numerous studies have explored IAQ, specifically in terms of PM2.5, within diverse indoor environments, including households (Li et al., 2021a, 2021b), apartments (Kim et al., 2020; Algarni et al., 2021; Ezani et al., 2021), restaurant (Chang et al., 2021), classroom (Predescu and Dunea, 2021) and house (Puttaswamy et al., 2022). In addition to PM2.5, some authors have investigated other measurements, including co$_2$, total volatile organic compounds (TVOC), NO$_2$, and O3 (Domínguez-Amarillo et al., 2020; Tryner et al., 2021; Pietrogrande et al., 2021; Roh et al., 2021; Zanni et al., 2021; Rodríguez et al., 2022). Furthermore, certain authors have conducted studies encompassing environmental factors such as temperature, humidity RH, co$_2$ concentration levels, acoustic environment, and air velocity, providing a holistic assessment of indoor air quality (Aguilar et al., 2021; Lu et al., 2021; Meiss et al., 2021; Tahmasebi et al., 2022; Alonso et al., 2021; Calama-González et al., 2021; Lovec et al., 2021; Di Gilio et al., 2021; Huang et al., 2021; Fayos-Jordan et al., 2021; Villanueva et al., 2021; Ulpiani et al., 2021). Moreover, VOCs have been investigated alongside PM2.5 and co$_2$ in numerous studies, as exemplified by (Domínguez-Amarillo et al., 2020; Pietrogrande et al., 2021; Zanni et al., 2021; Meiss et al., 2021; Gregorio et al., 2021; Kim et al., 2021). Lastly, some authors have used internet of things (IoT) sensors to evaluate indoor environments and employed machine learning (ML) for indoor air quality prediction (Mumtaz et al., 2021; Sharma et al., 2021; Taheri and Razban, 2021; Marzouk and Atef, 2022).

The upcoming sections will investigate engineering and non-engineering control strategies.

3.3. *Engineering and non-engineering control strategies*

of nine articles. Strategies such as relative humidity and temperature management, ultraviolet (UV) radiation, face masks, and social separation are underrepresented in the literature, with only four publications each. This distribution of study priority may indicate that, while many techniques.

Mitigating the airborne transmission of infectious pathogens are being investigated, the scientific community is focusing is imperative, and it hinges on controlling the concentrations of respiratory aerosols indoors. This goal can be achieved through various engineering strategies, such as controlling the humidity and temperature of the indoor air, improving ventilation, employing air filters, and incorporating ultraviolet radiation. Additionally, non-engineering control measures, such as the use of face coverings and practising social distancing, play a pivotal role in enhancing overall transmission prevention efforts. Furthermore, Fig. 6 summarizes the number of academic articles connected to various control measures aimed at reducing the transmission of airborne diseases. The data represent an investigation of 46 total articles, which were classified according to the type of control strategy explored. Ventilation is the most researched control approach, with 21 papers highlighting its perceived importance in airborne disease control. This is followed by air cleaners, which include purifiers and High Efficiency Particulate Air (HEPA) filters and are the subject more on ventilation and air purification as mechanisms for limiting the spread of airborne infections.

Controlling indoor relative humidity and temperature is a crucial factor in reducing infection risks in indoor settings. The maintenance of optimal conditions significantly influences the survival and transmission of airborne pathogens, which include viruses and bacteria. Numerous studies examining the stability of SARS-CoV, MERS-CoV, and SARS-CoV-2 in air samples indicate that maintaining temperatures between 20 °C and 25 °C and relative humidity levels between 40 % and 50 % protects the viability of these airborne viruses (da Silva et al., 2021; Ahlawat et al., 2020). Conversely, investigations propose that keeping relative humidity below 78 % and daily temperatures above 30 °C might effectively reduce COVID-19 transmission (Park et al., 2022; Raines et al., 2021). For influenza viruses, studies reveal that at 5 °C, transmission showed high efficiency, while it was blocked or less effective at 30 °C. Additionally, dry conditions (20 % and 35 % relative humidity) were observed to be more conducive to spread compared to conditions with intermediate (50 % relative humidity) or high humidity (80 % relative humidity) (Lowen et al., 2007; Lowen and Steel, 2014). In conclusion, previous research underscores the importance of maintaining a relative humidity range of 40–60 % for optimal human health in indoor environments (Ahlawat et al., 2020). Summarily, controlling temperature and humidity within specific ranges is vital for mitigating viral transmission indoors, as outlined in Table 6.

Another strategy is ventilation, which stands out as an engineering control strategy crucial for mitigating the transmission of infection in indoor environments and is closely tied to indoor air quality. Ventilation

Table 5
Mean values of indoor air quality measurements.

Ref	Building type	Mean T (°C)	Mean RH (%)	Mean co_2 (ppm)	Mean PM2.5 (μg/m^3)	Mean PM10 (μg/m^3)	Mean TVOC (ppb)	ACH
(Tryner et al., 2021)	House	20–27	<50	1200–5000	12–25	20–50	–	–
(Li et al., 2021a, 2021b)	House	12.4–17	–	–	62–142	–	–	–
(Roh et al., 2021)	House	24.6	52.8	–	5.6–12.2 in offices, 11.2–45.7 at homes	–	–	–
(Domínguez-Amarillo et al., 2020)	Apartment	Before lockdown 22.5–26, during lockdown 23.1–26	Around 40	Before lockdown 731–2136.8, during lockdown 798.6–2395.7	Before lockdown 10.63–16.07, during lockdown 7.19–16.94	–	Before lockdown 272.524–5550.11, during lockdown 15.285–748.88 ppb	Airflow leakage at 50 Pa (4.87, 1.2, 3.3, 8.22)
(Pietrogrande et al., 2021)	Apartment	20–30	45–50	470–2116	10–15	–	131–584	–
(Algarni et al., 2021)	Apartment	NA	NA	396 for kitchen, 551 for bedroom, and 505 for hall	1465–247 in kitchen, 1151–160 in bedroom, 1565–166 in hall	94 in kitchen, in bedroom, 62 in hall	–	–
(Predescu and Dunea, 2021)	University	22.4–26	20.4–42.4	–	29–41	30–42	–	–
(Ulpiani et al., 2021)	University	23.1	60	464.7	–	–	66.9	–
(Alonso et al., 2021)	School	18–23.1	36.8–57.3	604–1079	–	–	–	–
(Di Gilio et al., 2021)	School	–	–	720.7–1325	–	–	–	–
(Villanueva et al., 2021)	School	19–21	42–50	553–700 ppm	25–48	38–81	–	–
(Meiss et al., 2021)	School	7.8–10.7	35.4–46	577–2232	4.8–15.3	5.8–17.4	287–485	–
(Rodríguez et al., 2022)	Secondary school and university	18.2–19.3	51–57	97–220	–	–	–	–
(Lovec et al., 2021)	Kindergarten	Before COVID-9 is 22.0775, during COVID-19 is 21.955 °C	Before COVID-19 is 33.32, during COVID-19 is 31.125	Before COVID-19 is 1221.88 and during COVID-19 is 847.12	–	–	–	–
(Kim et al., 2021)	Daycare centre	23.6 for nursery room, 22.3 for activity room	32.3 for nursery room, 34.6 activity room	648.1 for nursery room, 608.3 for activity room	9.1 for nursery room, 6.3 for activity room	16.4 for nursery room, 10.8 for activity room	158.9 for nursery room, 158.6 for activity room	–
(Zanni et al., 2021)	Hotel	–	–	452.21–459.92	4.09–9.33	–	108.4–162.41	–
(Chang et al., 2021)	Restaurant	19.4–23.8	45–54	–	113.1 for the entire week	Is 548.1 for the entire week	–	–
(Puttaswamy et al., 2022)	Residential, industrial buildings	–	–	–	Pre-lockdown 24–32, during lockdown the hourly indoor PM2.5 concentrations 3–47	Pre-lockdown 62–78, during lockdown the hourly indoor PM10 concentrations 26–100	–	–

can be driven by mechanical ventilation systems, natural ventilation forces or a mix of both. Several authors have explored the dynamics of natural ventilation (Li et al., 2005; Niu and Tung, 2007; de la Hoz-Torres et al., 2021; Deol et al., 2021; Lepore et al., 2021; Liu et al., 2021; Park et al., 2021; Nunez and García, 2022; Vassella et al., 2021; Zhang and Ryu, 2021) while others have examined mechanical ventilation systems (Coyle et al., 2021; Borro et al., 2021; Chen et al., 2021; Kong et al., 2021; Li and Tang, 2021; Mirikar et al., 2021; Sha et al., 2021; Motamedi et al., 2022; Tzoutzas et al., 2021; Vlachokostas et al., 2022). Furthermore, others delved into mixed ventilation systems (Rey-Hernández et al., 2020; Barbosa and de Carvalho Lobo Brum, 2021; Stabile et al., 2021).

Alternatively, one of the most common engineering strategies for reducing the risk of aerosol transmission is the use of air cleaners (air purifiers) and HEPA filters. Several studies have explored aerosol transmission in various indoor settings using air cleaners. The results demonstrate that air cleaners can effectively reduce the risk of airborne transmission throughout the entire space (Rodríguez et al., 2021; He et al., 2021; Lee et al., 2021; Razavi et al., 2021; Cao et al., 2021; Duill et al., 2021). He et al. (2021); Narayanan and Yang (2021) suggested placing an air cleaner near an infected person for optimal effectiveness. Furthermore, HEPA filters have proven to be exceptionally effective, especially in poorly ventilated spaces. For instance, Y.-F. Ren et al. (2021) and C. Ren et al. (2021) found that in dental treatment rooms, HEPA filters significantly decreased aerosol accumulation. Similarly, Bluyssen et al. (2021) observed that while mobile HEPA systems might increase noise levels, they outperform scenarios with no ventilation in aerosol removal. Additionally, Lelieveld et al. (2020) highlighted that

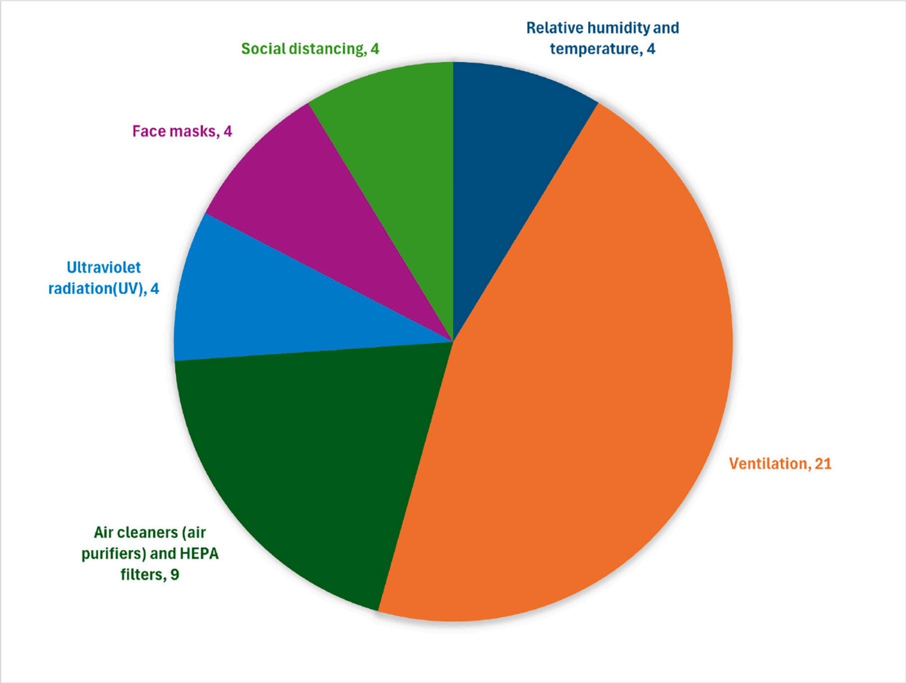

Fig. 6. Distribution of research publications by indoor air quality control strategy.

Table 6
Environmental conditions for the stability and inactivation of various viruses.

Ref	Type of virus	Stable at RH (%)	Mitigated at RH (%)	Stable at T (°C)	Mitigated at T (°C)	Description
(Van Doremalen et al., 2020)	SARS 2003	40	–	21–23	–	The decay rates of SARS-CoV-2 and SARS-CoV-1 in aerosols exhibited similarities.
(da Silva et al., 2021)	SARS 2003	40–50	–	20–25	–	Maintaining temperatures between 20 °C and 25 °C and relative humidity levels between 40 % and 50 % was found to have a protective impact on the viability of airborne SARS-CoV and MERS-CoV.
(Chan et al., 2011)	SARS 2003	40–50	>95	22–25	38	SARS-CoV has been found to remain viable for a duration of up to five days at temperatures ranging from 22 to 25 °C and relative humidity levels of 40 to 50 %. It was found that increased temperature and humidity led to a rapid decline in viability.
(Cheng and Liao, 2013)	Influenza	–	90	–	20	Based on experimental and simulated findings, 90 % RH together with 20 °C is recommended in an indoor environment to improve the prevention of influenza transmission.
(Lowen et al., 2007)	Influenza	20–30	80	5	30	It was found that lower relative humidities ranging from 20 % to 35 % were highly conducive to transmission, whereas transmission was entirely halted at a high relative humidity of 80 %. Additionally, when guinea pigs were housed at 5 °C, transmission occurred more frequently compared to 20 °C, while at 30 °C, no transmission was observed.
(Lowen and Steel, 2014)	Influenza	20–30	50–80	5	30	At 5 °C, transmission showed high efficiency, while it was blocked or less effective at 30 °C. Additionally, dry conditions (20 % and 35 % relative humidity) were observed to be more conducive to spread compared to conditions with intermediate (50 % relative humidity) or high humidity (80 % relative humidity).
(da Silva et al., 2021)	MERS	40–50	–	20–25	–	Maintaining temperatures between 20 °C and 25 °C and relative humidity levels between 40 and 50 was found to have a protective impact on the viability of airborne SARS-CoV and MERS-CoV.
(Van Doremalen et al., 2013)	MERS	40	–	20	–	At a temperature of 20 °C and a relative humidity of 40 %, MERS-CoV was very stable aerosol.
(Pyankov et al., 2018)	MERS	–	–	25	38	The efficiency of MERS inactivation was significantly higher at a temperature of 38 °C compared to 25 °C.
(Van Doremalen et al., 2020)	SARS-CoV-2	40	–	21–23		The decay rates of SARS-CoV-2 and SARS-CoV-1 in aerosols exhibited similarities.
(Ahlawat et al., 2020)	SARS-CoV-2	<40	40–60	–	–	Previous research indicates that a relative humidity range of 40–60 % was found to be optimal for human health in indoor settings.
(Park et al., 2022)	SARS-CoV-2	<40 and >80	<70	–	–	The transmission of the virus is not significantly affected by temperature. However, it is recommended that a safe humidity level be below 70 % relative humidity.
(Raines et al., 2021)	SARS-CoV-2	–	<78	–	30	Maintaining a mean relative humidity below 78 % and continuous daily temperatures above 30 °C significantly reduce transmission.

the use of HEPA filters could potentially reduce individual infection risk by a factor of 5 to 10, affirming their critical role in controlling airborne viruses.

The last engineering control strategy is ultraviolet radiation (UV), an effective engineering strategy for reducing infection risks. According to Kahn and Mariita (2021), optimizing UV-C in facility management involves balancing it with airflow; their findings suggest that enhancing recirculating airflow is more beneficial than merely increasing UV-C power. Additionally, Feng et al. (2021) revealed that indoor UV air cleaners, especially when paired with increased ventilation rates, are highly effective in reducing airborne SARS-CoV-2. Furthermore, Srivastava et al. (2021) demonstrated that integrating UV-C air disinfection with 100 % outdoor air in HVAC systems significantly cleans contaminated air with COVID-19. Complementing these findings, de Souza et al. (2022) successfully used UV germicidal irradiation in an ICU's HVAC system, noting its critical role in maintaining sterile air conditions, particularly when the UV system operates continuously.

On the other hand, implementing face masks or coverings is a crucial non-engineering strategy to reduce infection risks significantly. Research, including (Harrichandra et al., 2020), highlights the significant role of face masks in minimizing airborne transmission of SARS-CoV-2. Moreover, Lelieveld et al. (2020) suggest that face masks could reduce individual infection risks by up to 10 times. This is further supported by Coyle et al. (2021), who recommend combining mask usage with other measures like enhanced ventilation, HEPA filters, and physical distancing for more comprehensive protection. Shen et al. (2021) conducted a systematic review, finding that different types of masks, from cloth to N95, reduce infection risks by varying degrees, with N95 masks being the most effective. Supporting this, Rothamer et al. (2021) demonstrated that masks with moderate to high Effective Filtration Efficiency (EFE) significantly lower infection probability, particularly in enclosed spaces like classrooms.

Another strategy is social or physical distancing which is an important measure for mitigating infection risk, and it has been adopted in many indoor environments since COVID-19 started. This systematic review has explored its effectiveness in various settings, including educational buildings (Aguilar et al., 2021; Meiss et al., 2021) to demonstrate its significance in minimizing transmission. Hospitals, too, have seen positive outcomes, as evidenced by (Lu et al., 2021). The strategy's applicability extends to varied spaces like elevators (Peng et al., 2021), a high-rise institutional building (Sha et al., 2021), and the Lawrence Berkeley National Lab (Singer et al., 2022).

In conclusion, to control SARS-CoV-2 transmission in indoor spaces, several key strategies are required. First, maintaining indoor temperatures between 20 °C and 25 °C and relative humidity levels at 40 % to 50 % is critical for reducing virus viability. Second, ventilation systems should be optimized to ensure a balance between air quality and energy efficiency, focusing on increasing the air exchange rate. In addition, HEPA filters and UV-C radiation for air purification have also shown significant promise, with UV-C particularly effective when used in HVAC systems. Moreover, face masks, especially those with high filtration efficiency like N95 masks, are essential for personal protection, reducing the risk of transmission by up to 99 %. Additionally, maintaining a physical distance of at least 1 m (approximately 3 ft) in social settings further reduces the risk of virus spread. When implemented together, these strategies provide a robust framework for minimizing the spread of COVID-19 in various indoor environments, offering actionable insights for future health and safety measures.

The following section will provide an in-depth exploration of transmission modelling, utilizing the advanced techniques of Computational Fluid Dynamics (CFD) and numerical modelling to offer a more comprehensive understanding of pathogen spread.

3.4. Modelling transmission using computational fluid dynamics and numerical modelling

Aside from real-time air monitoring, computer models serve as another method to assess the risk of infectious disease transmission. Computational Fluid Dynamics (CFD) models employ numerical analysis and structures to follow the flow of contaminants based on factors, including their typical behaviours and the environmental conditions of the space. This approach enables researchers to assess the location and concentration of infectious materials, allowing for the evaluation of infection risk levels without relying on real case studies. Many studies reviewed in this systematic analysis have utilized CFD models either independently or in conjunction with real experiments to simulate or analyze airflow patterns and assess the movement of airborne particles in different indoor environments (Jiang et al., 2009; Yu et al., 2017; Jo et al., 2019; Crawford et al., 2021; Beaussier et al., 2022; Alaidroos et al., 2021; Zhang et al., 2022; Rivas et al., 2022; Motamedi et al., 2022; Ghoroghi et al., 2022; Razlan et al., 2021). Furthermore, in the study conducted by Mirzaei et al. (2022), an Eulerian CFD model was initially validated against experimental data. Subsequently, it was interconnected with a Lagrangian CFD model to simulate the trajectory and evaporation of numerous droplets of various sizes. Moreover, Barbosa and de Carvalho Lobo Brum (2021) utilized coupled multizone-CFD software from the National Institute of Standards and Technology to assess the relative performance of various design solutions related to different ventilation modes, filter efficiencies, and outdoor air flow rates. The role of HVAC systems in the diffusion of contagion through CFD simulations of cough in a hospital was modeled by (Borro et al., 2021). Garbey et al. (2020) applied CFD to test components of a hybrid stochastic compartment model, incorporating the mechanism of diffusion-transport of airborne particles at the surgical suite scale over a one-year period. Transient CFD simulations were conducted by (Shang et al., 2022) to evaluate infection risks under calm and wind scenarios. Moritz et al. (2021) simulated the aerosol distribution in the respiratory air of 4000 virtual participants using a CFD model. Additionally, Feng et al. (2021) used computational fluid-particle dynamics (CFPD) to simulate the generation, transmission, deposition, and clearance of airborne SARS-CoV-2-laden droplets under different main ventilation conditions and UV air cleaner operational conditions in a COVID-19 positive patient room. Furthermore, Dong et al. (2022) calculated the infection rate distribution in space using CFD combined with the Wells-Riley model. Sarhan et al. (2021) simulated a 3D numerical model of human respiration activities, including breathing and speaking, within indoor environments using CFD. These CFD models provide insights into airflow patterns, droplet dispersion, and the effectiveness of various ventilation and air-cleaning strategies. It is essential to consider energy consumption when the IAQ is improved.

The next section will explore the relationship between IAQ improvement measures and their associated energy implications.

3.5. Energy consumption

Addressing indoor air quality (IAQ) and implementing various strategies to mitigate infection risks often involves energy consumption considerations. Achieving a balance between enhancing IAQ and minimizing energy consumption is crucial for sustainable and effective indoor environments. Many of the strategies discussed earlier, such as ventilation, air filtration, and the use of air purifiers, may impact energy consumption. Therefore, understanding and optimizing energy use are essential to comprehensive IAQ management. Throughout this review paper, several studies have considered energy consumption in the context of improving indoor air quality (IAQ). Risbeck et al. (2021) proposed a variety of dynamic models to evaluate the risk of airborne transmission and associated energy consumption for HVAC systems based on controller setpoints and forecasts of weather conditions. Results showed variation in infection risk and the most energy-efficient disinfection strategy based on location and weather conditions. In the study conducted by Schibuola and Tambani (2021a, 2021b), the investigation focused on containing COVID-19 infection in indoor spaces by increasing ventilation rates through high-energy efficiency systems. The results demonstrated that employing an autonomous high-efficiency air handling unit (HEAHU) led to a significant reduction in energy consumption, ranging between 60 % and 72 %. Furthermore, the same authors, in another paper, compared the performance of two alternative systems based on an exhaust air heat pump (EAHP) or a heat recuperator under various weather conditions. They emphasized that HEAHU savings, compared to energy consumption for a heat recuperator, ranged from 31 % to 46 %. Conversely, the savings range for EAHP was between 2.5 % and 48 %. In a milder climate, EAHP offered slightly greater savings than HEAHU (Schibuola and Tambani, 2021a, 2021b). Saikia et al. (2021) designed a resource-conservative healthcare ward, showing that a high cooling energy supply may result in increased energy expenses and lower productivity. Ascione et al. (2021) investigated the effects of energy in terms of monthly and annual increases in energy needs for higher mechanical ventilation and interior distribution of microclimatic parameters. The results showed that increased outdoor air leads to higher energy demands but better IAQ. The work presented by (Wang et al., 2021) proposed a smart ventilation control to adjust ventilation rates based on occupant densities. The study's findings indicated that implementing the proposed ventilation control approach could result in energy savings of 11.7 % and a 2 % reduction in the risk of infection. Aliero et al. (2022) proposed a smart sensing framework for indoor occupancy, leading to potential energy savings of up to 50 %. Aviv et al. (2021) presented an alternative HVAC model that concurrently works with natural ventilation, reducing infection risk and significantly cutting energy use. Rey-Hernández et al. (2020) studied the performance of three systems to ensure that IAQ levels remain within allowable limits while maximising the use of natural resources and reducing energy consumption and carbon emissions. The findings indicated that the hybrid ventilation system, incorporating heat exchangers, successfully met the specified parameters for 70 % of the operating time. Sha et al. (2021) investigated reducing COVID-19 transmission and minimizing energy consumption in high-rise buildings. The authors concluded that a suitable setting for mechanical ventilation systems could reduce energy consumption by around 40 %. de Frutos et al. (2021) analyzed the impact of quarantine-induced occupancy changes on both energy usage and Indoor Air Quality (IAQ) within 12 residences in Madrid. The study highlighted that the initial conditions, encompassing household composition, habits, and daily activities, played a substantial role in influencing both power consumption and indoor environmental quality (IEQ).

In the following section, gaps and limitations will be outlined.

4. Gaps and limitations

This systematic review paper has provided a comprehensive overview of strategies to mitigate infection risk and enhance Indoor Air Quality (IAQ). While numerous studies have focused on understanding COVID-19 transmission, assessing IAQ, and optimizing energy consumption for creating safe and healthy indoor environments, several gaps and limitations are notable in the existing literature.

4.1. Lack of air and surface samples

Air and surface samples are crucial in assessing microbial contamination and measuring air quality. Although several studies have measured IAQ in indoor environments, especially in hospitals, most of them were conducted with small sample sizes (Rodríguez et al., 2021; Shankar et al., 2022). Notably, there is a lack of studies measuring IAQ in diverse indoor settings such as higher education buildings. The unique nature of higher education environments, serving both as workplaces and learning spaces, necessitates specific research in this context. Only one study in this review utilized air and surface samples to measure IAQ in higher education environments in Portugal (Viegas et al., 2021).

4.2. Overlooking occupancy conditions

The presence of individuals in indoor environments and their activities represent a crucial factor that significantly influences Indoor Air Quality (IAQ). Failing to account for the occupancy condition can introduce significant biases and impact the accuracy of IAQ studies. Unfortunately, this aspect was frequently overlooked in several studies, compromising the comprehensiveness of the research. For instance, a study conducted by Park et al. (2021) exemplifies this limitation, where the researchers conducted experiments under non-occupancy conditions. This approach neglects the dynamic nature of indoor environments when populated, leading to a potential mismatch between experimental conditions and real-world scenarios.

Another aspect of oversight is the assumption of even distribution of occupants in-home studies, as highlighted by Li and Tang (2021). In reality, occupants are distributed unevenly within indoor spaces, and this non-uniform distribution can profoundly impact IAQ. The movement of individuals within a confined space can influence the mixing of room air, altering pollutant dispersion patterns and ventilation effectiveness. Unfortunately, many studies did not consider these nuanced conditions during their experiments, potentially resulting in a limited understanding of IAQ dynamics in real-world scenarios (Singer et al., 2022).

4.3. Lack of indoor and outdoor parameters

The evaluation of Indoor Air Quality (IAQ) involves considering various parameters such as temperature, Relative Humidity (RH), and co_2 levels both indoors and outdoors. However, the existing literature on this subject reveals notable limitations concerning these parameters, raising concerns about the comprehensiveness of IAQ studies.

In several studies, assumptions and oversights regarding indoor parameters have been identified. For instance, Cammarata and Cammarata (2021) assumed constant temperature and RH throughout the calculation period, potentially overlooking the dynamic nature of these conditions in real-world scenarios. Additionally, the effects of air humidity variations and the impact of open doors on IAQ were often neglected, introducing potential biases into the analysis (Zhang et al., 2022; Bhattacharya et al., 2021).

One critical aspect that has been frequently overlooked is the lack of concurrent measurement of outdoor conditions in many IAQ studies. While numerous studies evaluated IAQ, they often did not measure or account for outdoor parameters such as temperature, RH, and wind speed. This omission limits understanding of the interplay between indoor and outdoor environments and hinders a comprehensive analysis of IAQ dynamics. Furthermore, the seasonal variations in IAQ, which can significantly impact pollutant concentrations and ventilation effectiveness, were not adequately considered in many studies.

The impact of outdoor particles and occupant activities on indoor particle concentrations was assessed in some studies. However, inconsistencies and missing results made it challenging to conduct a thorough and detailed analysis. The concentration of outdoor particles varied across different cases, and the simultaneous measurement of these particles posed challenges, further complicating the interpretation of results (Kim et al., 2020).

4.4. Evaluation and simulation shortage in studies

While numerous studies have aimed to evaluate Indoor Air Quality (IAQ) in various indoor environments during the COVID-19 pandemic, several notable gaps and limitations exist in the current body of research. The shortcomings in the evaluation and simulation methodologies employed in these studies raise concerns about the comprehensiveness of IAQ assessments and the applicability of findings to real-world scenarios.

One significant limitation identified in many articles is the focus on short work hours when evaluating IAQ. For instance, Motamedi et al. (2022) conducted IAQ assessments primarily during short work hours, potentially overlooking the dynamics of air quality during more extended periods, such as full workdays. This temporal constraint may limit the understanding of IAQ variations over extended periods, hindering the development of comprehensive guidelines for maintaining air quality in indoor environments.

Additionally, the evaluation of the effects of COVID-19 in indoor environments across different climates has been insufficient. Many studies have overlooked the influence of climate variations on IAQ dynamics during the pandemic (Aguilar et al., 2021). Considering the diverse climatic conditions worldwide, a more nuanced analysis that accounts for the impact of climate on IAQ is crucial for developing universally applicable recommendations.

The investigation of the risk of infection transmission has been a focal point in IAQ studies. However, there is a need for more in-depth research to characterize the potential for spreading infections, especially for viruses like SARS-CoV-2. Comprehensive assessments, such as Computational Fluid Dynamics (CFD) simulations or a thorough characterization of airflow patterns within specific indoor environments like classrooms, are necessary for a more accurate understanding of airborne transmission dynamics (Alonso et al., 2021).

The influence of furniture on airflow patterns within a room has been largely neglected in many studies. Furniture arrangement and placement can significantly affect the flow pattern of indoor air, influencing pollutant dispersion and ventilation effectiveness (Motamedi et al., 2022). Incorporating the impact of furniture in IAQ assessments is essential for developing more realistic and applicable guidelines.

While IAQ guidelines have been developed for some countries, such as the guidelines mentioned in the reviewed papers, there is a notable lack of guidelines for other regions, such as Saudi Arabia (Algarni et al., 2021). Bridging this gap by developing region-specific IAQ guidelines is crucial for addressing the unique environmental and cultural factors that may influence indoor air quality in different parts of the world.

4.5. Ignoring some critical conditions affected the ventilation system

Effective ventilation, whether achieved naturally or through mechanical systems, plays a pivotal role in enhancing indoor environments and mitigating airborne infection risks. However, several limitations observed in IAQ studies have compromised the comprehensiveness and applicability of findings, particularly regarding critical conditions affecting the ventilation system.

One significant limitation highlighted in the literature is the oversight of crucial conditions that impact the ventilation system, such as the aerosol circulation of an infected person in closed environments (Alaidroos et al., 2021). The presence of an infected individual significantly influences the dispersion and circulation of aerosol particles, which are key considerations in understanding the transmission dynamics of infectious agents. Ignoring these critical conditions may lead to an incomplete understanding of how ventilation systems perform in real-world scenarios, limiting the practical applicability of IAQ guidelines.

Moreover, variations in simulation parameters, particularly the boundary conditions, can exert a substantial influence on study outcomes. In many cases, these outcomes may not be universally applicable if modifications are made to the Heating, Ventilation, and Air Conditioning (HVAC) system, including changes to ventilation vents, their positions, or the volume flow rates injected or extracted in different indoor environments (Beaussier et al., 2022). The adaptability of IAQ guidelines to different HVAC configurations and setups is essential for ensuring their relevance and effectiveness across diverse indoor spaces.

4.6. Energy consumption and cost

Despite the wealth of research focused on investigating infection transmission risks, a notable gap exists in the literature concerning the analysis of energy consumption, noise, initial investment, and overall cost in the context of Indoor Air Quality (IAQ) improvements. This oversight limits the holistic understanding of the implications and feasibility of various IAQ enhancement strategies. The existing studies have primarily concentrated on assessing and mitigating the risk of infection transmission, often overlooking crucial aspects related to the practical implementation and sustainability of proposed IAQ measures. Notably, the absence of comprehensive analyses of energy consumption raises concerns about the long-term viability and environmental impact of the recommended interventions (Li et al., 2021a, 2021b). Furthermore, the omission of simulations involving heat recovery techniques, especially in winter seasons, represents a significant oversight in understanding the holistic energy dynamics of IAQ improvements. The effectiveness of IAQ strategies, particularly in cold climates, can be influenced by the integration of heat recovery mechanisms, impacting both energy consumption and the overall cost-effectiveness of these interventions (Sha et al., 2021).

4.7. Air quality based on dynamic data

Most of the previous studies were conducted in small indoor environments with few or no people to avoid the complication of collecting data from larger environments. Although few studies have investigated larger environments, these studies were mostly based on simulation data that lacked actual aerosol particle data, accurate IAQ data, and building operational data. The lack of data for outside concentrations may limit the ascertainment of the real contribution of ambient air pollution to IAQ in a classroom (Villanueva et al., 2021).

4.8. Digital twin model and machine learning models

There is a lack of studies on developing a single model for different indoor environments using digital twins integrated with machine learning (ML), which can help nonexperts in their decision-making process. Moreover, there is a lack of studies using ML, which can be used to predict thermal comfort and the concentrations of indoor air pollutants. This can examine various options and scenarios with the least environmental effects while recommending corrective measures through actionable ML. In their respective studies, Sharma et al. (2021), Mumtaz et al. (2021), Taheri and Razban (2021), and Marzouk and Atef (2022) addressed indoor air quality (IAQ) monitoring and forecasting. Sharma et al. (2021) proposed IndoAirSense, emphasizing low-cost IAQ estimation in university classrooms using the modified Long Short-Term Memory (LSTM-wf) model for air quality prediction. Similarly, Mumtaz et al. (2021) introduced an IAQ monitoring solution with IoT sensors and machine learning (ML), offering a platform for measuring diverse indoor contaminants. Marzouk and Atef (2022) focused on educational buildings, employing IoT-based continuous monitoring. Multiple sensors were used to collect indoor measurements, communicating with microcontrollers that wirelessly transmitted data to the cloud. Subsequently, a deep-learning model identified relationships among air quality variables. In a different vein, Taheri and Razban (2021) constructed a dynamic indoor co_2 model through machine learning algorithms to forecast concentrations over various horizons. However, a common limitation among these studies Mumtaz et al. (2021); Sharma et al. (2021); Taheri and Razban (2021); Marzouk and Atef (2022) was the absence of a digital twin that can be utilized to allow the continuous monitoring of physical facilities and reflect the findings in a digital prototype. Furthermore, the application of machine learning to analyze infection outbreaks and develop predictive models for assessing infection risks was not explored.

5. Future research directions

In the wake of the profound impact of respiratory viruses, particularly exemplified by the unprecedented challenges posed by SARS-CoV-2, the scientific community has engaged fervently in exploring the multifaceted dimensions of indoor transmission dynamics, air quality factors, and control strategies. This systematic review delves into key areas such as transmission pathways, indoor air quality, non-engineering and engineering control measures, computational fluid dynamics (CFD), and energy consumption, offering a comprehensive analysis of existing methodologies and applications. As we navigate the evolving landscape of respiratory virus threats, this review not only synthesizes current knowledge but also propels us toward envisioning the next frontier in research. In this context, the following sections outline potential future research directions, aiming to deepen our understanding, enhance preventive strategies, and foster sustainable solutions for the challenges presented by respiratory viruses in indoor environments.

5.1. Infection transmission in indoor environments

In the realm of future research directions, an advanced comprehension of respiratory virus transmission dynamics is imperative, necessitating an exploration of the intricate interplay between direct and indirect contact, respiratory droplets, and aerosols in various indoor settings (Leung, 2021; Kutter et al., 2018; Klompas et al., 2020). Tailored infection control strategies must be developed, considering the diverse nature of environments such as schools, hospitals, offices, and gyms. Optimization of ventilation strategies, building on insights from previous epidemics, requires a focus on high-rise buildings and a deeper understanding of air leakage, spatial positioning, and ventilation rates (Li et al., 2005; Niu and Tung, 2007). Integration of outdoor factors, particularly the influence of outdoor wind on indoor dispersion, should be a priority for adaptive infection control measures (Jo et al., 2019). Holistic approaches to infection control, encompassing various respiratory viruses, should be explored to identify common principles for comprehensive and adaptable control measures. Real-time monitoring and continuous vigilance in high-touch environments are essential, with a specific focus on the psychological impact of prolonged preventive measures and effective behavioural interventions (Nissen et al., 2020; Krambrich et al., 2021; Rodríguez et al., 2021; Shankar et al., 2022). Dynamic Computational Fluid Dynamics (CFD) models, incorporating human movement and real-world variables, can enhance the accuracy of indoor airflow simulations. Sustainability considerations should be integrated into infection control strategies, ensuring environmental friendliness without compromising efficacy. Finally, cross-disciplinary collaboration among epidemiologists, engineers, psychologists, and environmental scientists is crucial for fostering innovative and holistic solutions to indoor transmission challenges.

5.2. Indoor air quality factors

Future research in Indoor Air Quality (IAQ) should adopt a multifactorial approach, expanding monitoring beyond individual factors like co_2, PM, RH, and temperature to provide a more holistic assessment of IAQ, considering the complex interplay between various pollutants and environmental parameters. Special attention should be directed towards educational buildings, aiming for in-depth IAQ analyses to develop tailored strategies for air quality improvement in schools and universities, considering the high occupancy and unique characteristics of these environments. Additionally, studies should integrate outdoor conditions into IAQ assessments to recognize the impact of external factors on indoor air pollutants, enhancing the applicability of findings. Advancements in IAQ monitoring technologies, such as the development of a digital twin for continuous monitoring and reflecting findings in a digital prototype, can improve real-time IAQ management capabilities. Moreover, exploring the application of machine learning algorithms in IAQ studies to predict and manage infection risks represents an untapped avenue for future research, contributing proactively to public health strategies, particularly in the context of infectious diseases like COVID-19. These multifaceted research directions aim to advance our understanding of IAQ, especially in educational settings, and develop sophisticated monitoring and predictive models for comprehensive IAQ management.

5.3. Non-engineering control strategies

While non-engineering measures, such as face masks and social distancing, have demonstrated efficacy in reducing infection risks, future research should delve into optimizing their implementation for enhanced safety and user comfort. Investigating alternative materials and designs for face masks, especially considering potential health risks associated with prolonged use, can contribute to improved mask-wearing experiences. Addressing concerns related to the environmental impact of single-use masks and exploring sustainable alternatives should also be a focus (Si et al., 2021). Moreover, refining social distancing guidelines based on factors like wind scenarios and virus variants, as highlighted by recent studies like (Shang et al., 2022), warrants further exploration. Future research can provide nuanced recommendations on the appropriate distances for varying scenarios, considering both efficacy and practicality. This line of inquiry will contribute to the ongoing development of non-engineering measures as crucial components of infection prevention strategies.

5.4. Engineering control strategies

The field of engineering control strategies for Indoor Air Quality (IAQ) improvement has shown promising avenues, but further research is needed to optimize these measures. Some have proposed that the use of HVAC systems during pandemics can aggravate the problem, while others have advised the use of an HVAC system to dilute contaminants in indoor spaces (Borro et al., 2021). Therefore, the controversy surrounding HVAC system usage during pandemics requires in-depth analysis, emphasizing the importance of optimal system design and usage methods. Additionally, one of the most common optimisation technologies proposed in this epidemic is air cleaners or air purifiers, which depend on the filter medium used. The most suitable filters proposed for the current situation are HEPA, ionisers, and UVGI filters. These filters can be portable or integrated into the ventilation system. Portable filters can remove pollution only from the surroundings. For example, Y.-F. Ren et al. (2021) and C. Ren et al. (2021) concluded that PACs with a HEPA filter efficiently decreased aerosol accumulation and hastened aerosol removal in rooms with poor mechanical ventilation. However, Bluyssen et al. (2021) found that the mobile HEPA filter system led to an unacceptable background sound level. Therefore, future work should focus on necessitating further investigation into their practicality and potential drawbacks for HEPA filters. Furthermore, UV technology, exemplified by the RM3 UV-C units, offers an effective strategy for minimizing infection risks (Srivastava et al., 2021). Yet, considerations such as exposure time and service longevity can impact UV-C efficiency, warranting future research to explore novel approaches, conduct real-world assessments, and ensure sustainable enhancements in indoor air quality.

5.5. CFD

The Computational Fluid Dynamics (CFD) model has been a prominent tool in the studies reviewed and is extensively applied to explore airflow patterns in indoor environments. For example, Razlan et al. (2021) employed a CFD model to examine airflow patterns and temperature dispersion, providing valuable insights into the dynamics of air movement within enclosed spaces. Similarly, Barbosa and de Carvalho

Lobo Brum (2021) utilized coupled multizone CFD software to assess the performance of various design options concerning ventilation modes, filter efficiencies, and outdoor air flow rates. However, it's important to note that while CFD models offer sophisticated simulations, some studies may have overlooked the impact of factors like human movement and door openings on airflow patterns. To advance the field, future research should focus on refining CFD models to incorporate these factors, ensuring a more comprehensive understanding of indoor air quality dynamics. This approach would contribute to more accurate simulations, thereby improving the effectiveness of ventilation strategies and design options in real-world scenarios.

5.6. Energy consumption

Considering energy consumption is crucial in the pursuit of improving indoor air quality (IAQ). Various studies within this review article have delved into this aspect. Notably, Schibuola and Tambani (2021a, 2021b) emphasized that the use of an autonomous High-Efficiency Air Handling Unit (HEAHU) can lead to a remarkable reduction in energy consumption, ranging from 60 % to 72 %. Conversely, findings from Saikia et al. (2021) underscored that a high supply of cooling energy to a hospital could result in increased interior heat gain, leading to higher energy expenses. The study by Ascione et al. (2021) revealed that while increased outdoor air contributes to higher energy demands, it simultaneously improves IAQ, lowers co_2 concentration, and reduces air age. Therefore, adopting a suitable setting for mechanical ventilation systems, exploring alternative HVAC models, or implementing smart sensing frameworks are identified strategies that could effectively contribute to mitigating energy consumption (Sha et al., 2021; Aliero et al., 2022; Aviv et al., 2021). These approaches showcase the intricate relationship between IAQ improvements and the associated energy implications. Moreover, future research in the IAQ domain should strive for a more integrated approach that considers not only the efficacy of infection risk reduction but also the associated energy demands, noise implications, and economic considerations. A comprehensive understanding of the life cycle costs and benefits of IAQ measures is essential for guiding decision-makers, building managers, and policymakers toward sustainable and economically viable indoor environmental solutions. Integrating such considerations into IAQ research will contribute to the development of well-rounded guidelines that prioritize both health and resource efficiency.

6. Conclusion

In conclusion, this systematic review illuminates the complexities and challenges associated with respiratory infection transmission in indoor environments, particularly underscored by the unprecedented impact of the recent COVID-19 pandemic. The urgency of investigating and understanding the dynamics of viral transmission within indoor settings is evident, given the persistent threat posed by respiratory diseases. This study has delved into various methodologies related to respiratory viral infection transmission and the control of indoor air quality (IAQ) as a crucial mitigating factor, all while emphasizing the importance of sustainability in these efforts.

To thoroughly understand the complex dynamics of infection transmission and indoor air quality, a multifaceted approach is required; this includes using epidemiological and microbiological methods and computational fluid dynamics simulations to gain insights into how infections spread. The integration of digitalization technologies, such as Digital Twins, and the widespread use of IoT devices contribute to the management of indoor environments and the resolution of IAQ concerns. These technologies offer virtual planning, real-time monitoring, and predictive maintenance capabilities. Additionally, the analysis of unstructured Big data generated by IoT devices, when integrated with AI techniques like machine learning algorithms, offers valuable insights for informed decision-making. Additionally, it is important to integrate engineering and protective theories and behavioural theories, or a combination of these, to gain a well-rounded understanding of the issue. Using this combination of techniques, we can understand indoor infection risks' physical, behavioural, and protective aspects.

The review of 2722 articles resulted in the retention of 178, all of which contributed valuable insights into different facets of respiratory viral infection transmission and IAQ management. The focus on SARS-CoV-2 transmission, evaluation of IAQ in various pandemic contexts, and examination of control strategies further enriched our understanding of the intricate interplay between indoor environments and infectious transmission dynamics.

However, it is essential to highlight the identified gaps in current research, as only a fraction of the reviewed papers considered energy consumption in the context of IAQ control strategies. This underscores the need for a more comprehensive approach that integrates energy-efficient practices into IAQ management strategies. Additionally, the study revealed gaps in analyzing specific indoor environments, oversight of indoor and outdoor parameters, neglect of occupancy schedules, and the absence of considerations for energy consumption, thereby signaling areas for future research and development.

Moreover, the study distinctively identifies the indoor environmental conditions favoring the transmission of respiratory viruses, offering valuable insights for making IAQ trade-offs to mitigate the risk of dominant viruses at any given time. A noteworthy proposition arising from this study is the integration of digital twins in conjunction with machine learning (ML) techniques for future research endeavors. This innovative approach holds the potential to significantly enhance IAQ by analyzing transmission patterns of various respiratory viruses, all while carefully considering energy consumption.

In light of these findings, it is imperative for future research to address the identified gaps and leverage advanced technologies like digital twins and machine learning for a more holistic understanding of respiratory infection transmission dynamics and effective IAQ management. By doing so, we can pave the way for sustainable and resilient indoor environments that prioritize both human health and energy efficiency in the face of ongoing and future challenges posed by respiratory diseases.

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CRediT authorship contribution statement

Zahi Alqarni: Writing – original draft, Methodology, Investigation, Conceptualization. **Yacine Rezgui:** Writing – review & editing, Supervision, Conceptualization. **Ioan Petri:** Writing – review & editing, Supervision. **Ali Ghoroghi:** Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Data availability

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

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