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REVIEW ARTICLE

Implemented indoor airborne transmission mitigation strategies during COVID-19: a systematic review

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Abstract

The COVID-19 pandemic has inflicted major economic and health burdens across the world. On the other hand, the potential airborne transmission of SARS-COV-2 via air can deeply undermine the effectiveness of countermeasures against spreading the disease. Therefore, there is an intense focus to look for ways to mitigate the COVID-19 spread within various indoor settings. This work systematically reviewed articles regarding airborne transmission of SARS-COV2 in various indoor settings since the onset of the pandemic. The systematic search was performed in Scopus, Web of Science, and PubMed databases and has returned 19 original articles carefully screened with regard to inclusion and exclusion criteria. The results showed that the facilities, such as dormitories and classrooms, received the most attention followed by office buildings, healthcare facilities, residential buildings, and other potential enclosed spaces such as a metro wagon. Besides, the majority of the studies were conducted experimentally while other studies were done using computer simulations. United States (n = 5), Spain (n = 4) and China (n = 3) were the top three countries based on the number of performed research. Ventilation rate was the most influential parameter in controlling the infection spread. CO_2 was the primary reference for viral spread in the buildings. The use of natural ventilation or a combination of mechanical and natural ventilations was found to be highly effective in the studies. The current work helps in furthering research on effective interventions to improve indoor air quality and control the spread of COVID-19 and other respiratory diseases.

Keywords COVID-19 · Systematic review · Ventilation strategies · Indoor air quality · SARS-COV-2 · Airborne transmission

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Introduction

In late December 2019, COVID-19 emerged as a novel infectious disease in Wuhan, China. The rapid spread of the virus to other continents and countries has made its status developed into a global health epidemic by January 30th, 2020 [1]. Later on March 12th, 2020, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been declared a pandemic by World Health Organization (WHO) [2]. This forced the international agencies, governments and institutions around the world to adopt extreme measures to delay the spread of the virus in the form of national lockdowns, curfews, guidelines, workplace instructions and social measures to maintain the public health [3]. Studies showed that personal contact is the main route of transmission for COVID-19 [2]. However, there are many reports in the literature that indicate the potential transmission of the virus when there was no personal contact with the infected persons or infectious fomites. Additionally, there are numerous reports to WHO acknowledging the airborne transmission of the SARS-COV-2 [4]. Plus, it is reported that contaminated surfaces contribute insignificant risk of COVID-19 infection compared to inhalation of contaminated air [5]. The sphere-shaped COVID-19 virus has an approximate diameter between 60 and 140 nm and has been classified in the betaCoVs group. However, except for specialized settings such as hospital intensive care units that have advanced air filtration systems such as high-efficiency particulate absorbing filter (HEPA), the ventilation systems generally use filters with pore diameters not smaller than 1 micron [6]. On the other hand, the most common way of airborne transmission for respiratory diseases are respiratory droplets of variable sizes ranging from 5 to 10 µm in diameter for the droplet and less than 5 µm for the droplet nuclei. These droplets can be found in the immediate air near the infected person or on fomites. The airborne transmission is distinguished by the presence of microorganisms less than 5 µm inside the droplet nuclei and such pathogens that can survive for as long as 3 h within the droplet [7]. This can increase the risk of disease transfer to people residing indoors and located farther from the potentially infected person recommended around 6 feet safe distance [8]. This physical distance, which is called floor area per person, is one of the requirements of COVID-19 infection prevention [9]. Therefore, decreasing the number of nuclei droplets near the breathing zone can control COVID-19 transmission. It has been stated that 60–90% of human lifetime is spent in enclosed spaces and as a result, it has great impact in human health since breathing indoor air quality might usually be unhealthier than the outdoor air [10]. The indoor ventilation is a key element in providing comfort and reducing the risk of disease spread especially during crowded indoor gatherings [11]. So far, numerous research articles were published on the effects of different ventilation technologies and strategies against COVID-19 in various indoor settings such as hospitals, workplace spaces, educational facilities and residential areas: Li et al. (2021) studied ventilation rate and the risk of COVID-19 infection in different sections of an outpatient hospital building in Shenzhen, China [12]. With regard to parameters including the room densities, the number of occupants, and the rate of fresh air volume per person and the Chinese standard, they found that the daily chance of infection was ranged between 0.19 and 1.88% given that the proportion of the infected individuals withing the 20 rooms was 2%. It was also mentioned that the hospital's particular design had also helped in improving the ventilation [12]. Sopeyin et al. (2020) studied the effect of natural and mechanical ventilation on the airborne transmission of the SARS-COV-2 in African countries [13]. They concluded that both ventilation methods could be effective against the COVID-19 if designed properly and maintained consistently. However, they also noted shortcomings such as the potential failure of natural ventilation due to the rise of environmental temperature and humidity and unaffordability and the maintenance demand of mechanical ventilation systems [13]. Navaratnam et al. (2022) investigated the influence of the COVID-19 pandemic on the designs and approaches to achieve a healthy building [14]. They provided a comprehensive report on the engineering tools, building designs, building materials and technologies such as UV radiation, ionization and the use of plants in the buildings. Also, they suggested the application of heating, ventilation, and air conditioning (HVAC) systems, providing contactless routes, antimicrobial materials like copper alloys and modified building architecture with more open space features [14]. Elsaid et al. (2021) investigated the applicability and impact of the design of current HVAC systems against the COVID-19 spread within the buildings and stated that an improved ventilation systems has a vital role in restricting the transmission of SARS-COV-2 and disposing the airborne infectious agents, especially until an adequate supply of vaccines are provided for all countries [15]. Correia et al. (2020) reports that improper use of HVAC systems can contribute to the transmission of the virus across different indoor spaces [6]. Mouchtouri et al. (2020) found SARS-CoV-2 traces in samples taken from different locations including a ferryboat, a nursing home, isolation facility and COVID-19 hospital wards on spots including food preparation and service areas, hospital isolation wards, an air exhaust duct screen, air-conditioning filter, sewage treatment unit and air sample during investigations conducted in response to COVID-19 outbreaks [16]. The airborne transmission of the virus is at the center of investigations in many studies. Baboli et al. (2021) studied the airborne transmission of the virus using passive and active samples taken in a hospital in Ahvaz city, Iran. Their findings confirmed the airborne nature of the virus and identified the air transmission as the main route of SARS-COV-2 spread among the people and the indoor spaces [17]. This was in contrast with the Faridi et al. (2020) report on the airborne transmission of SARS-COV-2 in the largest hospital of Iran as their air samples were negative (faridi et. al [20]). However, the majority of the studies still indicate that proper ventilation is of highest importance when airdrops and aerosols are involved [18]. Additionally, numerous review studies were conducted to provide detailed summary on the potential airborne transmission of SARS-COV-2 [2]. The major focus of such articles was placed on healthcare buildings such as hospitals and their ventilation systems [1, 15].

In this study, we attempt to highlight the most contributing parameters involved in the disease spread and explore the implementations made via modifying the indoor physical settings that were reported in different research publications.

Search strategy

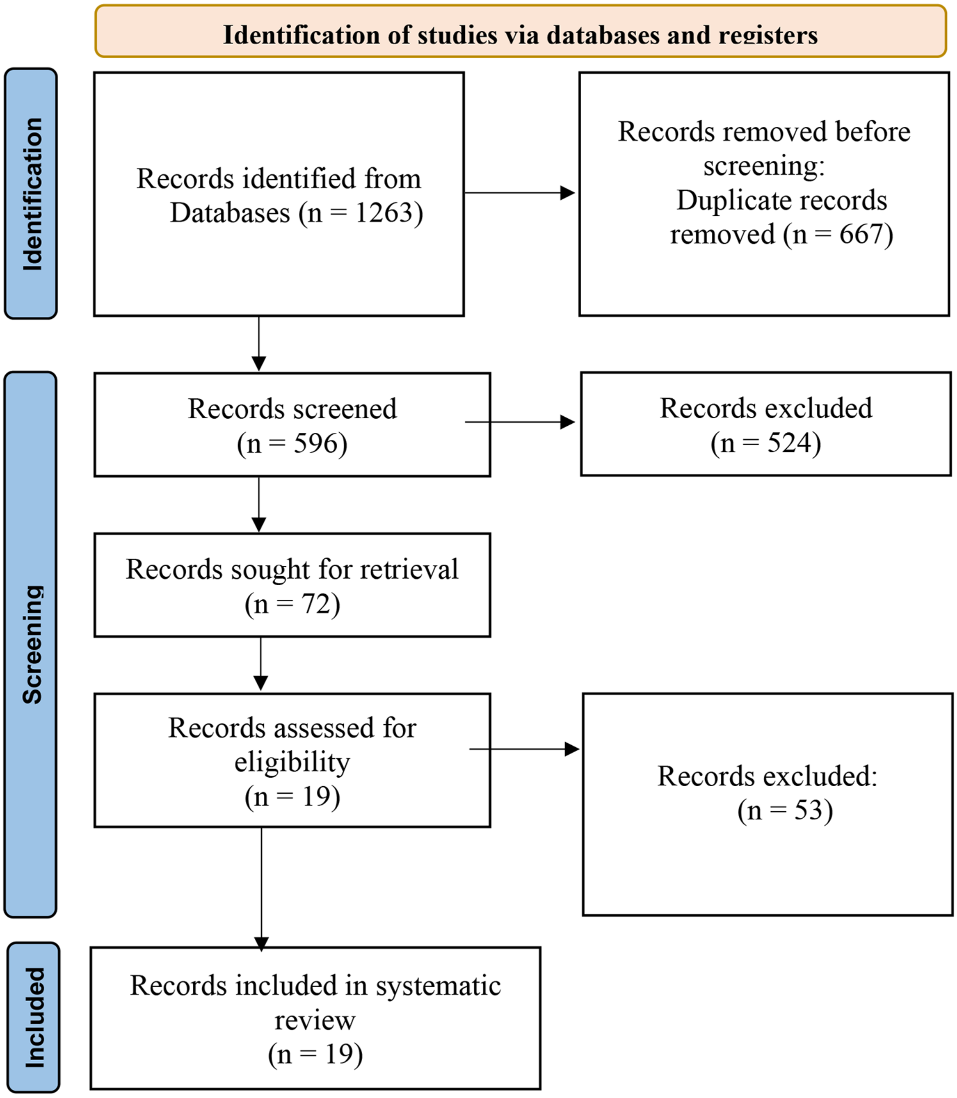
Search protocol

In this study, the articles on the air pollution management strategies to reduce the airborne transmission of the SARS-COV-2 in residential, healthcare and public settings were systematically reviewed using Cochrane guidelines according to PRISMA approach and was conducted in accordance with Cochrane guidelines [2]. Electronic databases, including Scopus, PubMed and Web of Science (WoS) were systematically searched for research articles published from the onset of COVID-19 pandemic. The combination of the terms used for this search were COVID-19” OR “SARS-COV-2” OR “COVID” OR “coronavirus” AND “indoor air” OR “airborne transmission” OR “ventilation” OR “air filter” OR “strategies” OR “indoor air quality” AND “mitigation” OR “air quality management”. These terms were search in article title, abstract and keywords. The selection of the articles was according to the inclusion and exclusion criteria adopted to reflect to the research objective of this work. **The inclusion criteria** were: availability of the electronic version of the selected article, the article published in English language, article available in full text and articles studying on strategies to reduce airborne transmission of the SARS-COV-2 in residential, healthcare and public indoor settings. **The exclusion criteria** were: articles that only contain abstracts, literature reviews, book reviews, guidelines, protocols, book chapters, letters to the editor, conference papers, non-English language published articles, oral presentations, dissertations, etc. The data were extracted by two independent reviewers from each original work. The information obtained from the articles were: author(s) name, study year, country, main objectives, study design, studied parameters, main key findings and recommendations. The articles underwent further scrutinization to remove duplicates and irrelevant publications. Next, the full texts of the selected articles were carefully read to be included in this work. Additionally, the citations of the screened articles were also investigated for potential publications that might have been missed in the screening step.

Results and discussion

The initial systematic search on the Scopus, Web of Science and PubMed databases returned a total of 1263 articles. 667 articles were removed by the reference manager software as duplicate. Then, from the 596 screened records 72 articles were retained for retrieval and the rest were discarded per exclusion criteria. From the 72 articles, 19 articles were found eligible in this systematic review (Fig. 1). Table 1 shows the key findings observed in the reviewed studies. Among the selected articles, 3 studies were in residential homes, 1 study was in a hospital ward, 5 studies were carried out in office buildings and 9 studies were conducted in educational facilities and 1 study was performed in a metro wagon (Fig. 2). Educational buildings are distinguished in that regard that both students and the education staff spend at least 5 h in the same indoor environment [19]. These articles were originated in USA (n = 5), Spain (n = 4), China (n = 3), Egypt (n = 2), Denmark (n = 1), Hungary (n = 1), Italy (n = 1), Slovakia (n = 1), South Korea (n = 1) (Fig. 3). The majority of the studies (n = 13) involved experimental analysis of parameters such as air temperature, CO_2, rate of air change (Air changes per hour or ACH), particulate matter (PM), volatile organic compounds (VOCs), humidity, sensible heat exchange efficiency, mean expire flow rate, virus nRNA count, total volatile organic compounds (TVOC), SARS-CoV-2 RNA, mean air velocity (m/s), draught rating, pressure (Pa) and surface deposition. CO_2 was used as an indicator of viral spread within the building. CO_2 is one of the widely used viral emission indicators due to the unavailability in reality. On the other hand, the simulation studies were mostly based on computational fluid dynamics (CFD) to calculate the model the ventilation patterns in an indoor setting. Such methods, including the computational fluid dynamics (CFD)-based adjoint method, CFD-based genetic algorithm method, and the proper orthogonal decomposition (POD) method, are generally known as inverse design methods [20].

Fig. 1 The PRISMA Chart of the process of article selection



In the indoor settings, increased level of CO_2 is due to the respiratory activity of the inhabitants. Studies suggest that increased concentration of the indoor-level of CO_2 in comparison with the corresponding outdoor level can increases the probability of inhaling the same air exhaled by the other people in the enclosed environment. Therefore, there is a high probability of infection spread if a patient is present among the inhabitants [19]. Maintaining environmental factors such as ventilation, temperature and population density, in optimal conditions can impact productivity and the quality of life in indoor settings [40].

The majority of the studies were conducted in educational buildings such as schools, classrooms and dormitories. Such locations are a key point in disease spread as they host a considerable number of people coming from different places and can hugely contribute to infection spread in case of the presence of a symptomless patient [41]. Poor ventilation in these spaces can led to airborne transmission of the disease to the adjacent rooms and possibly the entire building, especially more enclosed parts of the buildings such as elevators can serve to accelerate the transmission vertically [42]. A common finding among the studies carried out in educational buildings was the positive effect of increasing ventilation rate in the buildings. In these studies, the $_{CO2}$ concentration (ppm) was used as an indicator to parallel the risk of viral infection. Miranda et al. (2022) investigated the ventilation conditions and thermal comfort in exam rooms of an educational building in Spain during COVID-19 restrictions. They found that the adopted ventilation strategies have resulted in CO_2 concentrations that ranged from 450 to 670 ppm and no classroom exceeded the limit value set for category 2 (i.e. educational) buildings, [27]. Park et al. (2021) analyzed the performance of natural ventilation in a school building using field measurements. They found that wearing masks and opening more than 15% of the windows can lead to a less than 1% risk

Table 1 The retained studies based on inclusion and exclusion criteria

Author (Year)	Country	Title	Study type (Experimental/ Simulation)	Building type	Studied parameters	Ref
Szekeres et al. (2022)	Hungary	Investigation of Ventilation Systems to Improve Air Quality in the Occupied Zone in Office Buildings	Experimental	Office building	Temperature, Relative Humidity, Air Velocity, Draught rating	(21)
Afshari et al. (2021)	Denmark	Ventilation System Design and the Coronavirus (COVID-19)	Experimental	Office building	CO_2, ventilation rate, pressue (Pa)	(22)
Nafchi et al. (2021)	USA	Room HVAC Influences on the Removal of Airborne Particulate Matter: Implications for School Reopening during the COVID-19 Pandemic	Experimental	Educational Building	Particle concentration, Air change per hour, filtration, and surface deposition	(23)
Weng and Kau (2021)	China	Planning and Design of a Full-Outer-Air-Intake Natural Air-Conditioning System for Medical Negative Pressure Isolation Wards	Experimental	Hospital room	Sensible heat exchange efficiency (ηs) and air change rate (N)	(24)
Ren et al. (2022)	China	Ventilation Strategies for Mitigation of Infection Disease Transmission in an Indoor Environment: A Case Study in Office	Simulation	Office building	Pollutant concentration, Air Diffusion Performance Index (ADPI)	(25)
Stabile et al. (2021)	Italy	Ventilation procedures to minimize the airborne transmission of viruses in classrooms	Simulation	Educational building	Quanta emission rate distribution, air exchange rate, CO_2	(26)
Miranda et al. (2022)	Spain	Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with Mediterranean climate	Experimental	Educational building	CO_2, air flow per person (l/s). air exchange rate, thermal comfort	(27)
Abdallah and Nasr (2021)	Egypt	Using robots to improve indoor air quality and reduce COVID-19 exposure	Experimental	Educational building	Temperature (°C), relative humidity (%), CO2 (ppm), Particulate Matters and Volatile Organic Compounds (VOC)	(28)
Meyrs et al. (2022)	USA	Portable air cleaners and residential exposure to SARS-CoV-2 aerosols: A real-world study	Experimental	Residential	Questionnaires, PM, SARS-CoV-2 RNA (Saliva), ACH, Total suspended particles	(29)
Li et al. (2021)	China	Poor ventilation worsens short-range airborne transmission of respiratory infection	Simulation	Residential	Expired flow rate (m^3/min), ventilation rate (l/s)	(30)
Baˇcík et al. (2020)	Slovakia	Phollower—The Universal Autonomous Mobile Robot for Industry and Civil Environments with COVID-19 Germicide Addon Meeting Safety Requirements	Experimental	Residential building	-	(31)
Park et al. (2021)	South Korea	Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building	Experimental	Educational building	CO_2, ventilation rate (ACH), ventilation volume (m/s)	(32)
Aguilar et al. (2021)	Spain	Monitoring and Assessment of Indoor Environmental Conditions after the Implementation of COVID-19-Based Ventilation Strategies in an Educational Building in Southern Spain	Experimental	Educational building	CO_2 (ppm), ACH, ventilation rate, temperature (°C), humidity (%), Background noise level (dB	(33)
Patrick et al. (2022)	USA	Longitudinal analysis of built environment and aerosol contamination associated with isolated COVID-19 positive individuals	Experimental	Educational building	Demographic data (e.g., Sex, ethnicity and age), number of daily positive COVID-19 tests, COVID-19 symptoms, ACH, SARS-CoV-2 RNA	(34)
Liu et al. (2022)	USA	Investigation of airborne particle exposure in an office with mixing and displacement ventilation	Simulation	Office building	ACH, thermal load (W/m^3)	(35)
Leonard et al. (2021)	USA	Investigation of potential aerosol transmission and infectivity of SARS-CoV-2 through central ventilation systems	Experimental	Office building	ACH, virus concentration (indoor and outdoor air),	(36)

Table 1 (continued)

Author (Year)	Country	Title	Study type (Experimental/ Simulation)	Building type	Studied parameters	Ref
Meiss et al. (2021)	Spain	Indoor Air Quality in Naturally Ventilated Classrooms: Lessons Learned from a Case Study in a COVID-19 Scenario	Experimental	Educational building	Occupation (n), Mean window opening (m^2), mean door opening (m^2), cross-ventilation (%), Temperature (°C), RH (%), CO_2 (ppm), Mean PM2.5 and PM10 (μg/ m^3), TVOC (ppb)	(37)
Aguilar et al. (2022)	Spain	Assessment of ventilation rates inside educational buildings in Southwestern Europe: Analysis of implemented strategic measures.	Experimental	Educational building	Ventilation rate (ACH), CO_2 (ppm)	(38)
El-Salamony et al. (2020)	Egypt	Air change rate effects on the airborne diseases spreading in Underground Metro wagons	Simulation	Metro wagon	ACH, Water Volume Ratio (%WVR)	(39)

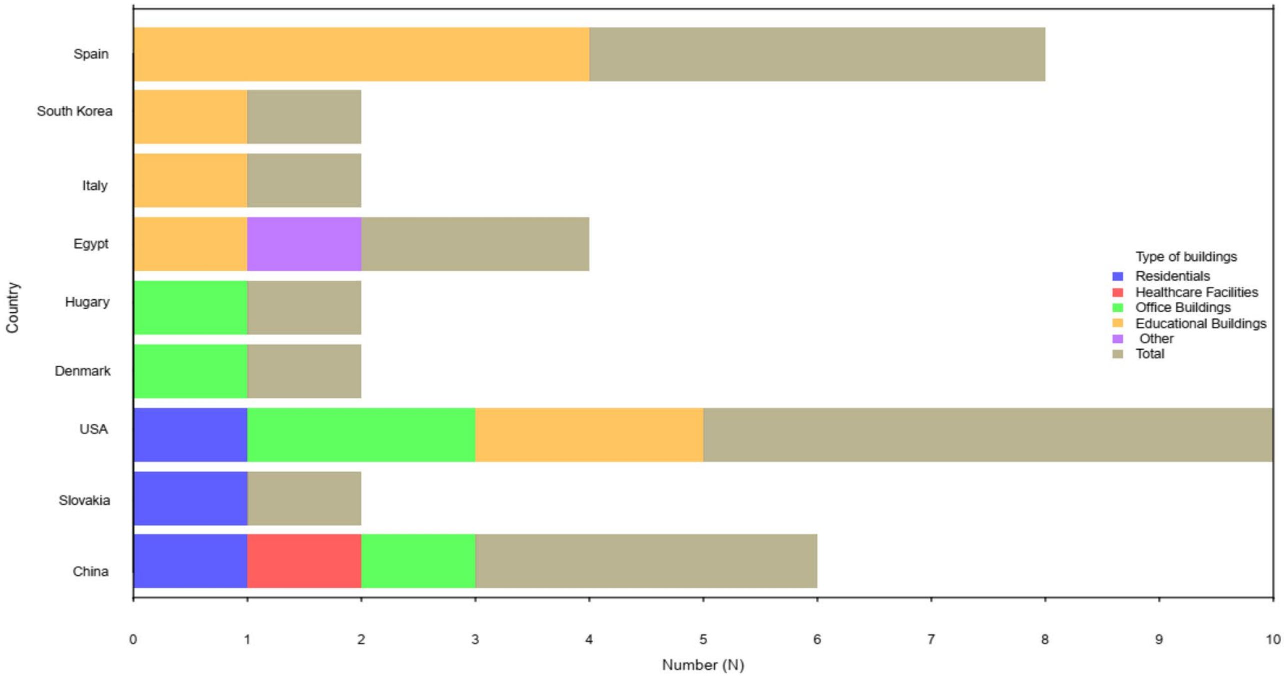


Fig. 2 The type and number of buildings in the screened articles

of infection probability in an hour exposure time duration [32]. Same results were found in the studies of Augilar et al. (2021) [33], Horve et al. (2022) [34], Meiss et al. (2021) [37], and Augilar et al. (2022) [38]. In addition, Stabile et al. (2021) studied the required air exchange rate in schools with mechanical and natural ventilation rates to reduce airborne transmission of COVID-19 using simulation techniques and CO_2 as an indicator in a classroom setting. They recommended the provision of a control unit to regulate flow of fresh air in the mechanically ventilated spaces and defining a scheduled manual airing in the rooms that depend on natural ventilations [26].

Office buildings were another important indoor zone in controlling infection spread. International agencies such as WHO, American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE), and the Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA) have recommended increased ventilation rates at working spaces to ensure a reduced level of airborne virus and bacteria in the workplace [43–45]. Szekeres et al. (2022) investigated the effect of increasing the fresh air rate in office buildings that undergone physical alterations to curb COVID-19 spread without overconsumption of energy by the HVAC system in office buildings. They

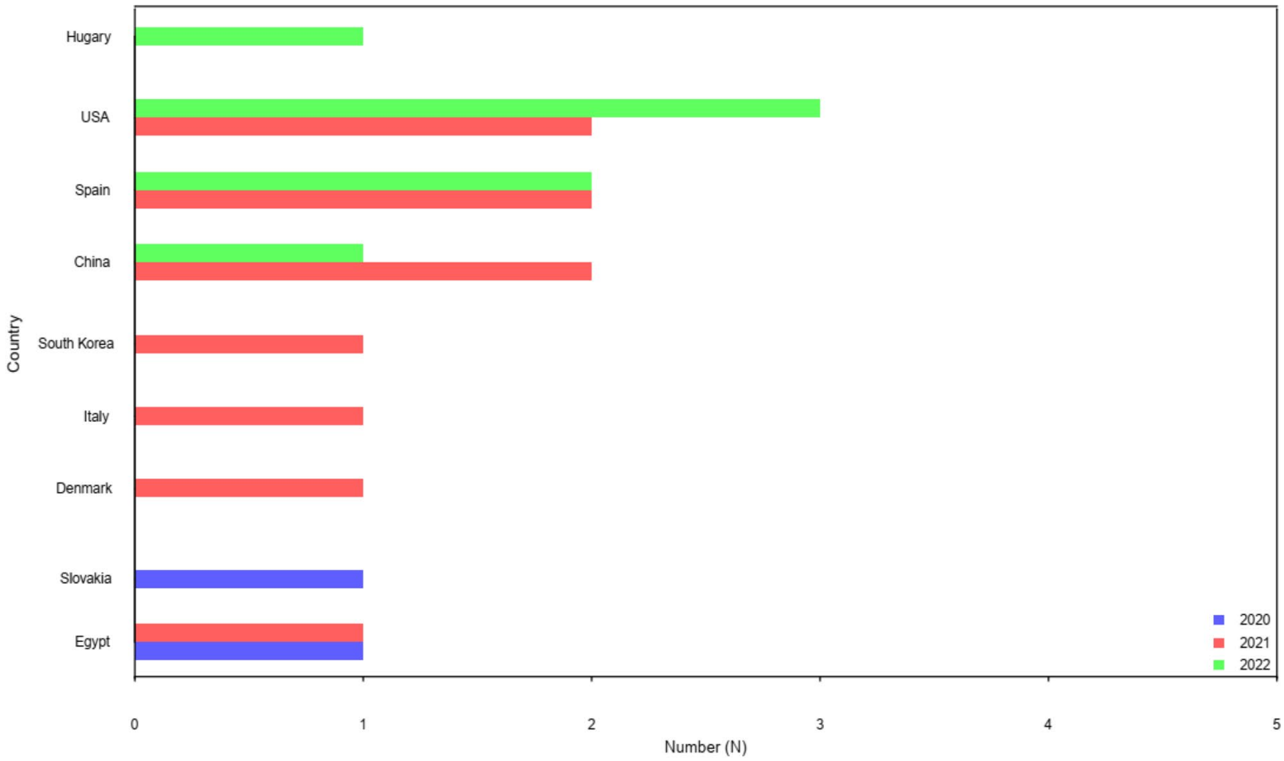


Fig. 3 Number of the screened studies per country

concluded that adopting modifications such as use of plexiglass sheets, air-jet control boxes and patterned air diffusers installed at the vent hatches can provide protection against airborne contaminants [21]. Afshari et al. (2021) determined the different risk areas for the spread of airborne pathogens in the office buildings of the three countries of Denmark, Norway and Sweden. They concluded that the design of the ventilation system in Sweden and Denmark were poorer and can contribute in the disease spread while the design of ventilation systems in the Norway, known as balanced-room ventilation system, was more efficient in reducing the risk of contaminant spread [22]. Ren et al. (2022) compared three ventilation designs, including mixing ventilation (MV), zone ventilation (ZV), stratum ventilation (SV) and displacement ventilation (DV) in a simulation for office buildings using ANSYS Fluent software. They found that SV achieved the highest performance (air distribution performance index (ADPI) of 90.5%) in reducing the spread of infection disease compared to MV, ZV and DV as well as obtaining a minimum infection risk of 13% [25]. The DV design was also the subject of a simulation research by Liu et al. (2022) as well. They studied parameters such as air velocity, air temperature, and particle number concentration in an office setting installed with a mixing ventilation (MV) system and a displacement ventilation (DV) system with different ventilation rates. In their simulation scenario the SV provided better IAQ due to vertical stratification particle number concentration and higher ventilation efficiency [35]. Pease et al. (2021) investigated the concentration and probability of SARS-COV-2 infection from internal and external sources in an office building equipped with central HVAC system. They found that at long respiratory exposure durations, adding air filtration and incorporating outdoor air into the HVAC system were recognized as the effective and most effective measures in mitigating aerosol transmission of the virus via HVAC systems. Additionally, they found that manipulating air change rate should be done with caution as it may increase the viral airborne transmission via HVAC systems [36]. Some the research reports on mitigating the COVID-19 spread in residential buildings were the use of novel technological devices such as portable air purifiers [29], application of autonomous robots to disinfect the environment [31]. Li et al. (2022) in found that a ventilation rate of 10 L/s per person can provide a similar contaminant concentration and distance decay profile equal to an outdoor setting for a person located in the indoor environment. They also found that low ventilation rate was associated with short and high range transmissions [30]. Supplying fresh air is even more critical in hospital settings. Weng and Kau et al. (2021) have designed a ward for COVID-19 patients to protect hospital staff and other patients. They reported that their proposed innovative system can provide an enhanced air change rate, maintain CO_2 concentration below 600 ppm, create isolated airflow pathways to prevent cross-contamination, reduce heat load and have the potential to be quickly deployed in any medical establishment [24]. Metro wagons are one of the extremely hazardous locations during COVID-19 pandemic. El-Salamony et al. (2021) investigated different ventilation scenarios in a metro wagon via simulation and recommended to opening windows and increasing the volume of flow rate [39]. All of the extracted studies contained limitations such as lack of parallel measurements along with measuring CO_2 [46]. However, human behavior, study duration, and inconsistent results when using methods such as decay method can be mentioned as other limitations [40].

Conclusion

In this systematic review, different strategies to curb airborne transmission of COVID-19 in indoor settings wereexplored. Educational buildings were the focus of the majority of the studies as they can generate potential disease clusters during the pandemic. In addition, various innovations were performed in form of experiments and computer simulations for disinfection, exposure mitigation and ventilation regulations such as the use of new air purifiers, disinfectant robots, room arrangements and modification of mechanical and natural ventilations. Ventilation rate has been recognized as a deciding parameter and the most cost-effective intervention in reducing the risk of infection. Besides, there has been an emphasis on the use of natural ventilation when possible and the combined use of natural and mechanical ventilation has been recommended as an efficient method to infection level and as a way to optimize energy consumption. The results of the present study can summarize the reader to the latest findings on the research conducted on reducing airborne transmission of SARS-COV-2, from the adoption of simple strategies such as natural ventilation, plexiglass and using CO_2 as an indicator to the application of robot sensors.

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Authors contribution Mohammad Safari: Conceptualization, Project administration, Methodology, Investigation, and Writing. Mohammad Sadegh Hassanvand: Conceptualization, Methodology. Ehsan Ahmadi: Conceptualization, Methodology. Samira Yousefzadeh: Conceptualization, Methodology, Mehrnoosh Abtahi Mohasel: Conceptualization, Methodology, Reza Saeedi: Conceptualization, Methodology, Supervision, Project administration. All authors have read and approved the final paper as submitted.

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Availability of data and materials Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication I give my consent for the publication of identifiable details, which include photographs and case history and details within the text to be published in the above Journal and Article.

Competing interests The authors declare that there are no conflicts of interest.

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