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REVIEW PAPER

Current approaches for preventing environment-associated contamination in healthcare facilities: a systematic literature review by open access database

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Abstract
This article presents a Systematic Literature Review (SLR) whose objective is to identify aspects related to the built environment of Emergency Rooms (ERs) and healthcare facilities that interfere with infection by respiratory diseases. The SLR presented is a relevant part of ongoing research dedicated to discussing the built environment's role on contamination, considering the COVID-19 pandemic scenario and the ER of the University Hospital of the University of São Paulo (USP), sited in São Paulo city, Brazil, as a case study. The results of this SLR showed that the main aspects discussed in the selected articles are: Heating, Ventilation, and Air Conditioning (HVAC) systems; disinfection and hygiene; layout and spatial organisation; air curtain and air purification; natural ventilation; door opening; and surface material. As major findings, the importance of properly designed mechanical ventilation systems and of the parameters' control for the maintenance of Indoor Air Quality (IAQ) are highlighted. In addition, the existence of isolation rooms; periodic assessments based on guides and protocols; self-sanitising materials surfaces; and environmental design strategies are presented, together with the development of technologies, often incorporated into hospital furniture. Thus, as contribution, the article highlights the importance of the association of several measures related to the performance of the built environment to minimise respiratory infections in healthcare environments. As a limit of this research, only open access articles and reviews from 2017 to 2021 were considered, so that the article reveals trends in this field of study, not covering the entirety of content.

Keywords Building performance · Built environment · Contamination · Emergency room · Healthcare facilities · Respiratory diseases

Introduction

The COVID-19 (Coronavirus Disease) pandemic highlighted the importance of the relationship between the built environment of healthcare facilities and contamination by respiratory diseases. When comparing the number of articles published from 2017 to 2021, there was a significant increase in publications related to the subject in the former year. As shown in this SLR, the articles mainly focus on hospital wards, intensive care units, operating rooms, or isolation rooms, which aroused interest in the search for articles dealing with other critical environments, such as ERs.

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Emergency rooms are the first point of contact for patients suffering from injuries or illness, usually from newly developing or recurring infections that are contagious [1]. People who visit these environments carry various types of diseases [2], which favours the contamination scenario. Besides, ERs are often overcrowded and require great agility by healthcare workers. We carried out multiple surveys related to such environment and contamination, using different synonyms, but there was little feedback. As there were few specific articles on the relationship between contamination and ER environment, the SLR approaches articles specifically related to healthcare facilities' built environment in general and contamination.

Taking into account that pathogen dissemination more often occurs through droplets and aerosols by the air [3], typically generated by coughing, sneezing, speaking, breathing, and even medical procedures performed on contaminated people, involving respiratory secretions [4, 5], most of the articles found are related to the ventilation system.

Another possible infection route is through contact with contaminated surfaces or objects (fomites), but the risk is considered to be low when compared to exposure to respiratory droplets carrying the virus [6]. In this way, the issues of HVAC systems; disinfection and hygiene; layout and spatial organisation are addressed, combined with issues related to air curtain and air purification; natural ventilation; door opening; and surface material.

Materials and methods

We are considering multiple methods for the research, qualitative and quantitative ones, using the ER of the University Hospital of the USP as a case study [7]. The research was approved by the Research Ethics Committee of the University Hospital of the USP, on 18th June, 2021, with the following Certificate of Presentation for Ethical Appreciation number: 47467921.0.0000.0076. It is intended to use the Post-Occupancy Evaluation (POE) [8] and the Computational Fluid Dynamics (CFD) simulation [9, 10] to evaluate the multiple flows (of users, materials, corpses, and equipment) of the ER and the airflow in a specific room of the case study. As the initial but equally important stage of the research, a SLR was done and its results will be presented and discussed below, which is the purpose of this article.

Systematic literature review (SLR)

We carried out a SLR to understand the state of the art on the relation between contamination by respiratory diseases and the environment of healthcare facilities. We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [11] and we conducted the SLR using the StArt (State of the Art through Systematic Review) tool [12]. Table 1 presents the parameters and the quest results, whereas the searches in the databases were done on 30th September, 2021.

Two questions were considered to be answered through the SLR: "What are the main aspects related to the built environment of emergency rooms (ER) and healthcare facilities that interfere with contamination by respiratory diseases?" and "What are the main ways to evaluate the built environment of healthcare facilities, considering contamination by respiratory diseases?". We did exploratory searches through Google Scholar to select the databases with the highest return on the subject. Scopus, Web of Science Core Collection, and PubMed Central were the databases used. The SLR considered the recent open access articles and reviews,[1] published in the last 5 years, and written in English. The proportion of open access articles and reviews in relation to the total articles in all databases with same criteria is presented on Table 2.

For the article identification step, we combined three groups of words related to: healthcare facilities, assessment of the built environment, and contamination by respiratory diseases. The searches returned 287 open access articles, with some duplicate results (120 articles). Thus, we established the inclusion and exclusion criteria for the 167 selected articles, as shown in Table 1. After reading the title, abstract, and keywords, it was possible to eliminate 100 articles, leaving 67 for a full reading. After complete reading, 12 articles were eliminated, using the same inclusion and exclusion criteria, and 55 articles were kept for analysis.

Results

It was possible to classify 55 articles based on their analysis. Considering the last 5 years (2017–2021), the increase in publications on the subject was notable and, together, the years 2020 and 2021 correspond to 64% of the selected publications, as shown in Fig. 1.

Regarding the country in which the article was conducted, we consider the first author's institution country to produce the graph in Fig. 2. Thus, the United States and China lead, each with 9 of the selected articles, followed by India (6 articles), and the United Kingdom (4 articles). Malaysia, France, Iran, South Korea, and Spain presented 2 articles each, and 17 other countries contributed with 1 article each. Brazil presented only one of the selected articles, published in 2021 and related to the COVID-19 pandemic, which justifies the importance and relevance of the search in the country in question, and the scientific production and dissemination of the results in English.

Then, the selected articles were grouped according to the main subject addressed, in order to guide the discussion of this article. Figure 3 and Table 3 show the predominance of articles related to HVAC systems (51%), followed by disinfection and hygiene (15%), and layout and spatial organisation (11%).

All other topics covered have a percentage lower than 10% (air curtain and air purification; various aspects; natural ventilation; door opening; and surface material).

Discussion

HVAC Systems

As 51% of articles deal with the HVAC systems, generally using case studies for the application of CFD simulations and experiments, the 28 articles were classified according to the environment considered for the discussion. In this

[1] Open access articles were adopted as one of the selection criteria. This was established by the relevance of the articles, the availability, and the open access by anyone to their results.

Table 1 SLR Protocol

Questions	What are the main aspects related to the built environment of emergency rooms (ER) and healthcare facilities that interfere with contamination by respiratory diseases? What are the main ways to evaluate the built environment of healthcare facilities, considering contamination by respiratory diseases?
Databases	Scopus; Web of Science Core Collection; PubMed Central (PMC)
Language	English
Timespan	5 years (2017–2021)
Document type	Articles and Reviews – Open Access
Identification – Query Search[a]:	
Scopus (141 results): ((TITLE-ABS-KEY (“emergency department*” OR "emergency room*" OR "healthcare facilit*" OR "health-care facilit*" OR "health care facilit*" OR hospital) AND TITLE-ABS-KEY ("built environment" OR "building performance" OR cfd OR "computational fluid dynamic*" OR "evidence-based design" OR "evidence based design" OR "post-occupancy evaluation" OR "post occupancy evaluation" OR poe) AND TITLE-ABS-KEY (aerosol OR airborne OR airflow OR circulation OR contamination OR droplet OR filtration OR flow OR "heating, ventilating and air conditioning" OR hvac OR iaq OR "indoor air quality" OR infectio* OR layout OR "social distanc*" OR surface OR ventilation)) AND PUBYEAR > 2016 AND PUBYEAR < 2022) AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English"))	
Web of Science Core Collection (110 results): TS = (“emergency department*” OR "emergency room*" OR "healthcare facilit*" OR "health-care facilit*" OR "health care facilit*" OR hospital) AND TS = ("built environment" OR "building performance" OR cfd OR "computational fluid dynamic*" OR "evidence-based design" OR "evidence based design" OR "post-occupancy evaluation" OR "post occupancy evaluation" OR poe) AND TS = (aerosol OR airborne OR airflow OR circulation OR contamination OR droplet OR filtration OR flow OR "heating, ventilating and air conditioning" OR hvac OR iaq OR "indoor air quality" OR infectio* OR layout OR "social distanc*" OR surface OR ventilation) Refined by: (LAST 5 YEARS) AND (OPEN ACCESS) AND (ARTICLE OR REVIEW) AND (ENGLISH)	
PubMed Central (PMC) (36 results): ABSTRACT: “emergency department*” OR "emergency room*" OR "healthcare facilit*" OR "health-care facilit*" OR "health care facilit*" OR hospital AND ABSTRACT: "built environment" OR "building performance" OR cfd OR "computational fluid dynamic*" OR "evidence-based design" OR "evidence based design" OR "post-occupancy evaluation" OR "post occupancy evaluation" OR poe AND ABSTRACT: aerosol OR airborne OR airflow OR circulation OR contamination OR droplet OR filtration OR flow OR "heating, ventilating and air conditioning" OR hvac OR iaq OR "indoor air quality" OR infectio* OR layout OR "social distanc*" OR surface OR ventilation Refined by: (LAST 5 YEARS) AND (OPEN ACCESS)	
Duplicate articles removed: 120	
Articles to be screened: 167	
Criteria:	
Inclusion: I) Related to building performance of human healthcare facilities and contamination by respiratory diseases I) Related to products, furniture, or new technologies that help reduce contamination by respiratory diseases in human healthcare facilities	
Exclusion: E) Related to medical procedures E) Related to urban scale or other building typologies without being only human healthcare facilities E) Not related to building performance E) Not related to contamination by respiratory diseases E) Related to microbiome analysis	
Articles excluded: 112	
Articles included in the review: 55	

The authors, based on Pati & Lorusso (2018) [11] and Fabbri et al. (2016) [12]

[a]The asterisk is used on the query search's words to ask the search program to find all documents that contain the initial part of the word (up to the asterisk) with any ending.

way, there are 8 groups of articles: hospital ward, isolation room, Intensive Care Unit (ICU) room, various, operation room, emergency department, Biocontainment Unit (BCU), and alternative care sites, according to Table 4. It is noteworthy that, in the case of the classification “various”, there are articles that address the entire floor of a hospital [18], which carried out a literature review article related to the subject [30], and that address more than one environment classification [19, 25].

Of the 28 articles selected, 22 (79% [1, 2, 13–22, 24, 26–29, 31, 33, 34, 36, 37]) considered CFD simulation as a tool to understand and visualize the influence of HVAC systems on airflow in the room, or to analyze the spread of the virus in the environment or even to identify areas that are

Table 2 Proportion of open access articles and reviews in relation to the total articles in all databases with same criteria

Databases	Open access articles and reviews	Total articles and reviews	Percent
Scopus	141	239	59%
Web of Science Core Collection	110	192	57%
PubMed Central	36	45	80%
TOTAL	**287**	**476**	**60%**

The authors

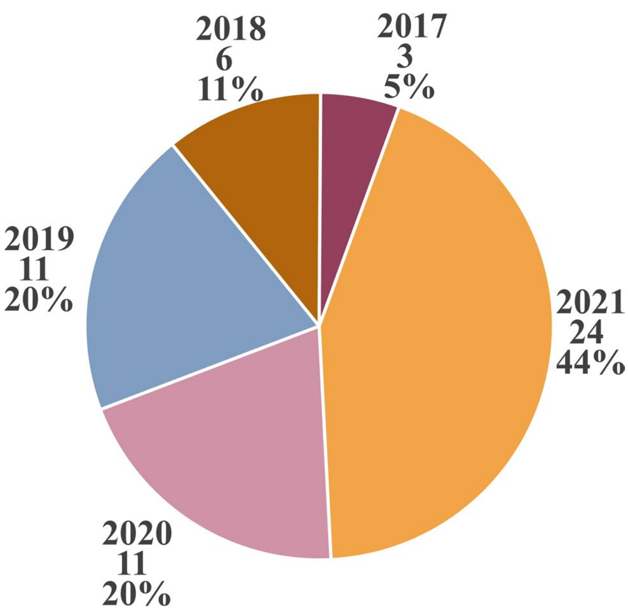


Fig. 1 Articles selected in the SLR, per year. Source: the authors

more susceptible to a viral transmission. In addition, these articles are usually associated with experiments or on-site measurements, to validate and compare the results obtained through numerical methods.

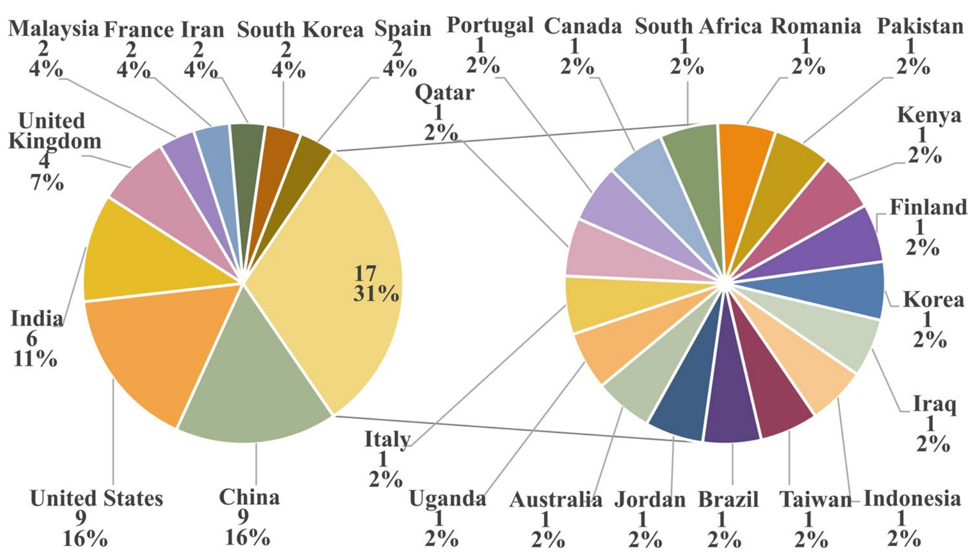
Regarding the software used in the simulations, there was a predominance in the use of Ansys Fluent [65], software developed by Ansys Inc. that is based in Canonsburg, Pennsylvania, United States, as shown in the graph in Fig. 4.

The other 6 articles address different subjects such as a fluorescent tracer particles experiment in a BCU unit [32]; a literature review on the impact that HVAC systems have on the well-being of patients [30]; good practices and strategies for HVAC system projects in ICU rooms [3]; an experimental study with field measurements to measure indoor air quality [25]; a dilution-based evaluation method for airborne infection risk [35]; and design strategies already utilized in biocontainment and in airborne infection isolation patient rooms and that improve infection control potential in alternative care sites [23].

Disinfection and hygiene

Disinfection and sanitisation are ways to reduce the transmission of respiratory diseases. SARS-CoV-2, for example, can be transmitted by aerosolized droplets that are expelled during coughing, sneezing, or breathing and by airborne transmission [41]. In this way, people may carry the virus in their hands, bodies, cell phones, keys, clothes, etc., and transfer it to the most diverse surfaces. Joshi (2020) [41] reports the development of a chamber, using CFD simulations and a prototype, to isolate the suspected patient from the healthcare worker when collecting nose or throat samples within a swab. The patient has to enter the chamber with

Fig. 2 Articles selected in the SLR, by country. Source: the authors



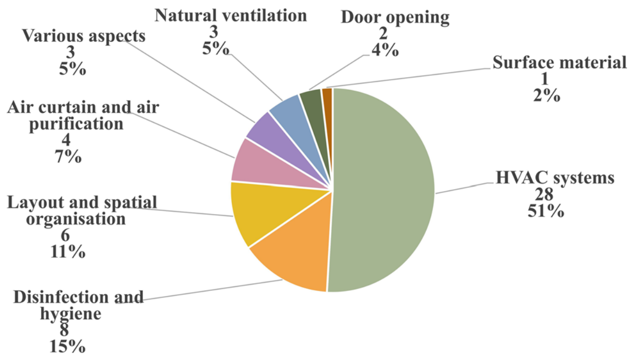


Fig. 3 Articles selected in the SLR, by the main subject covered. Source: the authors

Stone et al., 2020) [44]. However, excessive and inefficient use of disinfectants may increase the hospital's risk of becoming an incubator for resistant pathogens (Wand et al., 2017 apud Stone et al., 2020) [44]. The article showed that probiotic cleaner and plain soap fostered competitive exclusion far more effectively than disinfectants and that probiotic cleaners with microbial diversity could be worth considering for cleaning some hospital rooms [44].

In this direction, Schmidt et al. (2019) [43] compare the effectiveness of a trial persistent disinfectant and two disinfectants already registered used on critical touch surfaces, such as patient bed rails within a medical ICU. The article showed that this was the first-of-its-kind disinfectant with prolonged action, something that, until the moment, could only be done with the use of copper surfaces [43].

Table 3 Articles selected in the SLR, by the main subject covered

Main subject covered	Articles	Quantity	Percent
HVAC systems	Abed and Amer (2018) [13]; Alrebi et al. (2021) [14]; Anghel et al. (2020) [15]; Anuraghava et al. (2021) [16]; Barroso and Calcedo (2019) [17]; Beaussier et al. (2021) [18]; Borro et al. (2021) [19]; Cheong and Lee (2018) [2]; Crawford et al. (2021) [20]; Cho (2019) [21]; Ding et al. (2017) [22]; Gordon et al. (2021) [23]; Liu et al. (2020a) [24]; Nimra et al. (2021) [25]; Miller et al. (2021) [26]; Obeidat et al. (2021) [1]; Satheesan et al. (2020) [27]; Sahu et al. (2019) [28]; Santos et al. (2020) [3]; Saw et al. (2021) [29]; Shajanan et al. (2019) [30]; Thatiparti et al. (2017) [31]; Therkorn et al. (2019) [32]; Verma and Sinha (2020) [33]; Villafruela et al. (2019) [34]; Zhang and Lin (2021) [35]; Wong et al. (2019) [36]; Yu et al. (2017) [37]	28	51%
Disinfection and hygiene	Battacharyya et al. (2020) [38]; Buchan et al. (2020) [39]; Chen (2021) [40]; Joshi (2020) [41]; Maina et al. (2019) [42]; Schmidt et al. (2019) [43]; Stone et al. (2020) [44]; Thomas et al. (2019) [45]	8	15%
Layout and spatial organisation	Brown et al. (2021) [46]; Lesan et al. (2021) [47]; Lim et al. (2021) [48]; Pilosof et al. (2021a) [49]; Pilosof et al. (2021b) [50]; Yatmo et al. (2018) [51]	6	11%
Air curtain and air purification	Darvishi et al. (2021) [52]; Liu et al. (2020b) [53]; Liu et al. (2021) [54]; Wang et al. (2020) [55]	4	7%
Various aspects	Joseph et al. (2018) [56]; Opollo et al. (2021) [57]; Verderber et al. (2021) [58]	3	5%
Natural ventilation	Zhou et al. (2018) [59]; Zorzi et al. (2021) [60]; Jo et al. (2019) [61]	3	5%
Door opening	Battacharya et al. (2021) [62]; Saarinen et al. (2018) [63]	2	4%
Surface material	Abraham et al. (2021) [64]	1	2%
TOTAL		**55**	**100%**

The authors

the sample collection kit and the healthcare worker inserts his hands through the long cuff gloves to collect the sample [41]. The sample collection kit is returned to the patient, who must go out of the kiosk. Subsequently, all internal surfaces, including the gloves, are sprayed with disinfectant (5% sodium hypochlorite) and then with water to wash of disinfectant [41].

Stone et al. (2020) [44] discuss the importance of studying the cleaning of different surfaces with different products, in this case, disinfectant, plain soap, and probiotic cleaner. For the article, surfaces of a hospital were considered, where cleanings are commonly done with aggressive disinfection regimes and antimicrobial agents (Wand et al., 2017 apud

Bhattacharyya et al. (2020) [38] report that it is important, in addition to all the design requirements for Airborne Infection Isolation (AII) Rooms, that a thorough sanitisation of the room air be performed. In this way, they investigate the effectiveness of conditioned air released from air conditioning machines to mix the aerosol sanitiser to reach every corner of the AII room and kill the SARS-CoV-2 [38]. Chen et al. (2021) [40] combined fans with germicidal filters and installed them in hospital lighting to improve the air quality of hospitals. The researchers examined the performance of three embedded hospital germicidal lamp module designs,

Table 4 Articles selected related to HVAC systems

Environment	Articles	Quantity	Percent
Hospital ward	Liu et al. (2020a) [24]; Satheesan et al. (2020) [27]; Saw et al. (2021) [29]; Zhang and Lin (2021) [35]; Yu et al. (2017) [37]	5	18%
Isolation room	Anuraghava et al. (2021) [16]; Cho (2019) [21]; Miller et al. (2021) [26]; Thatiparti et al. (2017) [31]; Villafruela et al. (2019) [34]	5	18%
ICU room	Anghel et al. (2020) [15]; Crawford et al. (2021) [20]; Sahu et al. (2019) [28]; Santos et al. (2020) [3]; Verma and Sinha (2020) [33]	5	18%
Various	Beaussier et al. (2021) [18]; Borro et al. (2021) [19]; Nimra et al. (2021) [25]; Shajanan et al. (2019) [30]	4	14%
Operation room	Abed and Amer (2018) [13]; Barroso and Calcedo (2019) [17]; Ding et al. (2017) [22]; Wong et al. (2019) [36]	4	14%
Emergency department	Alrebi et al. (2021) [14]; Obeidat et al. (2021) [1]; Cheong and Lee (2018) [2]	3	10%
BCU unit	Therkorn et al. (2019) [32]	1	4%
Alternative care sites	Gordon et al. (2021) [23]	1	4%
TOTAL		**28**	**100%**

The authors

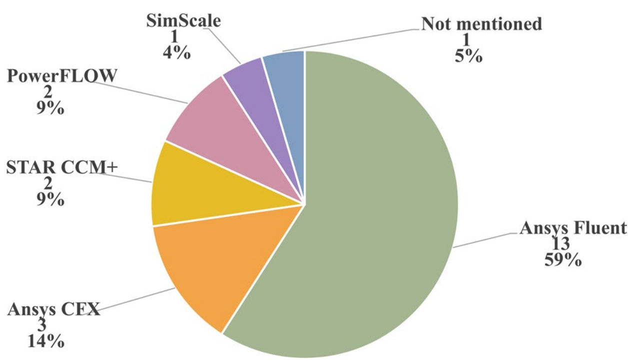


Fig. 4 Software used in the 22 articles that present CFD simulation. Source: the authors

with air filters and various fan configurations [40]. Based on that, the module that performed better was implemented and tested. The results showed that both air quality and fan energy-saving can be achieved economically and simultaneously [40].

Although typical Ultraviolet C (UVC) radiation is carcinogenic and cataractogenic, it has been used to kill microorganisms for decades [39]. Nonetheless, far-UVC is safe to be used around humans and efficient to disinfect in-room air, as shown in the article of Buchan et al. (2020) [39]. They developed a model, considering a hospital room with beds and patient regions with superimposed far-UVC, which evidences that disinfection rates increase by a further 50–85% when using far-UVC within the currently recommended exposure levels compared to the room's ventilation alone [39]. This information is essential to environments where it is not possible to use other security measures, such as adequate ventilation, social distancing, among others.

Thomas et al. (2019) [45] evaluated and improved the hand hygiene of healthcare workers and the decontamination efficacy from a program based on the World Health Organization (WHO) Multimodal Hand Hygiene Improvement Strategy (MHHIS). An assessment of the Neonatal Surgical ICU infrastructure was done, along with some changes such as traditional to elbow-operated taps, display posters and reminders, training sessions, autoclaved single-use paper towels for hand drying, among others, that contributed to the result [45]. Similarly, Maina et al. (2019) [42] assessed Water Sanitation and Hygiene (WASH) in 14 public hospitals in Kenya across four domains: organisation management, hygiene, sanitation, and water, creating and using the WASH Facility Survey Tool (WASH-FAST) that is based on WASH Facility Improvement Tool (WASH-FIT) of WHO and United Nations International Children's Emergency Fund (UNICEF) [42].

Layout and spatial organisation

The COVID-19 pandemic scenario contributed a lot to the acceleration of telemedicine technologies, not only for home care or home hospitalization but also for inpatient care, to support the lack of staff, the infection control, the space use, and overcoming limitations of distance and remote location [49, 50]. Pilosof et al. (2021a) [49] highlight the importance of physical visibility in the design of healthcare facilities since healthcare professionals need to monitor and manage different situations involving patients and it allows higher collaborative communication among nurses and doctors. Therefore, the use of telemedicine has important implications for hospital design and contributes to the resilience and flexibility of the built environment, transforming, for example, nurse station design into a central control room, because of the virtual visibility [50].

However, it is essential to understand, using evidence-based medicine, evidence-based design, and the post-occupancy evaluation [50], the impact of the reduced human touch between patients and staff, and of the isolation of patients without family support. It is necessary to incorporate issues such as patient-centered care, human connection, family involvement in the development of telemedicine and healthcare facilities layouts [50]. Pilosof et al. (2021a) [49] defend a hybrid model of virtual and physical forms of visibility since the complexity of the hospital operations demand a holistic approach to inpatient care and the best scenario is to balance physical and virtual modes.

Yatmo et al. (2018) [51] analyze the layout of two primary healthcare facilities' waiting rooms in Indonesia by using CFD simulation, in order to contribute to design considerations that could prevent the occurrence of airborne infection within the building. The objective is to trace the distribution of pathogens and their movement patterns in three different conditions (when the fan/air conditioner was on and the apertures were opened; when the fan/air conditioner was on and the apertures were closed; when the fan/air conditioner was off and the apertures were opened) [51].

The article of Lim et al. (2021) [48] shows how changes and adaptations in the physical environment of healthcare, especially in primary care, have influenced communication, situational awareness, heads-down work, social support and activities, and asynchronous information exchanges. Using two case studies, they show how design changes can either improve or hinder teamwork. For instance, while the safety precautions in response to COVID-19 are necessary, teamwork could be sacrificed depending on how the changes are implemented [48]. Similarly, Lesan et al. (2021) [47] highlight the role of healthcare layout configuration in combating pandemics, considering and examining the experience of health professionals that work on the front lines of the pandemic, through observations and 162 semi-structured interviews in four hospitals in Iran [47].

Among the problems identified through these instruments are poor isolation of the infectious ward; improper or absence of spatial isolation of patients with COVID-19 from others; long-distance between essential parts; problems with the main entrance/shared entrance for the Computerized Tomography (CT) scan and lung screening, and the inadequacy of facilities [47]. Problems of the emergency department and waiting rooms; improper or absence of spatial isolation of communication spaces and transporting patient tested positive; lack of sufficient elevators; non-segregation of hospital admission; and lack of social distancing measures were also identified [47]. Furthermore, there are improper clothing isolation and disinfection of equipment for non-COVID-19 patients; lack of indoor environmental conditions/improper lighting; inadequate resting places for medical staff; inappropriate eating conditions of treatment staff; and improper separation of sanitation services [47].

Lastly, Brown et al. (2021) [46] use three cystic fibrosis clinics as case studies to discuss aspects related to respiratory infections, which affect many patients who suffer from cystic fibrosis. From this, exploring antimicrobial resistance in the context of healthcare architecture and the staff experience of managing cross-infection, they focus on the management of patient flows and spatial segregation, on the layout, design, and furniture of the waiting rooms, and, finally, on issues related to air and the risk of aerosol infection. For this, qualitative instruments were used, such as interviews, observations, and co-design workshops [46].

Air curtain and air purification

The air curtain can be used as a way of changing the airflow pattern, isolating two adjacent spaces, cutting off airborne transmission routes, and reducing cross-infection risk as shown by the numerical simulation of Wang et al. (2020) [55]. Its efficiency varies with the human-curtain distance, the number of air pillars, the shape of the air curtain, and the jet velocity, but in all cases, the exhaled contaminants can drop to a low value outside the air curtains [55].

A pediatric isolation bed with integrated air isolation and air purification functions was designed, using CFD simulation and experiments under laboratory conditions that showed the isolation efficacy of the furniture [54]. The pediatric isolation bed consists of two compartments: a pediatric bed and an air filter system, with primary efficiency filters and a High-Efficiency Particulate Air (HEPA) filter [54]. This system is positioned to surround the child's head, to create a negative pressure at the inlet port, to capture the exhaled air, vapour, and microorganisms [54], and, after going through the filters, the purified air is returned to the ward [54]. Using a similar mechanism, a desk for medical use with air isolation, filtration, and purification functions was designed to isolate patients' exhale air from the doctor's respiratory area through an air curtain [53].

Darvishi et al. (2021) [52] designed and tested, using numerical simulations and centrifugal separation method, a system to purify hospitals' air from SARS-CoV-2. They investigated different parameters such as inlet velocity, pipe diameter, and aerosols' diameter that affect the percentage of purification. The article indicates that it is better to install the system on the floor (and not on the roof) since aerosols are heavier than air and its components will come close to the ground after some time [52].

Various aspects

Joseph et al. (2018) [56] relate the design of healthcare facilities to medication errors, falls, and Healthcare-Associated

Infections (HCAI), addressing issues such as evidence-based design (EBD) and bringing a set of strategies to avoid it, through a narrative review that the main purpose is to create safe and high-quality healthcare environments. Using the WHO's Infection Prevention and Control Assessment Framework (IPCAF) tool, Opollo et al. (2021) [57] evaluated the Infection Prevention and Control (IPC) compliance at a teaching hospital in Uganda. Problems were found, considering the eight core components of the IPCAF tool: IPC programme; IPC guidelines; IPC education and training; HCAI surveillance; multimodal strategies for implementation of IPC interventions; monitoring/audit of IPC practices and feedback; workload, staffing, and bed occupancy; and built environment, materials, and equipment for IPC at the facility level [57].

Through a literature review, Verderber et al. (2021) [58] investigate the ICU built environment, organising the material into nine categories: nature engagement and outdoor views; family accommodations in the ICU environment; ICU spatial configuration and amenity; noise considerations in ICU environments; artificial and natural lighting in ICU environments; ICU patient safety and infection control; portable field hospitals and disaster mitigation including COVID-19; ICU ecological sustainability; and recent design trends and prognostications. It was observed that single-bed ICU rooms; family engagement in the ICU experience; exposure to nature, view, and natural daylight; the importance of ecological sustainability; acknowledgment of the therapeutic role of staff amenities; and pandemic concerns have increased over the years [58].

Natural ventilation

There is sufficient evidence that demonstrates the association between airflow patterns, ventilation in buildings, and the spread of infectious diseases. Natural ventilation can be beneficial in helping reduce contamination in hospitals, as shown in some articles, however, as it is not possible to fully control the pattern and direction of airflow, it can contribute to cross-contamination, depending on the physical configuration of the hospital [59]. In the case of hospital wards with central-corridor type, for example, Zhou et al. (2018) [59] show, using a CFD simulation, that natural ventilation contributes to cross-contamination.

Zorzi et al. (2021) [60] assess, using a CFD simulation as well, the hypothetical circulation of the SARS-CoV-2 virus using only natural ventilation in a collective room located in a hospital built in Brazil to care for infected patients during the COVID-19 pandemic. The research showed, among other things, how the building elements and furniture present in the environment influence the air velocity and the airflow pattern [60]. Partitions in the environment can be used to direct the airflow and avoid contamination, in addition to the importance of being concerned with the surroundings of the hospital, with the air outlets, to avoid contamination [60]. The authors also highlight the greater difficulty in controlling natural ventilation, since the intensity of the wind patterns and velocity vary according to the seasons and meteorological factors [60].

Facing a case of nosocomial infection on one of the floors of a hospital, Jo et al. (2019) [61] perform an epidemiological investigation of the infection transmission route. The authors used CFD simulations for six situations, mainly considering the natural ventilation provided by the windows of the patients' rooms in a general ward. Simulations associating natural ventilation with the indoor mechanical ventilation system of some of the rooms in the ward were also carried out [61]. Through the analysis of the results, it was possible to show that, from a patient contaminated with MERS (Middle East Respiratory Syndrome) in one of the rooms, the contamination of nurses, family members, and other patients of the ward could probably have been caused by the airflow [61].

Door opening

The articles of Saarinen et al. (2018) [63] and Battacharya et al. (2021) [62] show the effect of the door opening of an isolation room (negatively pressurized) and an operating room (positively pressurized), respectively, on indoor airflow patterns, contamination, and infection control. While Saarinen et al. (2018) [63] simulate, through CFD simulation, perform experiments, and compare the results of opening a sliding door alone, with a temperature difference between rooms, and together with a passage, Battacharya et al. (2021) [62] use experiments, considering a hypothesized operation room where a COVID-19 patient is receiving a surgical intervention, with a hinged door.

Surface material

While hand hygiene, regular surface cleaning with disinfectants, applications of UV radiation, and infusion of hydrogen peroxide mists have all been investigated and practiced during the COVID-19 pandemic [64], the research in the area of surface material was behind schedule, mainly because of the previous wide availability of effective antibiotics [64]. Faced the increase in antibiotic-resistant pathogens, together with the emergence of new strains, Abraham et al. (2021) [64] suggest the installation of copper surfaces in healthcare facilities, public transportation, public places, and food industries, considering that this material has continuing self-sanitising properties, working as a reducer or barrier to touch-transferred infections.

Table 5 Major findings of the 55 articles selected and reviewed

Main subject covered	Articles	Major findings
HVAC systems	[1–3, 13–15, 17–20, 22, 23, 25, 29, 30, 32, 33, 36, 37]	HVAC systems play a key role in the risk of airborne infection
	[20]	Importance of adequately positioning the patients (bed orientation) and the mobile air treatment units in the environment
	[20]	Need to consider case by case when applying CFD simulation, since each room has its own parameters
	[1, 2, 13–22, 24, 26–29, 31, 33–37]	Numerical (CFD) simulations and experiments can be used to visualise the airflow, the dispersion of aerosols generated by coughing, to visualise which areas are most susceptible to virus spread, to study and visualise the best arrangement and area of inlets and outlets of HVAC systems, and the best separation of spaces (partitions), among others
	[32]	Possibility of using fluorescent tracer particles experiment to simulate airborne particle dispersion
	[2]	Ventilation rate, inlet and outlet diffuser positions, and partitions between beds, among others, influence the airborne pathogen dispersion
	[23]	Importance of modulate pressurization, direction of airflow, air exchange per hour, existence of air-handling systems with HEPA filters, UVC lighting, among others to reduce patient infection and exposure risk
	[17, 25]	According to ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), indoor air quality is determined by the distribution of temperature, relative humidity, air velocity values, and pollution levels in the room environment. Ventilation type (central air-conditioning system or non-central air conditioning system), increased visitor and doctors' activities, and cleaning sessions also interfere with indoor air quality
	[15]	Necessity of increasing the rate of air change, decreasing recirculation of air, increasing the use of outdoor air and HEPA filters for disease and infection control
	[30]	Indoor air temperature, relative humidity, indoor ventilation rate, air filtration system, differential pressure control, and mechanical strategies are related to patient medical outcomes
	[3]	Necessity of increasing air supply and exhaust ventilation on toilets to avoid the fecal–oral transmission due to the droplets generated when flushing with the toilet lid open
	[27]	The air exchange rate, the location of an infected patient, and the location of exhaust grilles in a ward influence the extent of the contamination. Generally, it is recommended that exhaust grilles are placed above each patient's bed
	[29]	Airflow patterns, distribution of aerosol particles, and thermal comfortability in patient rooms depend on several factors such as the presence and type of air conditioner, the location of fresh air diffusers, the location of room return, and the flow rate of fresh air diffusers
	[16, 21, 26, 31, 34, 37]	Airborne infection isolation rooms or isolation spaces (with negative pressure) are crucial for the control of acute respiratory infectious threats. The plan of these rooms includes many decisions: mechanical ventilation system specifications, location, layout, interior finishing, facilities, and return air, exhaust air, and supply air locations

Table 5 (continued)

Main subject covered	Articles	Major findings
Disinfection and hygiene	[41]	Importance of developing mechanisms and equipment to protect healthcare professionals and other users in the face of COVID-19 tests. As an example, there is a chamber to isolate the patient to be tested. After the examination, all surfaces of the chamber were sprayed with disinfectant
	[44]	Importance of knowing the different products for cleaning surfaces in hospital environments, since excessive and inefficient use of disinfectants may increase the hospital's risk of becoming an incubator for resistant pathogens
	[43]	Importance of developing and testing new products, such as long-acting disinfectants for persistent disinfection (similar to the effect of copper surfaces)
	[38, 40]	Need to develop systems that allow the disinfection of the hospital environment in a more complete way, in order to reach all surfaces and corners, such as aerosolized sanitisation system. Another system developed combines fans with germicidal filters that were installed in hospital lighting to improve the air quality of hospitals
	[39]	Need to think about mitigation measures for COVID-19 beyond those depending on human behaviour (minimise time exposed to the virus, social distancing, and wear personal protection equipment). An example is the use of far-UVC lighting to disinfect in-room air that has proven effectiveness
	[42, 45]	Need to carry out assessments based on existing recommendations, guides, protocols, and tools to ensure hand hygiene, healthcare facilities hygiene, water quality, sanitation, organisation management, among others
Layout and spatial organisation	[47]	Environmental design strategies can play a significant role in infection prevention and control. They can reduce problems related to poor isolation of the infectious ward; absence of spatial isolation of patients with COVID-19 from others; long-distance between essential parts; problems with the main entrance, waiting rooms, and emergency department; lack of vertical and horizontal circulations to transport patients with infectious diseases; lack of social distancing measures; improper clothing isolation and disinfection of equipment; inadequate resting places and eating conditions for treatment staff; among others
	[48]	In general, safe measures adopted in COVID-19 pandemics decrease the perception of teamness and depending on how the changes are implemented, teamwork could be sacrificed
	[49, 50]	Need to balance face-to-face (physical visibility) and virtual service (telemedicine) and to study how isolation and reduced contact with family members or healthcare professionals impact the patients
	[50]	Telemedicine allows for greater flexibility and resilience in the hospital environment
	[51]	Possibility of using CFD simulations to properly organize the layout of environments, considering the effect of fans, air conditioners, and openings on aerosol contamination
	[46]	Importance of coordinating the flow and the movements, the management of waiting, the materiality of the waiting room (layout, design, and furnishing), and questions related to the air, among other things, to prevent cross-infection and antimicrobial resistance

Table 5 (continued)

Main subject covered	Articles	Major findings
Air curtain and air purification	[52–54]	Use of numerical simulations and experiments to develop new air purification equipment and technologies
	[52]	Possibility of air purification using curved shape pipe to separate SARS-CoV-2 aerosols through centrifugal force, considering parameters such as aerosol's diameter, pipe diameter, and inlet velocity, that affect the percentage of purification
	[53, 54]	Possibility of integrating isolation, filtration, and air purification systems into furniture such as pediatric beds and desks for medical use
	[55]	Air curtains are effective in isolating two adjacent areas and preventing cross-contamination. Its effectiveness varies according to the human-curtain distance, the number of air pillars, the shape of the air curtain, and the jet velocity
Various aspects	[57]	Application and evaluation of infection prevention and control practices are important to reduce antimicrobial resistance and, consequently, healthcare-associated infections in healthcare facilities since these diseases are often caused by drug-resistant microbes present in the environment of hospitals
	[56]	Importance of hand hygiene practices (strategic positioning of sinks and gel alcohol dispensers); environmental cleaning and disinfection; environmental barriers (such as HEPA filters); single-patient rooms and copper-infused applied on frequently touched surfaces to avoid and to reduce healthcare-associated infections
	[58]	Patients admitted to single-bed ICU rooms usually present a lower nosocomial infection rate
	[58]	Decentralized nursing stations can contribute to better utilization of medication and supply rooms; to decrease energy expenditure by healthcare providers (less steps taken); and to improve documentation practices. However, usually, it doesn't favor teamwork and nurse-to-nurse collaborations
	[58]	Importance of patient visibility for teamwork, for workflow, and for patient outcomes
	[58]	Importance of Evidence-Based Design and Evidence-Based Research for facility planning, design, management, patient safety, and infection control
Natural ventilation	[59]	Despite natural ventilation providing high ventilation rates, something very beneficial to avoid aerosol contamination, an incorrect and undesired airflow can cause cross-infection transmission in hospital wards
	[59, 60]	Natural ventilation is an energy-efficient and maintenance-free solution, but it is unstable and difficult to predict and to control. Furthermore, wind patterns and velocity vary according to the season and meteorological factors
	[59, 60]	For the use of natural ventilation in hospitals, the architectural design and building elements must be very well thought out, including the use of partitions and furniture, which also influence the air velocity and the airflow
	[59, 61]	There is risk of infection being spread because of natural ventilation in the central corridor configuration
Door opening	[63]	The type of door opening and human passage through the doorway influence the airborne pathogen dispersal and the containment failures
	[62]	Door opening can disrupt the isolation conditions and can even reverse the differential pressure. This impact is related to the type of door, opening speed, and door opening frequency
	[63]	The hinged doors can present greater containment failure as compared to the sliding doors

Table 5 (continued)

Main subject covered	Articles	Major findings
Surface material	[64]	Use of self-sanitising and materials with antimicrobial properties, such as copper metal, on touch surfaces in healthcare facilities, food industries, public places, and public transport to avoid contamination
	[64]	Copper inactivates SARS-CoV-2 within 4 h, while in stainless steel (a material widely used in hospitals) the virus can stay viable for 3 to 28 days
	[64]	Using the correct surface material is practical and effective to reduce or to avoid contamination by infectious diseases in large public gathering places

The authors

Table 5 summarizes the major findings of the 55 articles selected and reviewed, organized by the main subject covered, according to the discussion presented above.

Conclusions

The results of the SLR highlight the importance of considering a set of measures to mitigate contamination by respiratory diseases in healthcare environments. It was possible to perceive that the COVID-19 pandemic highlighted the discussion about the subject and that a considerable number of articles related to technologies and equipment are being developed in order to contribute to a safer and cleaner healthcare facility. In addition, the authors found, through the SLR, that a lot of simulations and experiments are used to understand the behaviour of the fluid within the environment and thus propose changes or new technologies.

It was observed the predominance of HVAC systems articles from the search performed. Complying with the existing requirements in the standards, HVAC systems combined with air filtration, renewal, exhaust systems, and monitoring of air pressure, temperature, and humidity can be great allies in the control and maintenance of the IAQ and in minimising contamination in internal environments. It is noteworthy that the opening movement of the door and equipment such as air curtains and air purifiers also contribute. In the case of healthcare facilities, the use of natural ventilation is discussed because, as it varies with the season, the wind direction, and the positioning of the openings, it can favour the occurrence of cross-contamination.

Contamination by contact is also a possible route, therefore, issues such as hygiene, disinfection, and surface materials deserve attention. Only one article about surface material was selected, suggesting that this is an area that could be better explored. Something important to mention is that small changes in the built environment of healthcare facilities favoured an increase in employee hand hygiene, which is a highly impactful measure to reduce contamination. In this sense, articles on layout and spatial organisation are essential and show the impacts of telemedicine and of the safety precautions on the perception of users; the necessity of physical visibility for the monitoring of patients by the healthcare workers; the importance of setting up separated circulation routes and planning clusters of patients with different symptoms and suitable environments for those who need isolation; among other procedures.

Finally, it was not possible to identify recent articles that relate the different flows (materials, equipment, patients with flu symptoms, patients without flu symptoms, employees, family members, medicines, corpses, and waste) existing in an ER and the IAQ, when it comes to contamination by respiratory diseases. As limitations, a new SLR could cover a period longer than 2017 to 2021, considering more languages, databases, and articles that deal with other building typologies, such as schools, workplaces, restaurants, and hotels, without being only healthcare facilities. Lastly, but equally important, by considering only open access articles and reviews, this article presents trends in this field of study, being relevant to consider, in future research, additional articles that had been published in different ways than open access, to cover more contents and aspects that influence contamination by respiratory diseases.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare relevant to this article's content.

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