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A review of facilities management interventions to mitigate respiratory infections in existing buildings

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ABSTRACT

The Covid-19 pandemic reveals that the hazard of the respiratory virus was a secondary consideration in the design, development, construction, and management of public and commercial buildings. Retrofitting such buildings poses a significant challenge for building owners and facilities managers. This article reviews current research and practices in building operations interventions for indoor respiratory infection control from the perspective of facilities managers to assess the effectiveness of available solutions. This review systematically selects and synthesises eighty-six articles identified through the PRISMA process plus supplementary articles identified as part of the review process, that deal with facilities' operations and maintenance (O&M) interventions. The paper reviewed the context, interventions, mechanisms, and outcomes discussed in these articles, concluding that interventions for respiratory virus transmission in existing buildings fall into three categories under the Facilities Management (FM) discipline: Hard services (HVAC and drainage system controls) to prevent aerosol transmissions, Soft Services (cleaning and disinfection) to prevent fomite transmissions, and space management (space planning and occupancy controls) to eliminate droplet transmissions. Additionally, the research emphasised the need for FM intervention studies that examine occupant behaviours with integrated intervention results and guide FM intervention decision-making. This review expands the knowledge of FM for infection control and highlights future research opportunities.

1. Introduction

1.1. Background

- **Respiratory virus transmission and interventions**

The pandemic induced by respiratory viruses such as severe acute respiratory syndrome (SARS), SARS-CoV-2, influenza, and tuberculosis (TB), poses a global threat to humanity [1]. While vaccines and medical treatments are natural remedies, non-pharmaceutical interventions (NPIs) have been recognised as essential and effective in reducing virus spread before medical cures are developed and delivered. Interventions such as gathering restrictions implemented one century ago during the 1918 influenza pandemic have guided the global NPI against SARS in 2003, H1N1 in 2009, and the current Covid-19 pandemic [2–4]. Numerous studies have modelled the effects of the government NPIs on the Covid-19 pandemic worldwide and visualised the robustness of harsh measures such as travel bans, school closures, venue shutdowns, and stay-at-home orders [5,6]. Despite their effectiveness, these harsh measures and lockdowns have entailed huge costs and potential under-investigated psychological burdens and societal harms [7], calling for studies on other alternatives to prevent virus transmission while not dramatically interfering with people's lives.

On the other hand, statistics on quarantine failures globally during the Covid-19 pandemic, namely virus escaping from travellers staying in quarantine facilities to the public, have demonstrated our fragility in controlling indoor infection in existing buildings. For example, by June 2021, 32 COVID-19 "quarantine failures" had occurred in Australia and New Zealand, where quarantine hotel workers, security guards [8], for example, were infected and transited the virus to the community from the quarantine facilities [9], resulting in enormously costly consequences. Notably, the four original outbreaks in Melbourne were all

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traced back to quarantine hotel leakage, which led to one of the world's longest lockdowns, prompting the government to temporarily phase out the usage of quarantine hotels in the city [8,10]. In addition, although the exact cause of some outbreaks remains unknown, a poor understanding of SARS-CoV-2 transmission mechanisms during the early months of the pandemic appears to have been a critical factor, resulting in errors in focusing only on fomite-based controls and selecting inappropriate facilities as quarantine sites, leading to transmissions in hotel-managed quarantines [11]. Therefore, while vaccination of quarantine facilities workers was critical [9], successfully implementing quarantine strategies requires appropriate infrastructure and building operations solutions that effectively mitigate virus transmission from infected individuals to others in quarantine facilities.

Indoor infection control is crucial for preventing the transmission of respiratory viruses. Today, humans spend 90% of their time in constructed environments [13], but it emerged that most buildings were not safe shelters during the Covid-19 pandemic. In fact, according to Swinkels, 95.7% of super spreader events worldwide occurred indoors in 2019 (1283 out of 1341) [14]. Moreover, the current literature about the respiratory virus transmission mechanism has acknowledged three potential respiratory virus transmission routes: fomite (contacts), droplets, and aerosols [15–21], indicating that the respiratory virus can transmit from "human to human" or "building to human" in existing buildings [22]. However, the massive disruptions in numerous buildings during the pandemic revealed the critical significance of health-related components in non-healthcare contexts and existing vulnerabilities. In this context, epidemiologists have emphasised the problems and significance of strengthening engineering controls to mitigate the risk of infection indoors and protect healthcare personnel and the general public [22].

- **Facilities Management and infection control**

Facilities Management (FM) is defined as a profession and a function that "integrates people, place, process and technology within the built environment to ensure functionality, comfort, safety and efficiency of the built environment, improving the quality of life of people and the productivity of the core business" [23,24]. Since the operation and maintenance (O&M) phase in a building's life cycle is the longest, FM significantly impacts buildings' performance, thus contributing to indoor comfort and occupant health. Meanwhile, FM design and operations significantly impact occupant behaviours that affect pathogen transmissions [25]. For this reason, FM in healthcare has been recognised as an essential health management component [26]. Indeed, the history of FM practises for infection control could date back to 1854, when Florence Nightingale designed and implemented a robust practice in ventilation, indoor air quality control, and environmental cleaning to prevent Hospital-Acquired Infections (HAI) [27]. Therefore, all the indoor infection control mechanisms could be integrated into the FM discipline.

The indoor environment and its effects on occupant well-being have emerged as a research theme for FM. First, illnesses caused by respiratory pathogens have resulted in economic losses due to the reduction of employee productivity before the Covid-19 pandemic. For example, most short-term absences for office workers were caused by respiratory diseases, such as seasonal flu [28]. Moreover, green building certifications such as LEED and WELL have gained increased attention in recent years during the building operation phase because many organisations recognised that reduced absence due to sickness related to indoor environments would significantly benefit the organisation's overall productivity [29]. Nevertheless, studies on respiratory infection control through FM activities remain limited; thus, it is more important than ever to reevaluate how we manage our current facilities from a health perspective.

1.2. *Objectives and significance of this review*

Due to the Covid-19 pandemic, industry experts and academic researchers require a comprehensive overview of recent FM and Infection Control studies. This paper identified 15 related review articles, as summarised in Table 1. They are, however, usually limited in the scope of covered FM activities and building types because of a different research focus rather than FM. For example, some reviews focused more on organisational and healthcare interventions [7,30]; Several reviews focused on IAQ controls [19,31,32], while some focused on a specific technology, such as UVGI [33,34] or HEPA filtering [35,36], leaving gaps in other FM activities that may contribute to infection control. Therefore, this research attempts to bridge the gap by providing an overview of existing academic studies on FM intervention for infection control from the perspective of a Facilities Manager.

This paper will synthesise the context, mechanisms, and outcomes of various FM intervention studies to explain how infection control could be achieved from integrated FM. It will serve as the foundation for further research into FM solutions for battling the pandemic and enhancing building operations for occupant health. It will also inform environmental health policymakers when considering FM interventions for future pandemic control. This study will answer the following questions:

a. What are the current practices of FM interventions to prevent indoor respiratory virus transmission and their effectiveness?
b. What are the research gaps regarding FM intervention for respiratory infection control?

2. Method

This article adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [43] method to review the existing literature on academic publications focused on FM interventions for mitigating indoor respiratory infections. The review process consists of four main steps: (1) defining the study scope and identifying the keywords used for article searching; (2) searching and screening materials collected from databases and accessed articles; (3) reviewing materials and summarising the search result; (4) analysing content and discussing the studies in key areas and identifying research gaps.

2.1. *Study scope*

FM has a broad service scope [29,44]. After a preliminary search, the research scope has been limited to essential FM activities that significantly contribute to infection control of respiratory viruses among building occupants. First, hard services, including ventilation, air-conditioning, and drainage, were included since they are widely accepted as the most significant areas contributing to airborne transmission control in the built environment [32,45–48]. Second, cleaning services were included as a critical control for fomite transmission in buildings under the soft service category. This review acknowledges that other soft service activities such as security control, waste disposal, laundry service, and catering may transfer respiratory pathogens in buildings [27,45,46]. However, due to the scarcity of papers studying interventions in these FM activities for respiratory infection control, they were removed from the paper's coverage for the detailed analysis, with some thoughts and recommendations for future study in these areas in Section 4.2.4. Third, the review covers space and occupancy management interventions that directly contribute to occupants' behaviour and physical distancing in buildings. After defining the review scope, a series of keywords were developed based on included FM activities and the keywords included in Table 1. Fig. 1 shows the scope of FM and the scope of this research in terms of FM activities. Table 2 Lists the keywords used for article searching.

Table 1
Existing literature reviews on FMI for respiratory infections control.

Year	Settings	Pathogen	FM related interventions								Reference
			Ventilation	HEPA Filtering	UVGI	Air Pressure	Drainage system	Cleaning	Space management	Occupancy control	
2010	Multiple settings	airborne virus			X						[34]
2010	Healthcare	airborne virus		X	X						[37]
2016	General buildings	airborne virus	X	X	X						[38]
2016	Healthcare	airborne virus	X	X	X						[33]
2020	Healthcare and educational	SARS-CoV-2						X			[39]
2020	Hospitals	SARS-CoV-2						X			[40]
2020	Schools	SARS-CoV-2	X					X		X	[7]
2020	Healthcare and educational	airborne virus								X	[41]
2021	Universities	SARS-CoV-2	X	X						X	[30]
2021	General buildings	SARS-CoV-2	X								[42]
2021	General buildings	SARS-CoV-2		X							[36]
2021	General buildings	SARS-CoV-2	X	X	X						[31]
2021	General buildings	SARS-CoV-2	X	X	X						[32]
2021	Homes and workplaces	SARS-CoV-2		X							[35]
2022	Multiple settings	SARS-CoV-2	X	X	X						[19]

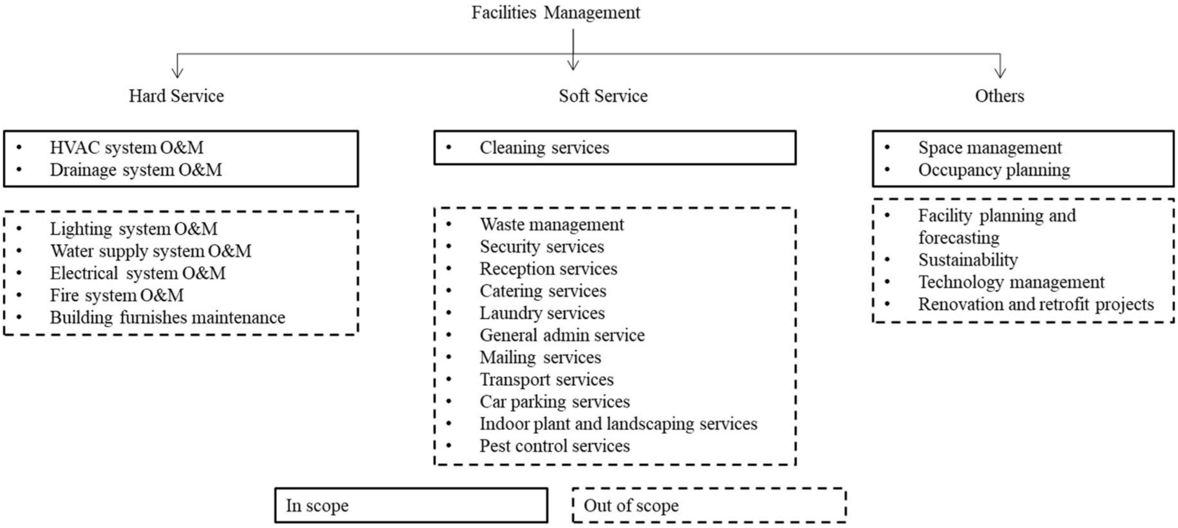


Fig. 1. FM activities [29,44] and the scope of this research.

2.2. Systematic search

As illustrated in Fig. 2, the study first collected 1029 sources from Scopus, Compendex, and Web of Science using the keywords indicated in Table 2. Then, after eliminating duplicates and non-English articles, 725 records were obtained. Next, the titles and abstracts of these results were verified and filtered on the Rayyan platform to eliminate publications unrelated to FM. Moreover, all non-journal items, including conference papers, government reports, and commercial briefs, were excluded due to concerns about their quality. Following this, 128 publications were retrieved and reviewed thoroughly for analysis. Subsequently, 42 papers were removed because they were either review papers or background articles that lacked quantitative outcomes of interventions. Finally, 86 articles were picked for further analysis.

Table 3 illustrates the distribution of study mythologies in included articles. The studies were grouped into two research categories: epidemiological and engineering. Epidemiological studies are “into the frequency of occurrence, distribution, and causes of health-related events, states, and processes " in specified populations [49], with distinct methodologies to investigate health outcomes [38]. This review included 11 epidemiological studies that measured the relationship between FM variables such as ventilation rates, UVGI installed, or

Table 2
Keywords used to article searching.

Themes	Keywords for searching (any of the following under each theme)
FM Interventions	“Non-pharmaceutical intervention”, “NPI”, “Facilities management”, “Facility management”, “operation and maintenance”, “O&M”, “building operation “or “maintenance and repair”, “space management”, “space planning”, “workplace planning”, “relocation management”, “Engineering plan”, “HVAC”, “air purifier”, “Smart building”, “Engineering controls”, “Building ventilation ",” BIM-FM”, “FM intervention”, “building measures”, “Facility Service”, “environmental cleaning”, “housekeeping”, “interior finishes”, “Indoor Surface cleaning”, “environmental surface material”, “Drainage”, “UV”
Respiratory virus	Coronavirus, SARS-CoV-2, Covid-19, 2019 nCoV, SARS, H1N1, tuberculosis, influenza, “airborne virus”,” respiratory virus.”
Effectiveness	Efficacy, effectiveness, outcome

cleaning frequency and disease occurrence through observations or intervention trials (i.e., experiments with a control group). By contrast, the included 75 engineering studies explained the relationship between FM factors and respiratory virus transmission or predicted the probability of disease occurring using various methods, including 12 case studies, 31 experiments and 32 modelling studies.

Readers shall be aware of the parallels and contrasts between the two study groups. For example, both intervention trials and engineering experiments assess the relationships between variables by comparing before/after situations to changes in some FM variables. However, engineering studies observe the effects of interventions in a laboratory or a specific physical environment, where aerosol-size smog or droplets were spread to simulate the spread of virus-laden particles; thus, experimental data do not directly reflect the actual concentration and removal of the virus. By contrast, epidemiological trials assess the effectiveness of interventions using direct metrics such as virus-laden particle or aerosol clearance rate in real-world patient-infected settings or direct data of infection results based on infected population or disease development, thus presenting more direct and convincing evidence [38].

2.3. Content analysis

This review organised the search findings with a CIMO framework

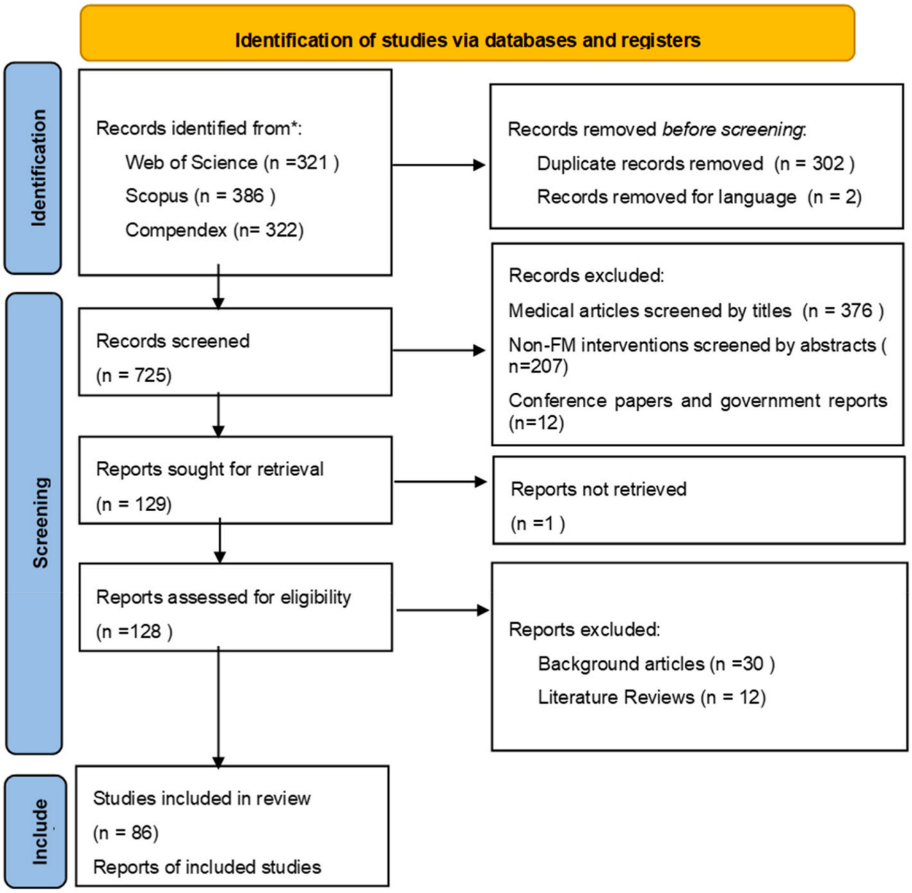


Fig. 2. PRISMA Flow diagram.

Table 3
Study methodologies of included articles.

Numbers of studies	Epidemiological studies		Engineering Studies			Total
Category	Observational	Intervention	Case studies	Experiments	Modelling	
HVAC	2	5	4	26	19	56
Cleaning	1	2	0	2	4	9
Drainage	0	0	3	3	6	12
Space and occupancy	1	0	5	0	3	9
Total	4	7	12	31	32	86

[50], systematically integrating evidence-based information from included articles. All the included publications were subjected to a thorough assessment in the following areas with the CIMO logic as shown in Fig. 3: (1) Context(C): facility types and pathogen type; (2) Intervention (I): FM intervention approaches and FM activities involved; (3) Mechanisms (M): mechanisms to mitigate virus transmission; (4) Outcomes (O): intervention outcomes achieved and measured. The details of the findings will be described in Section 3.

3. Results

3.1. Context

- **Facility Type**

As illustrated in Fig. 4, the studies were categorised into five groups based on the facility type in which the FM intervention was implemented or modelled: (1) Educational facilities, namely schools and universities; (2) Healthcare facilities, such as hospitals, dentist offices, and nursing homes; (3) Commercial facilities, including offices, gymnasiums, and restaurants; (4) Residential properties, including single-family homes and apartment buildings; (5) Not specified or mixed: simulated confined spaces or multiple scenarios.

Healthcare facilities, particularly hospitals, were the most studied facility type, followed by educational buildings. Twenty-two studies were conducted on healthcare buildings, including two dental service facilities [51,52], one nursing centre [53], and 19 studies on different hospital space types such as operating rooms, wards, examination rooms, and emergency departments. However, the facility type cluster varies across studies examining various FM activities. For example, residential buildings accounted for more than 80% of drainage system studies (10 out of 12), and most studies (10 out of 14) in residential buildings were conducted for drainage systems and infection control. By contrast, more than 50% of space and occupancy studies were conducted in educational settings. Overall, there were fewer studies in commercial facilities, where twelve studies were conducted, covering exercise facilities [54,55], recreational facilities [56], restaurants [57–59], retail stores [60], and office buildings [28,61–63].

- **Pathogen type**

As shown in Fig. 5, all materials were classified according to the pathogen type examined. Due to the worldwide devastation caused by the Covid-19 pandemic, most studies (60) have been conducted on SARS-CoV-2 in the last two years (2020–2021), followed by Influenza (9), SARS (8), and TB (3). The remaining six studies did not specify the respiratory pathogen type.

3.2. FM interventions

To gain an understanding of the research status in different FM activities for infection control, the papers were grouped into four intervention groups shown in the CIMO framework (Fig. 3): (1) HVAC system, (2) Drainage system, (3) Cleaning, (4) Space and occupancy management. The review revealed that few studies addressed multiple FM service categories; we identified only six studies that focused on IAQ controls and included occupant density, which we classified as HVAC studies based on their primary research focus. As depicted in Fig. 6, HVAC systems have been the subject of most studies, accounting for 65% of all included publications, followed by drainage system studies (14%), cleaning (11%), and space & occupancy (10%). A detailed analysis of these interventions is provided in Section 4.

3.3. Mechanisms

As stated in Table 4, all papers were categorised according to the intervention measures and mechanisms. The content analysis shows that HVAC interventions reduce airborne transmission by lowering pathogen concentrations in the air through four strategies: air dilution, air filtration, air purification, and air pressure controls. Following that, efficient

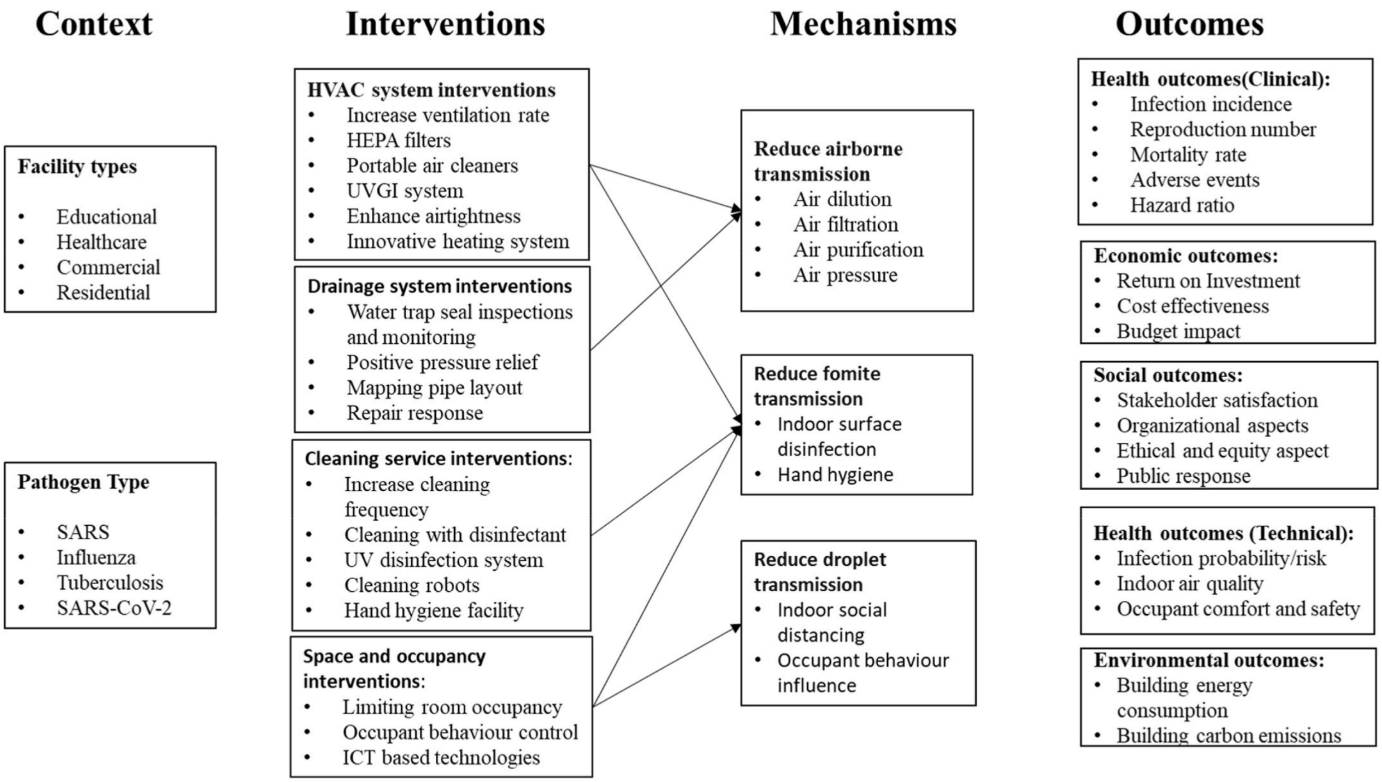
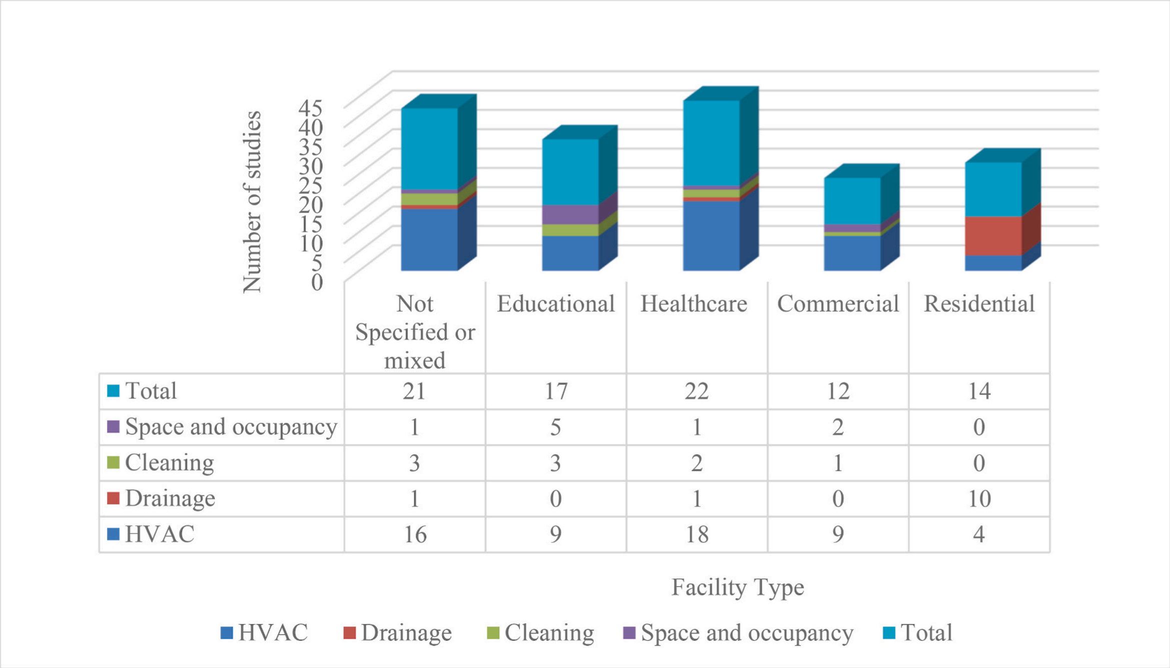
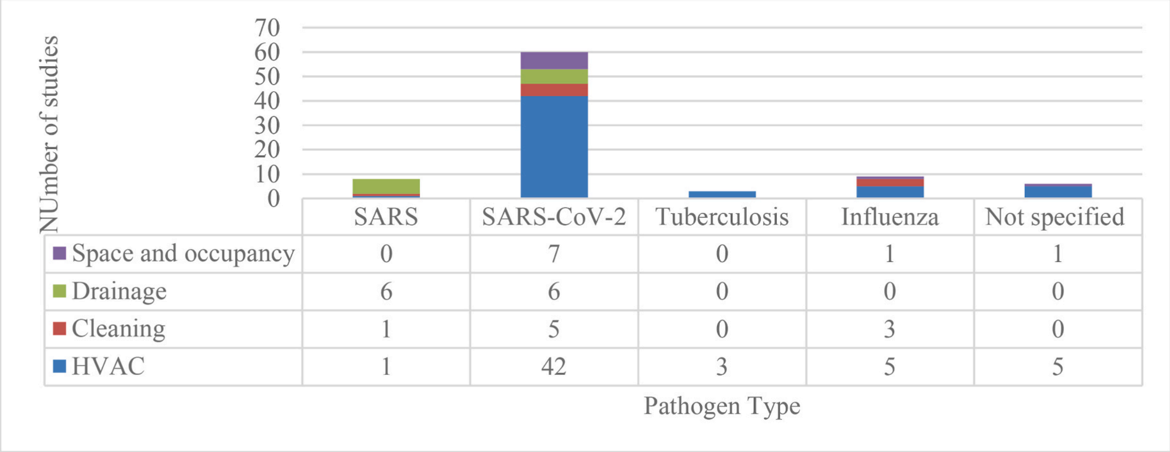


Fig. 3. Studying FM interventions with the CIMO framework [50].



	Not Specified or mixed	Educational	Healthcare	Commercial	Residential
Total	21	17	22	12	14
Space and occupancy	1	5	1	2	0
Cleaning	3	3	2	1	0
Drainage	1	0	1	0	10
HVAC	16	9	18	9	4

Fig. 4. The number of included articles by facility types.



	SARS	SARS-CoV-2	Tuberculosis	Influenza	Not specified
Space and occupancy	0	7	0	1	1
Drainage	6	6	0	0	0
Cleaning	1	5	0	3	0
HVAC	1	42	3	5	5

Fig. 5. The number of included articles by virus type.

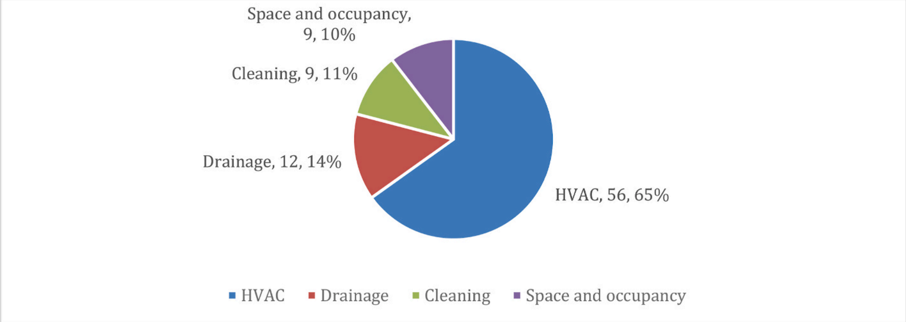


Fig. 6. Studies categories based on FM activities.

drainage system operation and maintenance prevent airborne transmission via the drainage system. Additionally, cleaning operations and hand hygiene measures control fomite route transmission, whilst occupancy and space management aim to reduce droplet transmission by facilitating social distance. Whereas many studies cover multiple intervention methods, readers should notice that no studies in our

Table 4
Mechanisms of FM interventions on infection control.

Transmission Route	Intervention Mechanisms	Number of studies	Intervention Methods	Reference
Airborne route	Air Dilution	18	- Natural ventilation - Displacement ventilation - Mixing ventilation	[52,54,60, 62,64–77]
Airborne route	Air Filtration	24	- Mobile air purifiers - HEPA filters on recirculated air	[51,52,54, 55,59,61, 62,72,75, 78–92]
Airborne route Fomite route	Air Purification Surface disinfection	16	- Sunlight exposure - Upper-room air lamps - HVAC in-duct UVGI lamps - Portable UVGI device	[62,63,72, 78,93–102]
Airborne route	Air Pressure controls	10	- Airtightness - Air pressure control for specific space	[53,62,86, 87,91,95, 103–106]
Airborne route	Prevent virus transmission via the drainage system	12	- Proper operation and maintenance of drainage system	[107–118]
Airborne route	Reduce air recirculation	3	- Electric heat pump (EHP) operation - Disinfected Trombe wall	[58,119, 120]
Fomite route	Indoor surface disinfection	8	- Increase cleaning frequency - Disinfectant use - Electrostatic sprayers - Disinfection robots	[57, 121–128]
Fomite route	Occupant hand hygiene	5	- Hand hygiene facility - Cleaning operations - Cleaning robots	[57,121, 123,126, 128]
Droplet route	Occupancy control	10	- Decrease occupancy rate - Adjust occupancy schedule	[28,60,62, 70,72,76, 77, 129–131]
Droplet route	Space management	6	- Indoor navigation system - Spatial configuration - Rearranged floor plan - Smart surveillance - Elevator operations	[28,56, 132–135]

review covered all three transmission routes. The detailed intervention mechanisms will be discussed in Section 4.1. In addition to the PRISMA method, we have incorporated additional highly related review papers as identified through the peer-review process. The content of these papers was also included in our discussions.

3.4. Outcomes

The outcome analysis of interventions is critical for policymakers and building managers to make evidence-based decisions. While health and economic outcomes are the key concerns when weighing the costs and benefits of interventions, other social factors such as stakeholder acceptance and implementation feasibility are also essential assessment criteria for health-related decision-making [136–138]. Additionally, as building operation impacts building energy and emission performance [71], the environmental impact of FM interventions should also be considered. As shown in Table 5, this review classified the intervention outcomes into five categories: (1) Health outcomes (clinical), direct health efficacy observed or determined by infection incidence, mortality, attendance/absence rates of subjects, or hazard removal ratio/rival loads in real settings infected by respiratory virus; (2) Health outcomes (technical), implies indirect health outcomes as estimated by infection probability/risk modelling, aerosol particle concentrations or particle removal ratio observed in labs or other simulated settings; (3)Economic outcomes, such as cost-effectiveness and return on investment; (4) Environmental outcomes, such as energy efficiency and emissions from buildings; (5) Social outcomes, including stakeholder satisfaction, ethical and equity aspects and others.

All studies evaluated the health outcomes of interventions, with engineering studies relying on technical measures such as infection probability based on modelling findings or hazard reduction rate calculated through experiments, and only epidemiological trials were on direct health outcomes from epidemiological trials, as explained in Sec.2.2. Additionally, it is worth noting that most of the modelling research focuses on infection risk at the room level, with only a few studies examining infection risk at the building or community level. For example, only three community-level studies simulated infection outcomes in Hong Kong via ventilation interventions in residential buildings [64], schools and houses [65], and multiple public building types [66].

In general, there is a lack of thorough understanding of these interventions' economic, environmental, and social outcomes. (1) Economic outcomes: several studies on IAQ related interventions have discussed cost considerations, but none have been quantitative. The most comprehensive was Shen's paper, which classified IAQ control interventions into three cost categories, categorising personal ventilation, displacement ventilation, double supply air, or 100% outdoor air as "high cost," air cleaners, upper room UVGI systems, partition installation, and HEPA filters as "medium cost," and occupancy control as "low cost" [72]. (2) Social outcomes: We only identified three articles that explored the social effects of limited-coverage FM strategies. Two studies gathered feedback from occupants and stakeholders on the noise level generated by portable air purifiers installed in classrooms; however, the findings were inconsistent [82,83]. Moreover, Zhang et al. analysed the effects of varying occupant schedules on occupant productivity with a somehow unwarranted assumption that extended work hours boost worker productivity [76]. (3) Environmental outcomes: Five studies examined the environmental consequences of FM interventions, focusing on energy consumption and emissions associated with HVAC and occupancy management solutions. Section 4 will discuss the intervention outcomes and research gaps in detail.

4. Discussion

4.1. Research evidence on the effectiveness of FM interventions

4.1.1. HVAC interventions

Under the Covid-19 pandemic, numerous HVAC-related organisations, such as the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and the Federation of European Heating, Ventilation, and Air-Conditioning Associations (FEHVAA), issued HVAC operations guidelines to prevent airborne virus transmission in buildings. However, while they all recognised the vital role of increasing ventilation, significant variations in HVAC operation requirements, such as ventilation rates, indicate a research gap [42]. In

Table 5
Intervention outcomes discussed.

Outcomes	Health (Clinical)	Health (Technical)	Economical	Environmental	Social
HVAC	6	50	10	3	2
Cleaning	3	6	0	0	0
Drainage	0	12	0	0	0
Space and occupancy	1	7	1	2	1
Total	10	75	11	5	3

addition, there are no rules for periodically monitoring indoor air quality in a facility [32]. In this review, 56 articles addressed airborne transmission and evaluated HVAC interventions. Table 4 shows the distribution of HVAC system interventions. Readers shall be aware that many studies cover more than one intervention measure, comparing the effects of different HVAC intervention methods on airborne virus transmission.

4.1.1.1. Ventilation and air dilution. Increasing outdoor air ventilation dilutes the contaminated room air, thus reducing occupants' infection risk. In this review, 18 articles discussed the effectiveness of building ventilation for infection control. Unsurprisingly, all included studies agree that enhanced ventilation could lower the indoor infection risk. However, ventilation alone cannot prevent indoor airborne transmission.

All ventilation studies considered ventilation rate a critical air dilution indicator for pathogen removal. Significantly, the widely used Wells-Riley equation has established the numerical links between ventilation rate and indoor airborne transmission risk. However, the quantitative outcomes across studies differ because of different settings and study methodologies. For instance, Gao et al. concluded that an air change rate of more than 5 ACH in schools and residential rooms could diminish an influenza outbreak at a community level and delay the rise of the epidemic curve with any airborne virus [64,66]. Shen et al. estimated that 100% outside air (OA) could lower Covid-19 infection risk by 27%, and doubling the overall supply airflow rate could reduce the risk by 37% on average [72]. Zafarnejad and Griffin estimated that doubling ventilation could reduce the mean transmission risk by 25% [75].

Numerous investigations revealed that the current ventilation standard, such as the minimum fresh airflow requirements in various building codes, is insufficient to prevent airborne transmission, particularly in high-occupancy buildings such as school classrooms, gyms, restaurants, care facilities, and hotels [54,72,73]. For instance, Blocken et al. demonstrated that the required ventilation rate for the gym during the Covid-19 pandemic is more than twice the Dutch Building Code (995 m3/h vs 433 m3/h) [54].

On the other hand, there are some adverse outcomes of increasing ventilation rate: (1) Indoor comfort: draught and noise level; (2) Cost: Increased energy consumption and thus higher cost [54,72]. Furthermore, increasing the ventilation rate excessively under a mechanical ventilation system is costly since it needs additional energy to condition the external air (heating, cooling, and (de)humidification) [54]; (3) Environmental outcome: more CO2 gas emissions [71]. Nevertheless, the proper ventilation rate for various buildings to control airborne transmission remains unknown.

Eight articles adopted CO2 level as a variable to assess airborne infection risk with different ventilation arrangements. Carbon dioxide concentration is recognised as an indicator for determining the outcome of air dilution based on the well-mixed air assumption. Gammaitoni and Nucci (1997) modified the Wells-Riley equation and established the mathematical relationship between CO2 level and airborne transmission risk [139]. However, when air filtration or purification is used, particles can be eliminated by filters or UV lamps without reducing the CO2 concentration in the air; thus, airborne viruses do not necessarily link with the CO2 level. Nevertheless, equipping public buildings with CO2 sensors might aid in assessing infection risks and monitoring overall air quality for occupant health and comfort.

Three types of ventilation mechanisms were discussed: (1) natural ventilation, (2) displacement ventilation, and (3) mixing ventilation. Shrestha et al. measured that air flushing before and post-occupancy is ineffective in reducing maximum daily concentrations of particles in the air; hence the ventilation intervention requires a constant high percentage of outdoor air supply [62]. For this reason, controlling of ventilation rate is critical for effectively removing pathogens in the air. Unfortunately, natural ventilation is highly influenced by outdoor air quality, wind speed, the room layout, the dimension of the inlet-outlet openings (doors and windows), furniture arrangement, and other complex elements, and thus difficult to control the ventilation rate [38]. Nevertheless, four studies investigated ventilation effectiveness in natural ventilation settings, including school classrooms [77], retail stores [60], hospitals [67], and residential rooms [74]. It is concluded that the layout of openings to achieve cross-ventilation is the key to ventilation in buildings that lack HVAC equipment, and constant window opening can be a short term strategy to dilute the air [77]. However, a significant concern with natural ventilation is cold weather when windows are often closed to keep warm and lack outdoor airflow. Gilkeson et al. thus proposed a hybrid ventilation strategy to ensure adequate ventilation throughout the year with less energy consumption and emissions [67].

By contrast, mechanically ventilated rooms have a far more tightly controlled ventilation rate, making it easier to test, report, and compare across buildings. However, ventilation rates in different rooms within a central ventilated facility often vary significantly depending on their location and the layout of their ventilation system. For example, a case study in dental facilities demonstrates that dental treatment rooms situated at the distal ends of the air supply duct system have much lower ventilation rates than other rooms, particularly those with more exhaust air returns [52]. For this reason, most studies in the central ventilation context were also at the room level.

Displacement ventilation promotes vertical stratification and removes polluted warm air near the ceiling by utilising the room's inclination, and hence has higher ventilation effectiveness than the mixing ventilation system [140]. Shen et al. calculated that displacement ventilation could reduce infection risk by 26% and 46% with partitions around individual workplaces, achieving similar effects (37%) of doubling the ventilation rate on average. However, the cost-effectiveness of displacement ventilation is mixed. For instance, Shen et al. argued that displacement ventilation is expensive since it requires an initial investment to upgrade the ventilation system [72], while Bhagat & Linden consider displacement ventilation an inexpensive solution by installing extraction vents or fans at the space's top. Nevertheless, displacement ventilation's efficacy should be further investigated in integrated outcomes such as ventilation effectiveness, energy efficiency, and acoustic performance.

As assumed in the Wells-Riley equation and its extensions used by ten studies, mixing ventilation is supposed to mix air equally over an area. However, Computational Fluid Dynamics (CFD) simulations indicate that the air in rooms with a mixing ventilation system is often partially mixed, resulting in an atypical distribution of micro-organisms [97,103]. For this reason, some studies included "air distribution effectiveness" as a factor in their models instead of assuming a well-mixed air to estimate the infection risk more accurately. For instance, Sun & Zhai adopted air distribution configurations based on the ASHRAE standard

[73]. Moreover, indoor airflows are found to be very ‘turbulent’ and closely related to transient events such as the occupant behaviour and movement [12], door opening and closing [103], and changes in external conditions [12]. Therefore, further study on indoor air mixing and airflow patterns is required to understand virus transmission patterns better.

4.1.1.2. HEPA and air filtration. Air filtering is considered to have long-term health benefits for occupants due to lower average particle matter (PM) levels in an indoor environment [82]. In this review, 24 papers explored high-efficiency particulate absorption (HEPA) filters to filter virus-laden particles and reduce indoor viral transmission, including filters installed in central HVAC systems and standalone HEPA equipment, specifically Portable Air Cleaners (PAC). However, only one article investigated the effects of installing HEPA filters over the ventilation grills [91]; other studies either evaluated the effects of HEPA filters in lab settings or measured outcomes of PACs in natural settings.

Sixteen studies investigated the effects of PACs, covering spaces including restaurants [59], houses [90], classrooms [70,82], conference rooms [61], Gyms [54,55], clinical exam rooms [88], and dental facility [51,52]. Most of them were experimental studies with simulated aerosol particles. For instance, Curtius et al. estimated that staying in a confined classroom for 2 h with a highly infectious individual reduces the inhaled dosage by six when utilising air purifiers with a 5.7 h-1 air exchange rate [82]. These experiments demonstrated that HEPA-filtered PAC could attract room air towards the purifiers and clean the “contaminated” air with proper locations and capacities. Notably, Rodríguez et al. conducted a direct intervention trial in residential settings by comparing COVID-19 testing results of collected air and surface samples in 29 households with Covid-19 patients [90]. They found only 1 sample with COVID-19 positive after PAC intervention compared to 75% positive samples before the intervention, concluding an 80% intervention effectiveness [90]. Despite the limited sample size, this finding is significant because it is the only direct study on PAC intervention during the covid-19 pandemic.

It emerged that PAC could supplement the ventilation for buildings with central ventilation systems, but the combined effects are mixed. For instance, Blocken et al. compared the effects among ventilation only, PACs only, and the two combined measures in a gym and concluded that combining ventilation and PAC could reduce 80% aerosol concentration, 20% higher than ventilation or PAC alone (60%) [54]. By contrast, other studies argue that PACs’ efficiency diminishes as mechanical ventilation in the rooms increases because of the additional air turbulence [92,141]. On the other hand, PAC provides a practical and cost-effective method of reducing pathogen contamination for buildings that lack mechanical HVAC systems since PACs can rapidly reduce the aerosol load in a confined space, even without ventilation when windows are kept closed [92]. However, PACs cannot replace ventilation and air conditioning systems since they could neither remove gas such as CO2 nor maintain the air temperature and humidity.

Several studies investigated the optimal position of PAC by measuring the effects of putting PAC in different positions in space. For instance, Mousavi et al. showed that the best location for PAC in an isolation room is near the patient’s bed [86]. In addition, Blocken demonstrated that PAC positioned at the ground level is more effective than other vertical positions in a gym [54]. Likewise, Bluyssen et al. discovered that placing PACs in various locations inside a classroom results in significantly different air turbulence patterns and particle removal effects [79]. Furthermore, Heo et al. demonstrated that the distance between the air purifier and the nebuliser significantly determines the air purifier’s influence on the distribution of respiratory droplets in a dental room [85]. In a word, PAC’s efficacy is highly associated with the device placement, and they are likely to be most effective when put as near to the occupants as possible, as demonstrated in gyms [54] and classrooms [79]. This poses difficulties when there are multiple occupants spaced apart in a room.

The effectiveness of HEPA filtration also relies on effective operation and maintenance, especially the monitoring and regular replacement of filters. First, when filters are not correctly sealed, particles may escape and become circulated by the fan, as illustrated by the experiment in a dental clinic [51]. Additionally, filters gradually get saturated and congested, lowering airflow through the filter and hence the number of particles filtered in the room over time, and thus require changing filters regularly [82,83]. The changing frequency of filters differs across different equipment types. For instance, Brouwers showed that integrating HEPA with a Rotating Particle Separator (RPS) based on sustainable technology could reduce the frequency of filter replacement [80]. Nevertheless, the filter replacement is expensive and harms the environment because the disposal of filters often includes non-recyclable components that end up as hazardous waste [80,90].

On the other hand, most studies considered installing HEPA as a cost-effective intervention measure. For instance, Yeo et al. argued that installing a HEPA filter over the ventilation grills is a low-cost solution with ease of installation [91], but they never discussed the potential reduction of airflow rate caused by the filters. Moreover, Duill et al. and Zhai et al. mentioned that PAC has a lower initial cost and a faster solution than upgrading HVAC systems by installing HEPA filters [59,83]. Likewise, Broken et al. suggest that PAC has a medium initial investment and lower energy consumption than ventilation measures [54]. However, the initial cost benefits and energy savings must be weighed against the expense of regularly changing filters and the adverse environmental outcomes resulting from filter disposals.

A drawback of PAC is that its operation will raise indoor background noise levels, which vary according to the type of equipment and its settings [82,83], generating concerns about its use in quiet environments. For instance, Ren et al. showed that when PAC was set to its highest setting, noise levels increased by 14 dB in dental rooms [141]. However, the analysis of the stakeholder response regarding the noise is mixed. For instance, Bluyssen et al. found that the noise levels (more than 40 dB) generated by the mobile HEPA filter system are unacceptable for classroom usage, based on user feedback and Dutch school guidelines, which demand a background noise level of less than 35 dB [79]. In contrast, Duill et al.‘s experiment demonstrated that the noise level of PAC operation in a classroom was less than 40 dB, and their poll results demonstrate that the noise level was acceptable for users [83].

4.1.2. Air pressure

Since indoor airflow patterns significantly impact airborne virus transmission in buildings, air pressure created by HVAC systems has been widely used in sensitive settings to reduce virus transmission from contaminated spaces to other areas. In our review, ten articles discussed air pressure as an intervention measure, and they validated the effectiveness of air pressured facilities in various clinical settings, such as negative air ionisation [95], positively pressured operating rooms [103], negative pressure hoods [87,105], negative pressure isolation stretcher [104]. For example, Kim et al. conducted a before-and-after intervention study at a South Korean hospital and discovered that the average frequency of medical cessation was considerably lowered following the intervention [104]. Likewise, Phu et al. confirmed that confining Covid-19 patients in negative pressure systems equipped with HEPA filtration effectively reduces pathogen transmission to health care personnel [87]. Moreover, during the Covid-19 pandemic, nonclinical spaces were converted into isolation rooms with air pressure intervention with mechanical methods due to the increased need for isolation space. Miller et al. for example, demonstrated how negative pressure isolation space could be produced by modifying existing HVAC systems at a nursing home in the United States as a temporary and emergency solution [53].

However, the efficiency of air pressure controls is affected by various factors: (1) Air leaks: air pressurisation systems require further optimisation to avoid unfavourable air leaks that diminish efficacy. For example, Bhattacharya et al. observed that door operations cause a temporary shift in interior airflow and air escape from a pressurised operating room, releasing 7.5 m3 of contaminated air each time the swing door is opened [103]. (2) Particles accumulation: A critical drawback of negative air ionisation is the accumulation of pathogenic particles on the ioniser and surrounding surfaces, necessitating additional cleanings [95].

4.1.2.1. UVGI disinfection. The role of sunlight exposure in health buildings is reflected by rating systems such as WELL standard [142]. In this review, two recent studies have evaluated the efficacy of simulated sunlight on the airborne virus during the Covid-19 pandemic. First, Schuit et al. conducted an experimental investigation to determine the effect of simulated sunshine on the stability of SARS-CoV-2 in aerosols [98]. They found that 90% of the virus inactivated in less than 20 min of exposure to simulated sunlight. Additionally, they discovered a statistically significant reduction in decay rate when exposed to high-intensity sunshine, indicating that the UV index is a critical parameter [98]. Second, Dabisch et al. further demonstrated that the effect of sunlight on SARS-CoV-2 was much more significant than that of humidity and temperature [94]. However, we have not located articles assessing and comparing the infection risk associated with lighting factors that reflect sunlight exposure.

The literature shows that the ultraviolet germicidal irradiation (UVGI) technique has a long history. The initial studies on the UVGI system's ability to disinfect micro-organisms were conducted in 1942 by Wells et al. The first research cluster occurred in the 1980s and 1990s when several trials on TB in clinical settings were undertaken in the upper-room UVGI system [97]. UVGI research was reinvigorated during previous influenza pandemics and the 2003 SARS pandemic [34]. The effectiveness of UV light at a wavelength of 254 nm in inactivating respiratory viral aerosols in healthcare settings had been well established before the Covid-19 pandemic [33,34,100]. In this review, eleven studies assessed the efficacy of UVGI system, including four modelling studies [72,97,99,101], four experimental studies [78,93,96,100], and three intervention trials [63,95,102]. While some research examined UVGI technology in general, others examined three distinct UVGI implementations.

(1) In-duct UVGI system:

Three articles evaluated the effectiveness of in-duct UVGI systems for air purification. The lamps can be installed in various locations in the HVAC system, such as supply or return air ducts or in individual fan cabinets, to disinfect air before it is distributed to occupied spaces. Shrestha et al. modelled SARS-CoV-2 aerosols and assessed the effects of UVGI installed in the return air duct of the AHU. They concluded that they are as effective as HEPA filters installed under the same ventilation conditions, while the combination of UVGI and HEPA treatment could be more efficacious [62]. Moreover, Barnewall et al. tested the efficacy of an air purification system installed with UVC light and found it successfully removed the virus from the air as efficiently as the HEPA filter [78]. Notably, Menzies et al. conducted an intervention trial in a mechanically ventilated office building, assessing the health effects of the in-duct UVGI system on occupants [63]. Even though the intervention was not directed at preventing the spread of a specific respiratory virus, the study found that it reduced overall indoor airborne concentrations and decreased occupant respiratory symptoms. However, logic suggests that the effectiveness of an in-duct UV system is limited by the ventilation system's efficiency and the fans' capacity. Thus in-duct UV system appears to be an excellent supplement to other HVAC interventions in existing buildings.

(2) Portable UVGI cleaner

Portable UVG sterilisers were used to disinfect indoor air, surface, and objects in clinical settings. For instance, Kierat et al. evaluated the efficacy of UVGI cleaner to sterilise contaminated HEPA filters and masks [96]. However, UVGI's ability to disinfect indoor surfaces is diminished in the presence of dirt and debris [143,144]. For this reason, they perform poorly in disinfecting indoor surfaces in vast open spaces, and they are utterly ineffective in shadowed areas such as the bedrail and telephone in a ward. Therefore, it must be studied more thoroughly on its efficiency than traditional cleaning of the building's floor, walls, and furniture.

(3) Upper-room UVGI system:

Six articles evaluated the upper-room UVGI system's effectiveness and acknowledged it as a fast and highly efficient solution in high-risk and resource-constrained settings such as hospitals. Notably, two intervention studies demonstrated upper-room UVGI in preventing tuberculosis transmission in hospital settings, providing compelling real-world evidence [95,102]. In addition, while there might be ongoing concerns regarding exposure to UV for occupants, recent research and studies indicated that the risk is within the current bands of acceptability because specially designed lamp fixtures ensure that occupants will only be exposed indirectly to low UV-c intensities under a threshold limit value [145]. Some researchers even hold that the current threshold is "overly conservative" and has degraded the efficacy of upper-room UVGI intervention based on experimental evidence [145,146].

On the other hand, the literature indicates that the upper-room UVGI system's disinfection effectiveness depends on several factors: (1) Building parameters such as space size, room height, and ventilation characteristics that would determine room air mixing and thus affect the effectiveness of upper-room UV systems [95,97]. For instance, Shen et al. estimated that when UVGI is combined with a displacement ventilation system, its performance may be lowered by 20% [72]. (2) Upper-room irradiance level determined by system design, installation and operations. First, the system's design must balance the irradiance intensity in the upper and lower rooms to ensure disinfection effects and occupant safety [145]. Second, UV devices' location and operations also affect their effectiveness in delivering the required UV dose [93]. For example, Sung and Kado proved that by installing an upper-room UVGI system away from the exhaust openings and dividing the exhaust openings, the system's effectiveness might be increased while maintaining the same ventilation rate and other parameters [147]. (3) Climatic circumstances such as temperature [37] and humidity [95]. For example, as humidity levels rise, the efficiency of upper-room UVGI systems declines [37]. Nevertheless, the optimal design and arrangement of upper-room UVGI systems, especially the proper irradiance level with maximum effects, requires more research.

Compared to other HVAC interventions, the upper-room UVGI system is considered inexpensive, easy to implement, and easily accessible for maintenance and repair [95]. For instance, Escombe et al. mentioned that upper-room UV is a relatively low-cost intervention compared with mechanical ventilation. Likewise, Shen et al. suggested that the approximate cost of an upper room UBGI system would be less than the cost of an air cleaner or installing HEPA [72]. However, a more quantitative cost study is required, and ongoing maintenance and bulb replacement costs must be considered.

4.1.2.2. Heating system. Three articles discussed interventions in building heating systems to reduce virus transmission. First, Yu et al. demonstrated that direct airflow from electric heat pump (EHP) systems could act as a virus transmission pathway for virus-laden droplets and aerosols during the winter. Therefore, they recommended modifying the heating air angles and decreasing the EHP heater's wind speed [58]. In addition, innovative heating systems were proposed to alleviate airborne transmission risk and reduce energy consumption by traditional HVAC systems. For instance, Korichi et al. proposed a radiator panel heating system coupled to horizontal ground source heat pumps to provide cleaner heating for limited enclosed spaces, minimising the danger of airborne transfer via traditional HVAC systems [119]. Similarly, Xie et al. proposed a solar-powered hybrid disinfected Trombe wall system with space heating and virus inactivation functions for dealing with return air in ventilation systems [120].

4.1.3. Drainage system

Twelve studies discussed interventions in the drainage system. The first research cluster on drainage systems and infection prevention was started following the 2003 SARS outbreak when 42 deaths were attributed to SARS virus transmission via the building drainage system in HK Amoy Gardens [111]. Six publications in this review confirmed that viral aerosols in Amoy Gardens' building plumbing were sucked into unit bathrooms through floor drains, contributing significantly to the outbreak, with case studies [110,113], experimental studies [107], and simulations [108,111,112]. Unsurprisingly, another study cluster emerged during the Covid-19 pandemic, employing similar research approaches, such as case studies [117], experiments [115,116], and modelling [109,114,118]. However, the settings of SARS drainage studies were all high-rise Multi-Unit Residential Buildings (MURB), while Covid-19 studies extended the research on hospitals and general high-rise buildings.

According to the research, faulty floor drains and toilet flushing may facilitate the transmission of airborne infections via the building's drainage system. For instance, Huang et al. suggest that the airflow in the vertical drainage stack is upward and affected by the positive pressure inside the drainage stack [148]. Furthermore, Jack et al. demonstrated how a small amount of suction pressure could produce significant air movement, resulting in the reverse airflow into the occupied space. Indeed, a well-designed trap seal retention system is essential for preventing airborne virus leakage into the space from the drain, whereas a poorly designed or maintained system results in foul odour and introduces a potentially lethal hazard during an airborne virus pandemic [111].

Past research suggests that the risk of transmitting respiratory viruses via the building drainage system is relatively low if the indoor drainage system is maintained correctly [114]. As a result, the drainage system intervention's primary objective was to operate and maintain the existing drainage facilities properly: (1) Regular inspection: FM team is recommended to regularly inspect or deploy a defective trap identification system [108] to monitor water seal [114], such as sanitary fixtures equipped with U-traps [113]. Moreover, it is critical to control tenant installations of equipment that might cause drain lines to get clogged, resulting in pipeline congestion [115]. (2) Repair and maintenance: The case study by Wong et al. highlighted the challenge of maintaining sewage systems in hospitals during the Covid-19 pandemic and the importance of accurately mapping the sewage pipework, especially in older architectures, for rapid response to pipe leakage [117]. Nevertheless, systematic guidance of drainage system operation and maintenance for infection control is lacking.

4.1.4. Cleaning and housekeeping

Respiratory viruses can be transmitted as droplets from the human saliva of infected people to shared indoor surfaces such as doorknobs and furniture and then spread to others who contact the contaminated surfaces afterwards [18,20,21]. Thus, hand hygiene and surface cleaning have been viewed as the main measures to remove pathogens in indoor environment surfaces, and the two were often implemented in conjunction in the literature. For instance, a simulation study shows that hand hygiene and surface cleaning are more effective when they are combined [57]. Additionally, the risk of respiratory virus transmission via interior surfaces is highly associated with the overall frequency of occupant hand-surface contact, which depends on occupant interaction with buildings.

One measure to reduce fomite transmission is controlling the occupancy rate and minimising accessible surfaces in spaces to occupants. For instance, Li et al. used BIM-based simulations to extract building occupancy and accessible surface information and developed a fomite-mediated transmission model to forecast contamination risks in the built environment. As a result, it determined that minimising accessible surfaces in rooms and limiting room occupancy are the two most effective techniques for reducing outbreak risks via the fomite route [149].

Another measure is to improve cleaning frequency or efficiency. Cleaning practices at healthcare facilities are critical because contaminated healthcare facilities are a significant source of pathogen acquisition to medical staff protection [150]. As a result, hospital wards have more often cleaned surfaces. For example, Wang et al. demonstrated an effective cleaning method for a Covid-19 isolation facility in China by consistently cleaning surfaces with 1000 mg/L chlorine-containing disinfectant every 4 h in intensive care units and every 8 h in ordinary wards [151]. Regarding cleaning disinfectants, alcohols have been described as most efficient against respiratory viruses such as SARS, influenza A virus, and Covid-19 [151,152]. On the other hand, the surface cleaning approach and frequency are highly associated with the interior surface materials [125] and environmental factors [40], such as temperatures and relative humidity. Nevertheless, Ronca et al. suggest that contacted surfaces and items require routine disinfection within a 12- to 24-h timeframe [125].

Under the covid-19 pandemic, there is growing interest in adopting emerging surface decontamination technologies rather than traditional surface wiping, such as electrostatic sprayers used in classrooms [122], cleaning robots adopted in subway hubs [39], and UVGI cleaners used in health care settings as discussed in Sec.4.1.1.4.

4.1.5. Space and occupancy management

Higher occupant density usually results in more physical contact and increased exposure to shared air with potentially infected occupants and thus a higher infection probability. Therefore, the primary interventions in space management are to control occupant density and facilitate social distance to limit droplet transmissions from human to human in buildings. Six articles considered occupancy density as a variable in their models assessing the effectiveness of IAQ interventions [60,62,70,72,76,77]. Moreover, nine studies assessed the effectiveness of space management and occupancy control in various settings such as schools [129,132–135], hospitals [131], clubhouses [56], and offices [28].

Several studies demonstrated that BIM and IoT-based applications could be adopted to visualise space occupancy, so the FM team can track space occupancy in real-time to ensure compliance with social distancing standards [127] and gain insights from sensor data for infection control [153]. Moreover, Fazio et al. developed an internal navigation system based on BIM that assists users in navigating smart buildings by tracking their location over time and recommending the most efficient route to their destination [154]. What is more, Bogdan-Petru et al. presented a system equipped with IoT that would enable office users to handle office items remotely without touching them, such as opening and closing the entry door, controlling lighting, and operating the coffee machine [155]. Additionally, Swinarski et al. simulated occupants' behaviours in an educational building to evaluate the four different interventions for elevator operation [135]. Likewise, Makhsous et al. demonstrated that a real-time aerosol sensor network could properly assess aerosol transmission in medical settings, providing information to assist intervention decision-making [51]. These innovations revealed the potential of emerging technologies adoption to assist FM in transforming space management for infection control.

Few studies discussed the cost-effectiveness and other outcomes of space management, except that Sari et al. compared the costs of refurbishing and O&M of facilities in an office building and the gains of reduced employee leaves and improved productivity [28]. Additionally, Mokhtari and Jahangir investigated the influence of occupant distribution on energy consumption, indicating that the environmental impact varies according to season and HVAC system operation type [129]. Nevertheless, the cost-benefit analysis of the technology adoption is required to justify the investment in FM and support FM's decision-making process.

4.2. Research gaps and future research directions

4.2.1. Integrated intervention outcomes

The literature shows that respiratory virus transmission dynamics at the architectural scale are complex since they are influenced by numerous aspects, including the design and maintenance of HVAC systems, lighting systems, sewage systems, environmental cleaning practices, space arrangement, furniture configurations, occupant density, and occupant behaviours. Although numerous tools have been built to evaluate the risk of SARS-CoV-2 infection in various indoor environments [19], few risk calculators account for all three routes of transmission: fomite, airborne, and droplets, potentially underestimating the virus exposure dose for occupants. Thus, integrated risk assessments are needed to examine the probability of pathogens being exposed via each exposure pathway (direct contact, indoor surface, and indoor air) and to calculate the reduced risk obtained via engineering controls (Hard Service), environmental management practices (Soft Service), and other FM activities to manage occupancy rate and occupant behaviours in buildings.

Furthermore, while the research included in this review explored various FM interventions, most of them do not add much value to the intervention decision-making process for policymakers and managers. To begin with, policymakers and building managers must know the integrated effects of solutions, for instance, if different interventions are additive, multiplicative, or contradictory in their outcomes, to make a sensible decision. Although many studies considered multiple interventions, such as ventilation and occupant density controls, a systematic analysis of interventions' combined effects is required. Moreover, the cost factor is crucial for intervention decision making [138]. However, the cost-effectiveness of various interventions and combinations was not thoroughly investigated. For example, only a few studies mentioned the costs of implementing their recommended control method but did not consider ongoing maintenance costs and additional energy consumption in the whole life circle, let alone the impacts on the FM budget. Thus, life cycle cost analyses (LCCs) and budget impact analyses (BIAs) of various intervention choices are required, as well as estimates of short- and medium-to long-term budget changes associated with intervention adoption.

4.2.2. Occupant behaviour

This review shows that occupants substantially impact the indoor environment via contributing heat, CO2 levels, aerosol particles, and actions affecting all the routes of infectious diseases transmission in buildings. On the one hand, occupants have a direct effect on indoor environments and affect the effectiveness of FM interventions through their presence and activities in buildings, including respiratory activities (breathing, whispering, speaking, singing) [12,71,92,156] and physical activities (resting, walking, intense exercising) [54,156]. On the other hand, occupants' behaviours can affect virus transmission in buildings as individual interventions, which include face masking [61,72], hand sanitisation [126], coughing/sneezing hygiene [156], and their actions in building HVAC systems, such as windows and doors operation and thermostat adjustment [157,158].

Some infection risk modelling studies have included some occupant-specific factors because of the intense effect of occupant activities on infectious aerosol load inhalation. For instance, Buonannoa and Stabile assessed viral load in various scenarios based on occupant density and activity in retail contexts [60]. Additionally, Shen et al. employed parameters for quantum generation and pulmonary ventilation estimated from the viral load model, taking into account occupant age distribution and three degrees of occupant activity: mild, medium, and intensive [72]. Nevertheless, more understanding of occupant behaviours for each transmission route is needed to establish robust parameters for assessing infection risk at a building level. For instance, the frequency of occupant contact with built surfaces and the practice of occupant hand hygiene for various settings must be considered.

Additionally, occupant behaviours are affected significantly by psychological factors such as protection motivation [159]. However, the related behavioural factors in various settings remain unknown. In our review, only one study considered related parameters in their risk model: Zafarnejad and Griffin included "Adherence to rules" and "stress level to follow the rules" as two behavioural parameters for school settings with assumed values [75]. Thus, it is required to understand the psychological principles governing occupant behavioural reactions to infectious diseases and the characteristics of occupant interaction with different buildings, so building designers and FM could develop solutions to influence favourable occupant behaviours.

4.2.3. Hard service and infection control

The literature indicates that current building systems are mainly designed to maintain specific temperature and humidity but have overlooked the hazard of the respiratory virus in buildings [1]. Past studies have demonstrated that indoor environmental characteristics such as temperature, humidity, ventilation rate, airflow velocity and sunlight exposure all affect microbe survival in aerosols and viral transmission in the air [94,98]. However, quantitative evaluation of all these factors is necessary to comprehend the environment's integrated results and the possible trade-offs between occupant health, occupant comfort, and building environmental performance.

It is widely agreed that current HVAC operation standards, such as minimum fresh airflow requirements, are insufficient to dilute indoor air to prevent airborne pathogen transmission in high-occupancy facilities. However, the optimal ventilation rate combined with other IAQ control measures to dilute, filter, and purify indoor air remains unknown. Moreover, despite modelling and experiments conducted, there are significant unknown areas in indoor airflow to be further investigated because interior airflows are highly dependent on transient events changes in external circumstances. Additionally, UVGI systems appear to be a potent supplement to other HVAC interventions in existing buildings, and more studies would be beneficial to provide quantitative evidence of its cost and benefits for FM decision-markings.

Another area to address is the implementation and social outcomes of IAQ interventions. Few publications examined the proposed intervention technology's operation phase, which led to the lack of supporting evidence to assess if these interventions are acceptable to the key stakeholders and feasible to implement. For instance, occupant risk perceptions towards the upper-room UVGI system are unclear, raising concerns about stakeholder acceptability of its implementation in various settings. Therefore, the current decision-making process in the FM domain must be studied, and a framework for assessing risks and selecting intervention combinations must be developed to assist practitioners in transforming building operations for infection control holistically. Moreover, empirical studies such as questionnaires, interviews, and case analyses are needed to elicit practitioners' insight into the feasibility and challenges encountered during the operation phase.

4.2.4. Soft service and infection control

The use of disinfection robots and UV systems in various public settings is an emerging research area, while some studies reported some limitations and concerns. Thus, the effectiveness, safety, and cost-effectiveness of disinfection robots must be further researched compared to manual cleaning. On the other hand, other soft service activities could also contribute to virus transmission. For instance, healthcare and household waste may contain virus-borne moisture and nutrients delivered to humans via numerous microbes in the environment and thus require proper infection control measures [46]. Similarly, while hospital laundry services are likely to be standardised for infection control purposes, there is uncertainty regarding how hotels will handle laundry during a pandemic to avoid contaminated linens spreading the virus. Additionally, while the current study indicates no evidence of Covid-19 transmission by food, more research on proper food handling and cleaning practices is essential to avert a future outbreak of food-borne infection. Therefore, more studies on other soft service operations such as waste disposal, laundry, and catering services are required for future respiratory infection control.

4.2.5. *Emerging technologies in use*

The Covid-19 pandemic has accelerated the fourth industrial revolution (Industry 4.0). New technologies such as Big Data, the Internet of Things (IoT), cloud computing, blockchain, artificial intelligence, and simulations have gained tremendous interest in pandemic control [160]. This study reveals that Industry 4.0 has the potential to transform building operations management. For instance, space and occupancy management interventions are mainly facilitated using ICT-based tools. Many studies in this review demonstrated that intelligent sensors, cameras, and artificial intelligence (AI) technologies could be integrated with building management systems (BMI) to facilitate infection control activities, such as occupant movement tracking [154], occupant counting, social distance and face masking monitoring, and the detection of feverish occupants [132]. Moreover, multiple articles have demonstrated how BIM and IoT-based apps could be used to visualise space occupancy [153], enabling occupants to reserve seats and control office facilities remotely [155] and facilitate social distancing [133].

Additionally, machine learning techniques show the potential to achieve predictive control of the HVAC system via a learning model to monitor and manage indoor air conditions in buildings, transforming existing building automation system (BAS) operation [25,161,162]. However, in general, the adoption of these IT-driven technologies in the FM domain is still in its infancy, far from creating an ideal solution. For example, current BAS relies on sensors to gather information about temperature, humidity, pressure, CO2 levels, and the presence of particles, but the exorbitant cost of installing numerous sensors in buildings has hindered their use in practice [162]. Furthermore, Smart Building applications rely significantly on algorithms developed before the Covid-19 pandemic, but the historical data may be inapplicable in the post-pandemic era and require further investigation [158]. Moreover, few studies discussed the outcomes of these implementations in the economic, social, and ethical fields. For instance, the ethical issue of capturing occupant information through sensors and cameras in buildings remains an under-investigated topic [162].

5. Conclusions

- **Indoor respiratory infection and FM interventions**

It was concluded from the content analysis that interventions for respiratory infection transmission in existing buildings fall into three categories under the Facilities Management discipline: HVAC and drainage interventions to prevent virus transmission via the airborne route, cleaning/disinfection methods to prevent virus transmission via the fomite route, and space & occupancy management approach to prevent virus transmission via droplet route. In general, any single structural or environmental solution is insufficient to prevent indoor respiratory virus transmission, and thus an integrated approach is required.

While the research included in this review explored various FM interventions, most of them do not add much value to FM decision-making. For example, few studies identified interventions' combined effects on different transmission channels via various FM activities. Moreover, the costs of various interventions were not thoroughly investigated, and only a few studies mentioned the costs of implementing their recommended control method but did not consider ongoing maintenance costs and energy usage in the whole life circle. Therefore, the Life Cycle Cost Analysis (LCCA) of proposed interventions and the quantitative outcome analysis of integrated solutions are needed to support building owners and facility managers in making intervention decisions. Additionally, a framework for assessing risks and selecting intervention combinations is required to assist practitioners in transforming building operations for infection control holistically.

- **Long-term problem**

The Covid-19 outbreak is alarming for all building professionals because it reveals how health-related components of building systems were overlooked during design and operation, posing a risk to occupants' health and safety during a pandemic [1,163]. However, this also creates an opportunity to rethink how we use our buildings and redefine how we manage our buildings with integrated Facilities Management.

The Covid-19 pandemic will not be the last one, and occupant health is a long-term worldwide issue for building experts. This review shows that there are still significant unknowns about the transmission dynamics of the respiratory virus at the architectural scale since they are influenced by numerous aspects, including building the design and maintenance of HVAC systems and sewage systems, environmental cleaning practices, indoor space arrangement, furniture configurations, occupancy rate, and occupant behaviours. Thus, more multidisciplinary research involving building professionals and epidemiologists to comprehend better the quantitative links between architectural and facilities factors, occupant behaviours, and pathogen infection probability.

- **Limitations and Practical Implications**

This article summarises academic research on the efficacy of FM interventions in preventing respiratory infection in existing buildings, identifies research gaps, and discusses future research directions. Despite the best efforts, this study has limitations, including the possibility that the review may have overlooked some relevant publications. For instance, this review did not include articles regarding some respiratory diseases such as measles and Middle East Respiratory Syndrome (MERS). However, this paper will serve as the basis for future research on FM solutions for battling the pandemic and improving post-pandemic building operations.

CRediT authorship contribution statement

Yan Zhang: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felix Kin Peng Hui:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Colin Duffield:** Writing – review & editing, Supervision, Methodology. **Ali Mohammed Saeed:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

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

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