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Quantifying airborne transmission in ventilated settings: A review

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ABSTRACT

As mandatory masking and social distancing measures decrease post-COVID-19, the risk of airborne pathogen transmission in crowded indoor spaces remains a significant public health concern. The pandemic highlighted the critical role of indoor air quality and ventilation in mitigating the spread of infectious diseases, underscoring the urgent need to improve our understanding and prediction of indoor airflow to minimise airborne transmission. In this review, studies on airborne transmission in indoor settings were systematically reviewed to identify research gaps and recommend changes in approach. The analysis is categorised into indoor airflow, dynamics of infectious respiratory particles (IRPs), and investigation methodologies. Findings reveal that almost 40% of the reviewed literature does not specify the type of indoor setting, with only 3% focusing on restaurant environments. Additionally, indoor air conditions are typically assumed to be constant, and respiratory activities are often limited to coughing and breathing. The review identifies the challenge of replicating the complex behaviour of IRPs in experiments and the computational expense of predicting turbulent indoor flows. Recommendations for future research include: i) focusing on social settings like restaurants, ii) considering varying air temperatures and humidity, iii) examining speech-related respiratory flows, and iv) employing visual and accurate tools to investigate particle-laden airflow. These insights aim to enhance public health guidelines and building designs to reduce the risk of airborne diseases.

Contents

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1. Introduction

Since the onset of the COVID-19 pandemic, over 600 million people have been infected by the SARS-CoV-2 virus, and over 6 million people have lost their lives as of last December 2023 [1]. A boom in scientific research focused on containing, limiting, and mitigating the spread of the SARS-CoV-2 virus has been observed since the outbreak began in Wuhan in early 2020 [2,3]. Numerous scientists made a critical suggestion that the concerned virus is airborne-spread [4–6]. Fortunately, the outbreak was managed with the help of public health guidelines on mandating masks, contact tracing, and social distancing. However, there was some resistance and debate on its transmission route. It was initially believed to be spread via direct deposition, direct, or indirect contact [7–11]. It took some time for health advice to catch up with the scientific findings as WHO took almost two years to include ’long-range airborne transmission’ in their official statements [12].

One of the steps taken to curb the spread of SARS-CoV-2 was the use of sufficient ventilation as it has proven to be an effective measure to curb the spread of viruses [13], pathogens [14] or contaminants [15]. Many studies have suggested that long-range transmission occurred inside poorly ventilated settings in the initial stages of the COVID-19 pandemic [2,16,17]. As most public health guidelines have been eased now and everyone is leading their usual lives, studying the airborne transmission of pathogens at this point is not an analysis of what happened in the past but a preparation for the next pandemic ahead of us. Therefore, the role of indoor ventilation in minimising exposure risk cannot be understated in the current scenario.

Previously, airborne transmission in an indoor environment has been looked at from epidemiological, biological, physical, and computer modelling perspectives [18]. The studies focused on modelling highlighted common limitations like averaging the effects of turbulence [19,20], neglecting the impact of small-scale eddies, and failure of tracer gases to understand volatility and depository aspects of infectious respiratory particles (IRPs) [21,22]. The importance of ventilation design is illustrated by various reviews like [23,24] & [25], which show how good ventilation design mitigates transmission. At the same time, Correia et al. [26] suggests how inadequate ventilation can become a reason for long-range transmission.

While researchers unanimously agree that indoor environments require sufficient ventilation, increasing the room’s ventilation rate will not reduce the risk of exposure to IRPs. Some more nuances in ventilating a room still need to be addressed. Although a high ventilation rate helps with the removal of pathogens in a room [27,28], it does not necessarily reduce the IRP concentration near an occupant [29]. Additionally, recirculating the same air within the room without proper filtering or treatment is another flaw in current ventilation systems [16]. There is a pressing need to develop methods to predict and quantify the airborne transmission potential of viruses based on model studies, experiments, and outbreak research. The present study is a systematic review of research on expelled IRPs in a ventilated setting and the associated risk of exposure. This review aims to understand different ventilation regimes and their effect on airflow and IRPs to minimise airborne transmission of pathogens.

Table 1
Broad concepts and keywords to construct the search query.

Broad concepts and keywords				
Transmission	Ventilation	Investigation	Setting	Risk analysis
Airborne transmission	Ventilat*	Model*	Indoor setting	Risk assessment
Aerosol transmission	Air cleaning	Simulat*	Environment	Infection probability
Indoor transmission	HVAC	Experiment*	Confined spaces	Exposure
SARS-CoV-2 transmission	Air change	CFD	Office	Wells-Riley
Indoor contamination	Filtration	Measurement	Restaurant	Dose–response
Environmental transmission	Air distribution	Validation	Classroom	
Airborne route		Estimation	Hospital	
		Machine learning		
		Deep learning		

2. Methods

For the review, Web of Science, Scopus, and PubMed were chosen as the databases for searching relevant literature. This review covers five broad topics: (a) transmission of the pathogen, (b) ventilation regime, (c) investigation approach, (d) setting, and (e) risk analysis. Keywords were chosen under each broad topic to identify relevant literature in the web databases as shown in Table 1. Boolean operators ‘AND’/’OR’ were used to combine the search terms and construct a query. The Boolean operator ‘OR’ was used to combine the keywords of each broad topic to form a search query for the corresponding category. The search query from each category was combined to create a final search query using the ‘AND’ boolean operator. This search query identified articles through the abstract, title, and keywords across all the databases.

The term “SARS-CoV-2 Transmission” was used under the family of keywords even though this study does not focus only on “SARS-CoV-2” because of the large number of articles that solely refer to the virus in the past two to three years. Additionally, under the category of ‘Ventilation’, the truncated form “Ventilat*” was used to identify articles that have used it in a different form, along with terms like “Air cleaning” and “Filtration”. The latter two were included because some settings used air purifiers instead of conventional ventilation systems. More truncated forms like “Model*”, “Simulat*”, and “Experiment*” were used to cover every ending of the root word under the ‘Investigation’ category. Search terms like “Machine learning” and “Deep learning” were included to look for articles using ML or DL to accelerate CFD. The review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) guidelines [30].

A total of 195 articles were found from Scopus, 258 from Web of Science, and 159 from PubMed. The duplicate articles were merged to obtain 385 unique papers from the databases. The initial screening of articles was conducted by reading titles and abstracts to classify them into different categories. Review papers were segregated from the articles for further screening for relevant studies. After separating the 38 review articles, the remaining 347 papers were screened for relevance to pathogen transmission in a ventilated indoor environment. Models based solely on theoretical reasoning, papers dealing with building-scale aerodynamics, papers not mentioning ventilation, purely epidemiological studies, and non-English and non-accessible papers were excluded. After excluding 130 papers that did not meet the first criteria, 218 papers that theoretically, experimentally, or computationally investigated airborne transmission of pathogens remained.

Papers including numerical simulations that were either paired with or validated against experimental studies were given preference, thus excluding purely qualitative studies, purely measurement-based studies, Reynolds Averaged Navier–Stokes (RANS) simulations that were not validated or were validated against theoretical models, and studies that focused on contaminants that were not contained within a particle. An exception was made for some Large Eddy Simulations (LES) or Direct Numerical Simulations (DNS) investigating the spread of pathogens via IRPs but not modelling ventilation. Their inclusion is essential as they are state-of-the-art in flow simulations for airborne transmission in ventilated settings. After the initial screening, 50 such research papers were selected for review.

The segregated 38 review articles were screened further for relevance, of which 13 papers reviewed articles on airborne transmission, approaches of research, and ventilation methods. There were 2046 references in the selected review papers, which were subjected to the same exclusion criteria as the initial screening. After screening

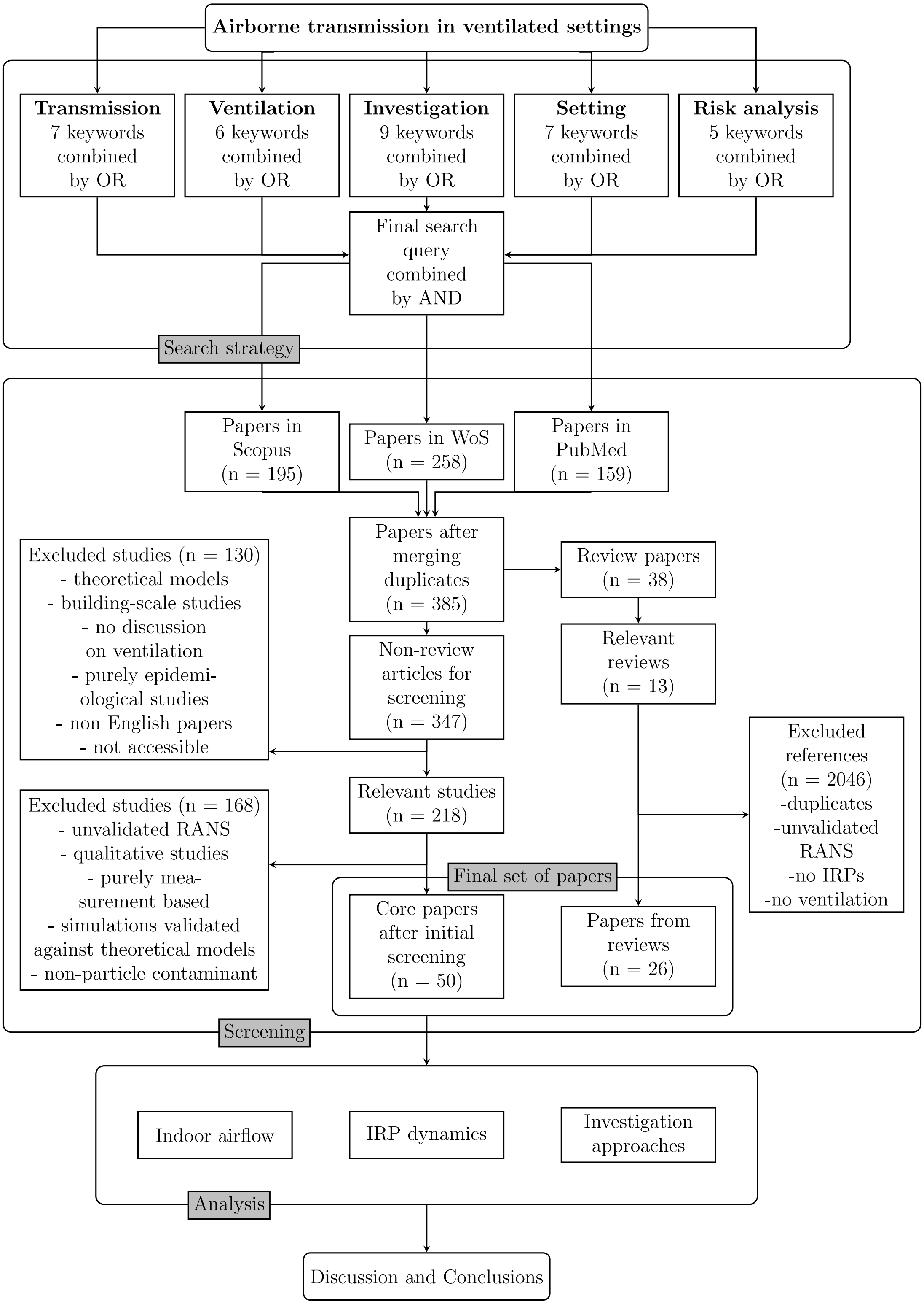


Fig. 1. The review process.

the review papers, 26 additional research papers were found. The 26 research papers included five studies that used DNS and ten studies that used LES. The final set of articles comprises 76 research papers thoroughly reviewed and analysed in the following sections. The review process is summarised in Fig. 1.

3. Outcome of review

The review summarises studies on common airflow patterns in different ventilated settings, the physics of IRPs for indoor conditions, and experimental and simulation studies to mimic airborne transmission scenarios.

3.1. Airflow in indoor environments

Airborne transmission in an indoor environment calls for discussing airflow patterns, which are the bulk carriers of IRPs. The indoor airflow has multiple components and differs according to the setting, air conditions, and occupancy. Indoor airflow mainly constitutes ventilation flow, flow due to temperature differences, and respiratory flows. Every setting has a unique configuration of occupants, obstructions and ventilation, making their interaction with different respiratory activities vary. The overlap between different sources of airflow inside various indoor environments is illustrated through Table 2, qualitatively highlighting the mixing potential of the flows. Some standard occupant configurations and ventilation regimes were found in the review, of which three were selected. The selected occupant configurations and ventilation regimes are represented in a matrix illustrating the variation among the nine scenarios. The scenarios are visualised as simplified schematics roughly adapted from the previous research with different sources of airflow illustrated with different colours. Occupant configuration 1 is where the occupants are facing each other, and occupant configuration 2 is where the occupants are facing the same direction. Occupant configuration 3 is specific to a healthcare setting where one occupant is lying, and another is standing beside the bed.

The first occupant configuration is observed in hospitals [31], offices [32], and restaurants [33] where the two occupants are sitting facing each other, across a table as shown in the schematics. For this occupant configuration, the respiratory flows (shown in blue) collide head-on and spread axially depending on the offset height and laterally [34,35] while the thermal flows (in red) rise upward with intensity depending on the temperature difference between the surface of the occupant and the air temperature [36]. The second occupant configuration is observed in classrooms [37], offices [38], and modes of transport [28,39] where the occupants are facing in the same direction. The respiratory flows in this configuration interact directly with the thermal flow [40]. The third configuration of occupants is unique to hospitals and healthcare settings where one or more occupants are lying and standing [41,42]. The lying occupants are patients, while the standing are healthcare workers or visitors. In this case, the respiratory flow is parallel to the thermal flow, which results in a net upward flow. The surface area of the lying occupant is greater than that of a sitting occupant, resulting in laterally spread thermal plumes [43].

In Table 2, Ventilation Regime 1 is mixing ventilation, Ventilation Regime 2 is displacement ventilation, and Ventilation Regime 3 is stratum and cross ventilation. Different overlaps between the three sources of airflow (differentiated by colour) are observed with the three different ventilation regimes. The schematics include directions for the ventilation airflow using arrows at the supply and exhaust. In Ventilation Regime 1, the direction of the flow is shown downwards, but the flow is not directly downwards; it is tangential to the ceiling surface. In the schematics, the respiratory flow originates from the mouth of the occupants, and thermal flow is upwards while originating from the occupant's body.

3.2. Dynamics of infectious respiratory particles

Pathogens are ejected via respiratory activity and transmitted from an infected individual to a susceptible one through airborne transmission/inhalation, direct deposition, or contact transmission [62,63]. In every transmission route, pathogens exist in the form of IRPs, which can evaporate, condense, merge, and deposit, making simulating their behaviour complicated [64,65]. The air conditions, the type of respiratory activity, and the IRP's size significantly impact their physical behaviour and potential to carry pathogens across space.

Air temperature and relative humidity are two primary parameters describing air conditions in a room. The room's air temperature mainly affects the intensity of thermal currents from the occupants and, consequently, the propagation of IRPs [66]. Relative humidity mainly affects how long the IRP is suspended in the air, which affects the evolution of the IRPs over time. Lower air temperatures result in higher buoyancy effects on the exhaled IRPs, which lead to their accumulation near the ceiling [36]. Whereas high relative humidity protects the expelled IRPs from evaporation [67]. The IRP puff cloud schematics in the first two columns of Table 3 show the effect on IRP dynamics for different combinations of air conditions.

Humans shed IRPs during respiratory activities like sneezing, coughing and speech [68]. These IRPs often differ in velocity, size, and number. The IRPs during a cough or sneeze are expelled at high velocities, thus reaching large distances away from the mouth in contrast to IRPs expelled during speaking and breathing [36,49]. Cough or sneeze IRPs are more prominent in diameter (10–100 μm), while breathing produces smaller IRPs (≈1 μm) [51]. On the other hand, speech sheds IRPs of sizes ranging from 1 μm to 1 mm, where the bigger IRPs settle down because of gravity while smaller ones follow the airflow [69]. Time scales for sneezing and coughing are relatively small (≈1 s) compared to speech or breathing, where the activity can last longer (≈1 min). Moreover, the number of IRPs produced is lower for coughing (1–1000 s^{-1}) than speaking, which produces an order of magnitude higher number of IRPs (1–10000 s^{-1}) [34]. Furthermore, the production of IRPs is higher if the occupant speaks loudly or makes plosive sounds [70]. The last two columns in Table 3 show the IRP puff cloud schematics for the four different respiratory activities discussed above, colour-coded with different IRP sizes.

3.3. Experimental and numerical approaches

Epidemiological studies were very successful in identifying the high spreading potential of SARS-CoV-2 [81] and previously provided strong evidence for airborne transmission of infectious diseases like Tuberculosis, chickenpox, SARS, measles, influenza, and smallpox. Since establishing a direct link between airflow patterns in an indoor environment and the transmission of infectious diseases, airflow studies simulating the transmission of IRPs have become more popular [82]. Ventilation design may be essential in reducing the IRP concentration near an occupant.

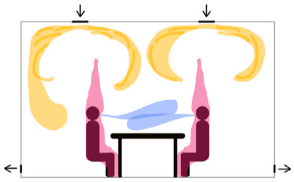
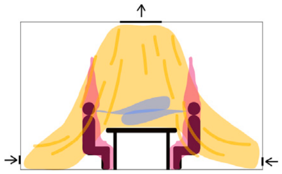
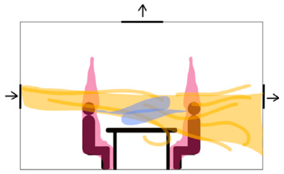
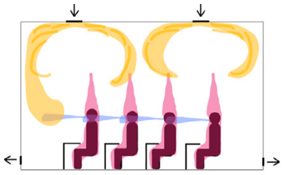
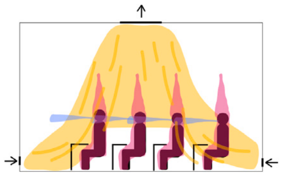
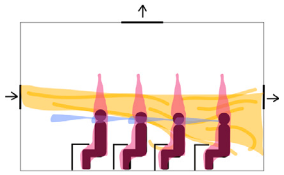
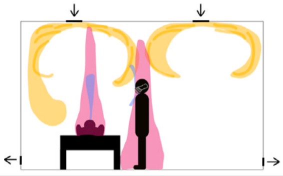
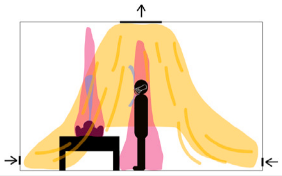
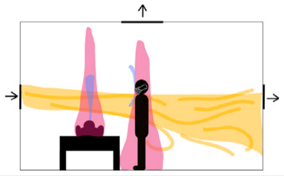
The two approaches for achieving an optimal ventilation design are experimental and numerical. Laboratory measurements in climate chambers with tracer gases or artificially generated aerosols have been performed to obtain the particle distribution in the presence of ventilation and occupant flow [31]. On the other hand, computational methods try to simulate the movement of IRPs by modelling the turbulence in respiratory flow, ventilation flow, physics of IRPs, and thermal flow using Computational Fluid Dynamics (CFD) [77]. CFD is a more popular method for researchers because of its accessibility and repeatability compared to full-scale experiments. Experimental studies have often been used for validating the CFD results, e.g. [83] is a popular benchmark for validating numerical results.

3.3.1. Experiments in a controlled environment

Mimicking airborne transmission in laboratory conditions involves accounting for numerous variables, making experiments challenging. Therefore, scaled-down [84] or full-scale experiments with limited parameters [79] are often more practical. Since scaled-down or limited full-scale experiments cannot be directly compared to extensive computational studies, they are frequently used to validate the numerical model [15,37,85]. Full-scale experiments include an initial flow rate measurement at the ventilation supply to assign boundary conditions in the CFD simulations [58]. Researchers have used different techniques to generate and measure the three major components of indoor airflow (i.e., respiratory jet, thermal plume, and ventilation flow), as shown in Table 4.

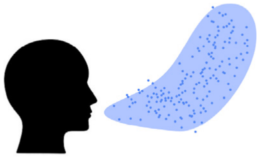
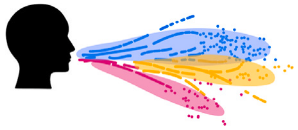
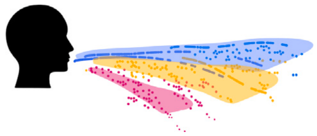
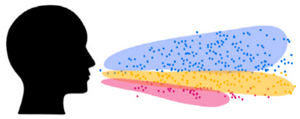
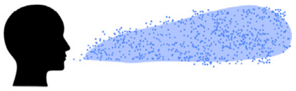
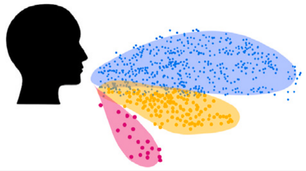
The studies listed in the first column of Table 4 show experiments conducted to either validate or complement the results from the numerical simulations. These studies have utilised various strategies

Table 2
Schematics for indoor airflow matrix with three common occupant configurations and three common ventilation regimes.

	Ventilation regime 1	Ventilation regime 2	Ventilation regime 3
Occupant configuration 1			
References	[15,31,44–46]	[31,47,48]	[43,49]
Occupant configuration 2			
References	[19,37–39,50–52]	[38,53,54]	[28,53,55,56]
Occupant configuration 3			
References	[27,31,42,57–60]	[31,41,42]	[42,61]

Note: The airflow is differentiated into three types with colours as follows: 🟦 Respiratory flow 🟧 Ventilation flow 🟥 Thermal flow.

Table 3
Schematics of IRP puff cloud in different air conditions and respiratory activity.

Air conditions	Schematic	Respiratory activity	Schematic
Low air temperature & low humidity		Coughing	
References	[36,66]	References	[13,19,31,39,42,49,64,67,71–77]
Low air temperature & high humidity		Sneezing	
References	[36,67]	References	[49,72,75,78]
High air temperature & low humidity		Breathing	
References	[36,66,74]	References	[38,41,51,55,77,79,80]
High air temperature & high humidity		Speaking	
References	[36,67]	References	[31,71,77,80]

Note: The different-sized IRPs are shown as: 🟦 Small IRPs 🟧 Intermediate IRPs 🟥 Large IRPs.

to mimic different sources of indoor airflow, as listed in the second column of Table 4. Aerosol generators, breathing manikins, or human test subjects have been used to mimic respiratory flow. The aerosol generators are either seeded with DEHS (Di-Ethyl-Hexyl-Sebacat) [54] or bacteria [59], or virus [33]. For ventilation flow in a room, most of the studies make use of ventilation supply from real-life settings [55,58] or test chambers [14,36]. At times, air cleaners have been used with or without standard ventilation to generate ventilation flow in the

Table 4
Brief breakdown of experimental techniques in previous literature.

Studies	Flow generation method	Measurement method	Type of flow
Berrouk et al. [14]	Aerosol spray gun, ventilation and thermal manikin	Anemometer and Particle counter	Respiratory, ventilation and thermal
Li et al. [86]	Ward patients and ventilation	Flow meters	Respiratory, ventilation, and thermal
Saarinen et al. [91]	Manikin dynamics	Tracer gas	Room air escape
Jiang et al. [61]	External wind	Tracer gas	Ventilation
Faleiros et al. [90]	A male subject	PIV	Respiratory and thermal
Romano et al. [58]	Ventilation and Nebuliser	Particle counters and Anemometers	Respiratory and ventilation
Quintero et al. [92]	Atomiser	Particle counters	Ventilation
Hang et al. [93]	Thermal manikin and ventilation	Tracer gas	Respiratory, ventilation, and thermal
Jain et al. [54]	Air cleaner	Aerosol generator and spectrometers	Ventilation
Li et al. [32]	Ventilation and thermal manikin	Anemometers	Ventilation and thermal
Ho and Binns [28]	On-board heater	Anemometers	Thermal
Deng et al. [47]	Two test subjects and air conditioning system	Exhaled CO_2 as tracer gas	Respiratory, ventilation and thermal
Oksanen et al. [33]	Ventilation, air cleaner and Nebuliser	ACI sampler and aerosol spectrometer	Ventilation and thermal
Arpino et al. [29]	Ceiling diffusers	Anemometers	Ventilation
Giri et al. [34]	Smoke generator	Flow visualisation	Respiratory
Liu et al. [89]	Ventilation and Bio-aerosol release	ACI sampler and plate counting	Ventilation and thermal
Qian et al. [87]	Breathing manikins	Tracer gas	Respiratory
Lu et al. [42]	Ventilation	Tracer gas	Ventilation
Poussou et al. [84]	Ventilation and moving body	PIV and PLIF	Ventilation
Liu et al. [59]	Bio-aerosol generator and ventilation	Anemometers and ACI	Respiratory and Ventilation
Cheng et al. [88]	Breathing thermal manikin	Tracer gas	Ventilation, respiratory and thermal
Liu et al. [60]	Bio-aerosol generator and ventilation	ACI and flowmeter	Respiratory and ventilation
Li et al. [50]	Breathing thermal manikin	Tracer gas	Respiratory, ventilation, and thermal
Duill et al. [55]	Test subjects and Air cleaner	Aerosol spectrometer	Respiratory and Ventilation
Zhou and Ji [31]	Thermal manikin, aerosol generator, and ventilation	Aerosol monitor	Respiratory, ventilation, and thermal
Zhang et al. [36]	Ventilation, Thermal manikin, and Aerosol generator	Aerosol monitor	Respiratory, ventilation, and thermal

room [33,54]. For mimicking thermal flows, thermal manikins [50] or heaters [28] are used. In some cases, human subjects are also involved in experiments for generating thermal flows [47,86].

Depending on the different methods of generating flow and the purpose of the experiments, the flow parameters are measured using various techniques shown in the third column of Table 4. Some studies inject tracer gas like SF_6, or N_2O at the origin of airflow [87,88] or exhaled CO_2 gas as tracer [47] and measure the spatial concentration of the gases using sensors. Aerosol generators using DEHS or other saline solutions that form fine droplets are usually measured using aerosol spectrometers [55], optical particle counters [14] or aerosol monitors [31]. While, nebulised bio-aerosol solutions are measured using Anderson Cascade Impactor (ACI), which samples bacteria or viruses from the air into petri dishes [59,89]. For setting up the numerical model, flow meters are used to measure the flow rate at ventilation supplies [60,86] and for validating it, anemometers are used to measure the velocity and temperature of the airflow inside the room [29,32]. A few experiments also use Particle Image Velocimetry (PIV) [90] or Planar Laser-Induced Fluorescence (PLIF) [84] to quantify the velocity and concentration fields, respectively.

3.3.2. *Numerical simulations*

While experimental techniques use anemometers, sensors, flowmeters, and visualisation methods, Computational Fluid Dynamics (CFD) is a numerical approach that uses computer processors to solve fluid flow problems. CFD uses codes that discretise the Navier Stokes equation into algebraic equations and solve them iteratively [94]. Commercially available codes like Ansys [95], STAR-CCM+ [96], ABAQUS [97] and open-source codes like OpenFOAM [98], SU2 [99], xcompact3D [100], PALM [101]. There are three approaches to numerical simulations (from low to high fidelity in turbulence representation): Reynold Averaged Navier Stokes (RANS), Large Eddy Simulations (LES), and Direct Numerical Simulations (DNS).

RANS averages the NS equations over time, using Reynolds decomposition, giving a Reynolds stress tensor term [102]. This term represents the effect of turbulence, which is assumed to be statistically steady and is modelled using k-ϵ or k-ω models [103]. In contrast to RANS, LES resolves the larger, energy-containing eddies while modelling the smaller, dissipative eddies [104]. It is useful for complex flow applications where it is important to resolve the large turbulent structures [105]. DNS directly computes the entire range of turbulent scales rather than modelling it like in RANS, making it computationally expensive [106].

Table 5 categorises the reviewed studies according to their numerical approach; a decreasing number of studies can be observed moving from RANS to DNS. This decrease is because of the high computational resources required for LES and DNS and the ease of running commercially available RANS codes. Among the RANS studies, the most used turbulence models are k-ϵ [13,40] and k-ω SST [39,73]. ANSYS Fluent is often used to perform indoor RANS simulations with additional modelling for droplet physics [15,80]. In the following column, the studies have resolved the most energetic turbulent eddies and modelled the subgrid scales using the Wall Adapting Local Eddy (WALE) viscosity model [36,66], Smagorinsky Lilly model [46,48], and one equation eddy viscosity model [49]. The codes used to perform LES are a mix of commercially available tools like Ansys [66,91] and open-source tools like OpenFOAM and PALM [71]. In the last column, studies have resolved all turbulent scales with the help of bespoke codes like AFiD [67], xcompact3D [34], Fujin [64], Megha-5 [35] etc.

4. Discussion

4.1. *Ventilation regime and setting*

From Table 2, it is evident that Ventilation regime 1, i.e. mixing ventilation, is the most widely used ventilation regime across all occupant configurations and almost all indoor settings. This is supported by the fact that mixing ventilation can dilute the pathogen or pollutant concentration in the room [115]. Ventilation regimes 2 and 3, i.e. displacement and stratum ventilation, are less common in comparison because the indoor airflow is directional, upward and lateral, respectively, making them less versatile in most scenarios but more effective in some. In some healthcare settings, a ventilation regime where the air is supplied vertically downwards is also implemented to deposit the suspended IRPs on surfaces immediately [42,53,59].

Table 5
Numerical studies classified based on varying levels of resolving turbulent scales.

Simulation type	RANS	LES	DNS
Studies	Ren et al. [13]	Feng et al. [66]	Giri et al. [34]
	Li et al. [15]	Khosronejad et al. [107]	Chong et al. [67]
	Dbouk and Drikakis [20]	Zhang et al. [36]	Diwan et al. [72]
	Liu et al. [89]	Berrouk et al. [14]	Singhal et al. [35]
	Dbouk and Drikakis [73]	Pendar and Páscoa [49]	Rosti et al. [64]
	Aliyu et al. [75]	Abkarian et al. [70]	
	Zhou and Ji [31]	Saarinen et al. [91]	
	Mirzaie et al. [19]	Li et al. [108]	
	Qian et al. [87]	Liu et al. [17]	
	Li et al. [86]	Quintero et al. [92]	
	Villafruela et al. [41]	Buchan et al. [109]	
	He et al. [38]	Wu et al. [48]	
	Jiang et al. [61]	Fontes et al. [78][a]	
	Yan et al. [39]	Salinas et al. [110]	
	Ren et al. [13]	Krishnaprasad et al. [111]	
	Faleiros et al. [90]	Vuorinen et al. [71]	
	Romano et al. [58]	Liu et al. [60]	
	Lu et al. [53]	Oksanen et al. [33]	
	Lordly et al. [76]	Li et al. [46]	
	Guo et al. [27]	Auvinen et al. [112]	
	Qin et al. [37]		
	Hang et al. [57]		
	Lu et al. [42]		
	Pan et al. [45]		
	Hang et al. [93]		
	Wu et al. [48]		
	Liu et al. [113]		
	Li et al. [32]		
	Poussou et al. [84]		
	Luo et al. [79]		
	Shao et al. [51]		
	Liu et al. [114]		
	Ho and Binns [28]		
	Ou et al. [40]		
	Liu et al. [59]		
	Cheng et al. [88]		
	Wang et al. [77]		
	Liu et al. [60]		
	Wei et al. [80]		
	Li et al. [50]		
	Cortellessa et al. [85]		
	Srivastava et al. [115]		
	Deng et al. [47]		
	Xu et al. [52]		
	Motamedi et al. [116]		
	Arpino et al. [29]		
	Pan et al. [44]		
	Yang et al. [117]		
	Sen [74]		
	Feng et al. [43]		
	Fontes et al. [78][a]		

[a] Detached Eddy Simulation with both RANS and LES approaches used.

Among the papers reviewed, Occupant Configuration 1, i.e., face-to-face occupant configuration, has received the least attention compared to the other occupant configurations. These occupant configurations are mostly found in restaurants, offices, and hospitals.

The common ventilation regimes shown in Section 3.1 consist of a fixed supply and exhaust, which makes the removal efficiency of IRPs depend on the occupant configuration. There are two more ways of ventilating the room that have recently been looked at for the purpose of reducing occupant exposure to IRPs. First, using mobile air cleaners [41,55], briefly mentioned in Section 3.3.1, and second, using personal ventilation solutions [38,85]. Mobile air cleaners are an affordable, accessible, and flexible way to circulate air throughout the room while removing IRPs in settings which do not have dedicated air handling units like classrooms [54]. The mobile air cleaners can positioned optimally in a room for a given occupant configuration [118]. On the other hand, personalised ventilation devices aim to reduce the IRP concentration at the personal level from the occupant's breathing zone by supplying clean air or exhausting air [119,120]. According to multiple studies, using such systems has advantages in isolating IRPs in an indoor space over centralised air-conditioning systems because of its personalised characteristics, higher ventilation efficiency and energy savings [121,122].

It was found that approximately 40% of the reviewed studies do not replicate a specific indoor setting, and the rest barely consider social settings, especially restaurants. This is clearly illustrated in Fig. 2 for restaurant settings, making up a measly 3% of the studies. Most studies focus on settings immediately affected by an outbreak, like healthcare settings (26%), or have vulnerable occupants, like classroom settings (14%). Office and transport settings constitute a total of 17% of the reviewed studies. The fact that these settings have received priority over restaurant settings can be attributed to the fact that almost 80% of the studies were conducted after the onset of the COVID-19 pandemic. However, there are no more restrictions on social gatherings in public places like restaurants, cafes, and bars, making these settings susceptible to massive spreading events in the case of a future outbreak.

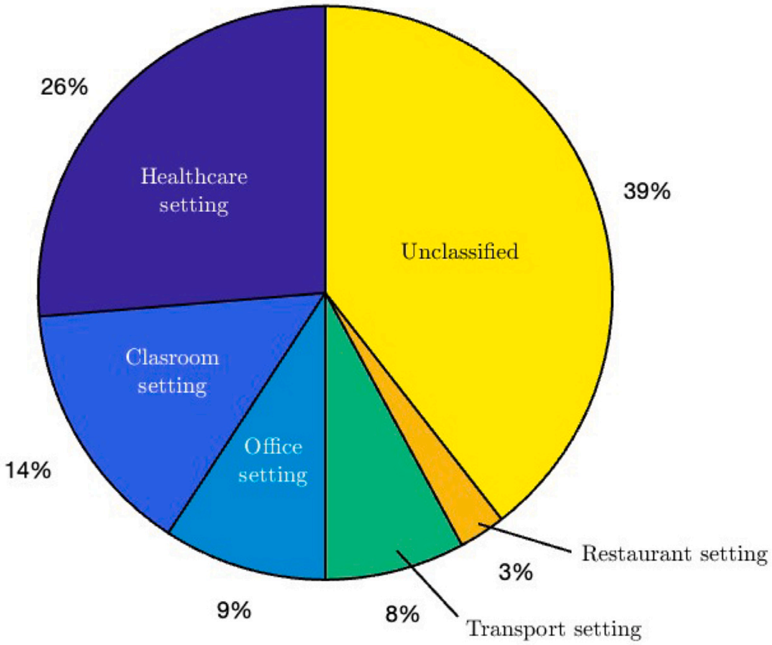


Fig. 2. Pie chart describing the lack of attention to restaurant settings.

4.2. Indoor air conditions and respiratory activities

In Table 3, The first couple of columns compare the four different combinations of air conditions, while the next two compare the different respiratory activities. Among the reviewed studies, very few looked at air conditions as a combination of various air temperatures and RH. The respiratory flow behaves differently in different conditions that might alter the spatial concentration of the IRPs in the room. Concerning the concentration of IRPs, the air conditions could affect the risk of exposure for a susceptible occupant inside a room. This makes the room's air conditions an essential factor to consider when minimising exposure risk for occupants, especially in tropical countries [123].

On the other hand, numerous studies referring to one of the four respiratory activities in Table 3, especially for coughing and breathing while sneezing and speaking, have not received that much attention. That is because most of the reviewed papers were published after the onset of the COVID-19 pandemic, where early research focused on short-range transmission through larger IRPs expelled via coughing. Long-range transmission, through finer IRPs expelled via breathing and their potential to stay suspended in the air, was recognised much later [11]. Now that people are more likely to interact in social gatherings, speech could play an essential role in airborne transmission as it expels IRPs of all sizes. The broad IRP size spectrum [124] and the different spreading mechanisms [10] highlights the importance of looking at both short-range and long-range airborne transmission for improved infection control measures [10,11,124–127].

The transmission route is closely linked to the size of the expelled IRP due to varying dynamics as qualitatively illustrated in the last two columns of Table 3. The larger IRPs shown in red tend to follow a semi-ballistic trajectory and settle down quickly due to gravity, which leads to direct deposition or surface contamination, leading to direct/indirect contact [10]. The smaller IRPs shown in blue can stay suspended in the air for long periods and travel through ventilation flows, reaching individuals far from the infected occupant [124]. There is no fixed cut-off for an IRP to be small, intermediate, or large, due to varying ambient conditions in the room, IRPs can change in size. However, for easier understanding, we have used three size levels of IRPs in the last two columns of Table 3, which, in practice, is a continuous spectrum [63]. Speaking can affect these transmission routes further as it generates even more IRPs than other respiratory activities [34], significantly increasing the exposure risk for a susceptible occupant. A combination of speaking and breathing needs to be examined more carefully to understand short- and long-range transmission routes in a social indoor space and prepare public health systems for future respiratory outbreaks involving similar transmission dynamics [126].

4.3. Investigation approaches

The airflow and IRP distribution in an indoor setting is usually mimicked using experimental or numerical approaches. In Table 4, all the experimental studies are broken down into the method of flow generation, method of measurement, and the flow type mimicked. Very few studies account for the three significant sources of airflow in their experiments [31,36]. Anemometers are the common choice of apparatus for measuring airflow parameters like velocity and temperature, while particle concentrations are measured using tracer gas sensors and particle counters. Tracer gases are good at providing insight into airborne transmission through the gas molecules but fail to replicate the behaviour of two-phase respiratory flow. This shortcoming can be addressed using aerosol generators that nebulise pathogen-containing solutions, which are the most accurate way to mimic IRPs. Moreover, conventional tracer gases are visually undetectable; therefore, they do not provide any visual cues for how respiratory flow evolves. Few studies address this issue by using optical methods like smoke flow visualisation [34,91], soap bubbles visualisation [128], fluorescent tracking liquid with UV-lights [129], and PIV/PLIF [84,90] to study the flow in the laboratory qualitatively. PIV and PLIF are also non-intrusive velocity and concentration measurement methods, making them ideal for studying IRPs and the effect of ventilation and thermal flows on their distribution.

In Table 5, the numerical studies are classified based on their approach towards resolving the turbulent structures in the simulated flow. The sheer difference in number is better illustrated in Fig. 3, which can be explained by the fact that RANS simulations are not computationally demanding and correlate with experimental results well enough in non-separating flows [48]. RANS involves modelling the turbulent kinetic energy and turbulent dissipation as $k-\epsilon$ and $k-\omega$ turbulence models, where k is the turbulent kinetic energy, ϵ is the turbulent dissipation,

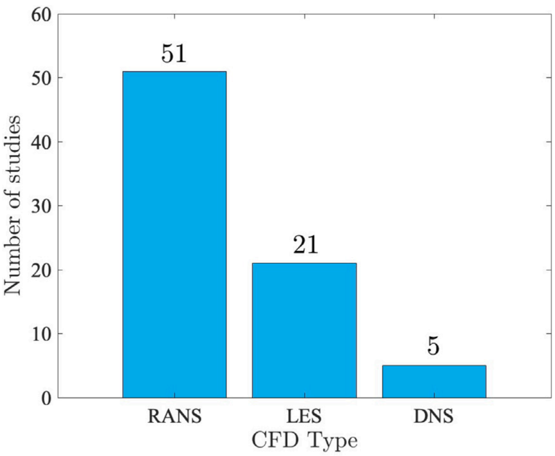


Fig. 3. Bar graph depicting the usage of different CFD approaches in indoor airborne transmission studies.

and ω is the specific rate of turbulent dissipation. These are some of the most widely used models in research and industry. In this review, 38 of the 51 RANS studies have performed RANS simulations with the $k-\epsilon$ turbulence model.

While the RANS approach models the entire turbulent kinetic energy spectrum, DNS resolves all the turbulent scales from the largest to the smallest (Kolgomorov) [130] scale. DNS has been used to simulate the respiratory jets emanating from people during coughing [64,67,72] or speech [34,35], or ventilation flow in a room with an occupant [131]. Resolving all the turbulent scales comes at the cost of significant computational resources, making it inaccessible to most researchers. In contrast, More studies recently are resorting to LES for studying airborne transmission in an indoor environment [66,71,107] as they show more substantial agreement with experimental data when compared to RANS simulations [48]. That is because LES decomposes the flow into two parts: (i) Large scales of turbulence that are resolved, and (ii) Small scales of turbulence that are unresolved but modelled. Some of the most popular SGS models are the Smaroginsky Lilly model, the Wall Adapting Local Eddy-viscosity (WALE) model, the Vreman model, and the One-equation model. Another approach is Detached Eddy Simulation (DES), where the flow is simulated using LES except within boundary layers and irrotational flow regions, where unsteady RANS simulation is used.

Numerical simulations also have two approaches to handle particle transport: Eulerian and Lagrangian. The Eulerian approach considers a fixed domain discretised into a grid, where the fluid properties are spatial fields at each grid point that can vary spatially and temporally within the domain [94]. The Lagrangian approach tracks the particles instead of the fluid properties, where each particle has its position and velocity [132]. Eulerian is advantageous for studying the advection and diffusion of aerosols [44,45], and is computationally cheaper than Lagrangian particle tracking. However, modelling all the turbulent scales in Eulerian RANS simulations often overestimates dispersion and leads to a well-mixed room condition [40]. Lagrangian simulations provide more detailed information about particle dynamics and evolution [52], which is ideal for complex and turbulent flows, as is the case here.

In addition to how the transmission of IRPs is modelled, the obtained data from the numerical simulations need to be analysed for easier interpretation. In the context of airborne transmission of pathogens, exposure risk and infection risk are two quantitative parameters often used for analysis. Often, exposure and infection risks are used interchangeably [15,51], which should not be the case. Exposure is the physical phenomenon of pathogens transmitting from an infectious to a susceptible occupant's respiratory tract, while infection involves the multiplication of infectious pathogens within the respiratory tract [63]. While exposure risk can be evaluated from experiments or CFD simulations, infection involves complex factors that lead to a successful infection of a susceptible occupant. The analytical model proposed by Wells and Riley [133,134] estimates infection risk with quanta generation of IRPs, number of infectious occupants, and ventilation rate as input. The model is valid only for certain assumptions, including the indoor air's well-mixed condition. This assumption is one of the major limitations of this model as seen in previous studies [110,135,136]. To overcome this limitation, the model has been adapted to include the effects of spatial variation by coupling with CFD [79,115], but its accuracy depends on the prediction of the numerical method used. Using infection risk models like the Wells–Riley model or Dose–response model [137] coupled with high-resolution numerical simulations have predicted reliable infection probabilities [112].

In both experimental and numerical approaches of mimicking IRP transmission in indoor environments, it is observed that often, the respiratory flow from the occupants is generated [31,58] or modelled [13,32,48] as a constant flow. However, respiratory flow is pulsatile, and the pulsating frequency depends on the respiratory activity [138,139]. Some have modelled coughs and sneezes like [19], and some have modelled breathing [38,51]. Speech has not received as much attention yet [34,35]—Additionally, the effect of occupant dynamics on the flow inside an indoor setting. Most studies studying indoor airborne transmission assume perfectly still occupants, while some look into monotonous movements or short sequences. Monotonous movements like walking down an aircraft aisle or inside a patient wardroom [48,84], while short movements could be opening a door, walking inside a room and then closing the door [91]. Moreover, in settings with more than one occupant, the airflow from the susceptible individuals is ignored [54].

5. Conclusions

In this review, we looked at previous literature from four broad perspectives: (a) transmission of the pathogen, (b) ventilation regime, (c) investigation approach, (d) setting and (e) risk assessment. These studies were reviewed, and the results were divided into (i) Airflow patterns, (ii) Dynamics of IRPs, and (iii) Experimental and Numerical approaches. There have been numerous attempts by engineers, scientists, and medical doctors to quantify airborne transmission through experiments, CFD simulations, theoretical models, and epidemiological studies over the last decade. The medical setting has been a primary subject of research in this field. Classroom and office room settings have received some attention among non-medical settings. However, social settings like restaurants have not received much attention in these studies despite having a high potential for airborne transmission. Since temperature and relative humidity play an essential role in the evolution of pathogen-laden respiratory flow, it has unfortunately remained understated in previous studies. Similarly, the dominant respiratory activities in restaurant settings, such as speaking and breathing, have not been considered for analysis. Risk assessment is expected in airborne transmission studies and is often performed with the help of theoretical models and quantitative tools. Therefore, the experimental and numerical approaches must be reasonably accurate in replicating the physics, and researchers must be careful about their conclusions. Risk assessment is crucial in determining high-risk zones inside a room, as it helps HVAC engineers and planners develop an optimal ventilation regime. A ventilation regime that either exhausts IRPs from the high-risk zones or keeps them away from the susceptible occupants' breathing zone. This gives public health organisations precious time to react in the event of an outbreak and implement active measures to contain it.

CRediT authorship contribution statement

Arghyanir Giri: Writing – original draft, Methodology, Investigation, Conceptualization. **Clara García-Sánchez:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Philomena M. Bluyssen:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Arghyanir Giri reports financial support was provided by Pandemic & Disaster Preparedness Centre (PDPC). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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