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A review on indoor airborne transmission of COVID-19–modelling and mitigation approaches

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ABSTRACT

In the past few years, significant efforts have been made to investigate the transmission of COVID-19. This paper provides a review of the COVID-19 airborne transmission modeling and mitigation strategies. The simulation models here are classified into airborne transmission infectious risk models and numerical approaches for spatiotemporal airborne transmissions. Mathematical descriptions and assumptions on which these models have been based are discussed. Input data used in previous simulation studies to assess the dispersion of COVID-19 are extracted and reported. Moreover, measurements performed to study the COVID-19 airborne transmission within indoor environments are introduced to support validations for anticipated future modeling studies. Transmission mitigation strategies recommended in recent studies have been classified to include modifying occupancy and ventilation operations, using filters and air purifiers, installing ultraviolet (UV) air disinfection systems, and personal protection compliance, such as wearing masks and social distancing. The application of mitigation strategies to various building types, such as educational, office, public, residential, and hospital, is reviewed. Recommendations for future works are also discussed based on the current apparent knowledge gaps covering both modeling and mitigation approaches. Our findings show that different transmission mitigation measures were recommended for various indoor environments; however, there is no conclusive work reporting their combined effects on the level of mitigation that may be achieved. Moreover, further studies should be conducted to understand better the balance between approaches to mitigating the viral transmissions in buildings and building energy consumption.

1. Introduction

The entire world has faced the spread of a new virus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), accompanied by significant numbers of deaths worldwide [1]. COVID-19 (or coronavirus disease) is the official name given to the disease caused by this virus, SARS-CoV-2 [2]. The primary transmission routes include inhalation of small virus-carrying particles, deposition of virus-laden particles on exposed mucous membranes in the mouth, nose, and eye, as well as touching mucous membranes with contaminated hands [3]. Researchers have also confirmed that SARS-CoV-2 can be transferred via virus-laden particles in the air, i.e., airborne transmission [4–10]. Respiratory particles generated are either in the form of droplets or aerosols based on their aerodynamic...
size. The World Health Organization (WHO) named larger particles (>5 μm) as droplets while smaller ones (≤5 μm) as aerosol or droplet nuclei [11,12]. This means that the term “particle” is a general representation of both droplets and aerosols.

Many studies have been conducted in the past two years on COVID-19 airborne transmission modeling, especially simulation-based investigations. The present work reviews simulation-based research papers investigating indoor airborne transmission of SARS-CoV-2 to summarize available simulation tools adopted to model the disease transmission and general mitigation strategies offered. The purpose of this review is to provide an overview of the current status of simulation studies on coronavirus disease transmission, including underlying theory and assumptions, inputs/outputs, general approach, and accompanied validation/experimental studies, for a better understanding of the strengths and limitations of these different approaches and the identification of future research needs, especially for near future of the post-COVID-19 pandemic era, based on a comprehensive while critical review.

1.1. Scope of the review

The main focus of the present work is to review simulation-based articles studying the airborne transmission of COVID-19 indoors and the mitigations offered based on them. It should be noted that, some recent and relevant experimental works conducted to study the airborne transmission of COVID-19 are summarized in the present work. The available data in these experiments can be used to assess the reliability of numerical results in future studies. Moreover, most of transmission mitigation strategies discussed in the present review are based on modeling-based studies; however, a minority of them are based on measurements.

In order to identify different models adopted in previous studies investigating COVID-19 transmission, 191 modeling-based articles have been gathered. Based on majority of them (175 out of 191 papers), the models commonly adopted are organized in Fig. 1. These models have been classified into two main parts: 1) infection risk assessment and 2) numerical approaches (zonal and computational fluid dynamics (CFD)).

Wells-Riley and dose-response modes are the most well-known models that quantify the airborne infection probability [13]. However, in-depth details relating to the geometry and the virus propagation cannot be taken into account using risk assessment models. Therefore, numerical models such as zonal and CFD (species transport modelling and multi-phase approaches) have been performed to cover these details and assess the infection risk based on comprehensive information. Moreover, based on Fig. 1, the red-dashed arrows point out that the predictions of a model can be or need to be used as an input for another. Specifically, numerical models (zonal or CFD) can provide input for infectious risk assessment models, estimating the infection probability based on many details (indoor geometry, non-uniform distribution of contaminants, etc.). Moreover, the connection between the CFD and the zonal blocks means that some predictions from CFD are required to conduct zonal modeling. Section 3 of this paper discusses different models adopted to predict the airborne transmission of COVID-19 indoors, unfolds many data adapted in previous studies, and discusses available knowledge gaps for future works.

Transmission mitigation strategies suggested based on recent works as well as standards’ recommendations concerning COVID-19...
airborne transmission are discussed in section 4. The general mitigation strategies in recent modeling-based studies are found to be controlling occupancy, upgrading ventilation facilities, using filters and air purifiers, installing UV air disinfection, and complying with personal protective measures (such as wearing masks and social distancing). Fig. 2 shows the share of these interventions recommended. As it can be seen, most studies have used CFD modeling for airborne transmission predictions, suggesting a more complete list of transmission reduction plans, which most of these CFD papers have been published after 2021. Moreover, modifying ventilation facilities, using air filters and purifiers, and wearing masks are recommended by most studies using different simulation tools.

Different buildings may need various mitigation strategies. It is therefore observed that most of the studies have considered following indoor environment as their case study: educational, office, public, residential, and hospital. Educational areas cover elementary school, middle school, high school, and universities. Theaters, grocery stores, restaurants, market areas, discos, and so on are categorized as public environments, and hospitals include healthcare centers. In addition, some of these papers have considered other environments which cannot be classified into these categories. However, their mitigation recommendations are used here to summarize the general countermeasures. Fig. 3 illustrates various indoor environments taken as a case study in previous works. As it can be seen, educational, public, and hospital areas have been paid more attention when compared to other buildings regardless of transmission mitigation measures. In addition to summarizing the general mitigation measures identified, section 4 also summarizes mitigation strategies regarding the COVID-19 transmission based on different building types as well as identified knowledge gaps.

1.2. Contributions of present work compared to previous reviews

To distinguish the present work from other existing reviews, a summary of the review articles on indoor COVID-19 transmission studies has been summarized in Table 1.

To the best of our knowledge, there is no comprehensive work concentrating on different models used to study the airborne transmission of COVID-19. Thus, different models used to predict COVID-19 airborne transmission are introduced together, and their mathematical description is elaborated based on recent papers. A list of assumptions adopted to develop these models are discussed as well, identifying limitations and potential improvement ideas. Moreover, a complete list of inputs to model the transmission of COVID-19 is summarized in well-organized tables, discussing the knowledge gaps and showing typical ranges adopted for parameters that have not been done previously. These data are various information related to the emission of particles (viral load, emission rate, size, deposition rate, inactivation rate, injection speed, and numbers), ventilation rate, important information adopted for the CFD modeling, and mitigations implemented. Furthermore, strategies to mitigate COVID-19 propagation have not yet been comprehensively discussed. To be more specific, most previous reviews did not focus on how much the mitigations can be effective to reduce the transmission, which approaches are more effective, and the current research gaps regarding the mitigation measures based on the current status of state-of-the-art simulation-based studies. Thus, as the other contribution of this review, we discussed a list of measures to combat the airborne propagation of COVID-19 in buildings, analyzed them based on their capabilities and limitations and their effects on the level of transmission reduction, and provided detailed discussions for future works, as shown in Table 1. It has to be mentioned that section 4 mainly provides an overview of the outcomes through the simulation methods explained in section 3. This can provide the readers with an idea of what these models can do and what can be concluded from them. It should not be left unmentioned that as a limitation of the current review, we did not combine the studies from the disciplines of virology, micro-biology, and epidemiology. In other words, this paper is from the perspective of building engineering-related studies. Last, recommendations for
future studies are elaborated in the main text when knowledge gaps are introduced and discussed.

2. Methodology of collecting papers

Articles published in recent years are gathered after comprehensive searches for papers on COVID-19 airborne transmission. To do so, various combinations of keywords are used to find the most relevant papers from the databases. Table 2 lists the keywords used in our searches to collect relevant papers. In this table, the keywords in line 2 (for the airborne transmission) and line 6 (related to the buildings) were the main restrictions for our searches and further analysis of papers to create our final candidates from the articles found. Although Scopus has been used as the main database in our searches due to its flexibility and features offered to narrow down papers found, other databases such as Google Scholar, PubMed, medRxiv, ScienceDirect, and arXiv are also used. Peer-reviewed and English articles are given priority to other articles.

Furthermore, Fig. 4 illustrates the methodology we followed in deciding whether to select the articles that appeared in the search results as final candidates. The search results based on the keywords in Table 2 would result in an extensive list of papers which, in fact, not all of them are within the scope of our review. Therefore, following the rules in this figure, the final papers in our assessments were collected.

3. COVID-19 transmission modeling

Risk assessment, zonal, and CFD modeling have been introduced in the majority of studies in recent years studying the airborne transmission of COVID-19. General mathematical descriptions of these models and assumptions are discussed in this section. Moreover, input data assumed to investigate the airborne transmission of COVID-19 are analyzed, and potential future ideas are elaborated on as well.

3.1. Infection risk assessment models

Wells-Riley and dose-response are two infection risk models adopted recently to quantify the infection probability of COVID-19. The weaknesses and the application of these two models to study infectious disease transmission have been discussed in the previous review papers [13]. However, the main focus here is to review the papers that investigated the COVID-19 airborne transmission, assumptions made, and modifications done. In other words, section 3.1 introduces the latest modifications for these two models in the wake of the COVID-19 pandemic and covers how different mitigation measures have been translated into infection risk assessments and what newest steps have been taken by researchers to overcome limitations exist in previous versions of these two models.

3.1.1. Wells-Riley model

A fast and straightforward infection risk assessment method for respiratory diseases, such as COVID-19, is the Wells-Riley model. The Wells-Riley model is [26]:

![Airborne transmission models](image-url)
Table 1
Comparing this review and the previous review studies on COVID-19 transmissions.

| Ref. | EE on VLPs<sup>a</sup> | VLPs size dist.<sup>b</sup> | TR<sup>c</sup> | Eva. of VLPs<sup>d</sup> | Airborne transmission modeling<sup>e</sup> | Comprehensive mitigation measures (MM)<sup>f</sup> | Mitigation measures (MM) for different buildings<sup>g</sup> | MM effects<sup>h</sup> |
|------|------------------|------------------|---------|-----------------|------------------|-----------------|------------------|------------------|
|      |                  |                  |         |                 | IR    Zon   CFD  | Occ   Ven   Fil & AP | E     O     P     R    H |
| [14] | ✓                | ✓                | ✓        | ✓               | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [15] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [16] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [17] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [18] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [19] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [20] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [21] | ✓                | ✓                |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [22] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [23] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [24] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| [25] |                  |                  |         |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |
| Present review | ✓                | ✓                | ✓        |                 | ✓     ✓     ✓   ✓   ✓     ✓    ✓   ✓     ✓    ✓     ✓    ✓     ✓    ✓ |

<sup>a</sup> Environmental effects on virus-laden particles.
<sup>b</sup> Virus-laden particle size distribution.
<sup>c</sup> Transmission routes.
<sup>d</sup> Mathematical insight into the evaporation of virus-laden particle.
<sup>e</sup> Transmission reduction (quantified report for impacts).
<sup>f</sup> Infection risk (IR), zonal (Zon), and CFD models (in order).
<sup>g</sup> Abbreviation for mitigation measures, including occupancy (Occ), ventilation (Ven), filter and air purifier (Fil & AP), UV air disinfection (UV), mask and social distancing (M&SD).
<sup>h</sup> Abbreviation for building types, including educational (E), office (O), public (P), residential (R), and hospital (H).
where \( P \) is the virus infection probability or risk (−), \( C \) denotes the number of infection cases, \( S \) is the number of susceptible people, \( I \) is the number of infectors, and \( q \) means the quanta of airborne infection produced per infector per minute \((1 \cdot \text{min}^{-1})\). \( p \) shows the pulmonary ventilation rate of each person per minute \((\text{m}^3 \cdot \text{min}^{-1})\), \( t \) is the exposure time (min), and \( Q \) is the indoor ventilation rate with germ-free condition \((\text{m}^3 \cdot \text{min}^{-1})\). Moreover, a quantum is the minimum number of infectious airborne particles necessary to infect a person, which may be one or more airborne particles, and the pulmonary ventilation rate is the rate at which the air flows into the lungs during inhalation and out of it during exhalation. Wells-Riley model is based on the well-mixed assumption for the quanta of airborne infection produced. In other words, it is considered that the quanta of infection is uniformly distributed throughout the air. The term “\( Iq/Q \)” in Eq. (1) is the room’s quantum concentration, which has a constant value in the original Wells-Riley equation [27].

In addition to this, other assumptions to develop the Wells-Riley model are [28]:

i. Particles are so small that they have been randomly distributed inside the space, which satisfies the well-mixed assumption
ii. Susceptibility of individuals in the room is equal
iii. A constant rate of quanta \((q)\) is added to the space by infectors
iv. The scale of time in the right hand of Eq. (1) is shorter than the latent time of the disease (the time period at which a person is infected and finally becomes infectious)
v. The number of infectors is constant
vi. Virus-laden particles are uniformly and instantaneously distributed inside the room [29].
vi. Particles are removed from the space at a constant rate
viii. The ventilation air condition supplied is similar to that of the current air in the room
ix. The number of infected individuals is proportional to the number of encounters between susceptible individuals and the quanta infection

Note that, due to the limitation of these assumptions, the Wells-Riley model is incapable of considering the varying exposure risks of short-range transmission and the changing viral load affected by the host immune responses and the ambient airflows from doors, windows and walking that makes such airborne viral load exposures variable, which limited the application and accuracy of the model.

As it is observable in Eq. (1), the parameter \( q \) should be known to be able to estimate the infection risk using the Wells-Riley model. An exact value of the quanta generation rate \( q \) is unknown when a pandemic starts and can be calculated when the population of susceptible persons who were not infected is known [28]. Furthermore, the quanta generation rate can be estimated based on the viral load.
load. Buonanno et al. [30] introduced a formulation to calculate the quanta generation rate of COVID-19 using the viral load in the sputum as available data. The viral load in the sputum is measured in RNA copies mL⁻¹ or PFU mL⁻¹ (PFU stands for the plaque-forming unit). The methodology introduced by Buonanno et al. [30] is based on the concept that particles released by an infected person have the same viral load as the sputum. This assumption brings up the idea that the viral load emitted can be obtained using a mass balance, provided that the concentration of the virus in the sputum and the number of particles released during different activities are known. This methodology has been followed by other studies as well [31–34]. However, the assumptions adopted by this method are not rigorous enough in view of virology because the emitted viral-laden particles can be affected by factors such as the host immune responses and the physical properties of the oropharyngeal fluids [35] and, in addition, the aerosol viral loads can be much lower than the viral swab load [36]. With this regard, a more interdisciplinary effort is needed to identify the viral load for indoor studies. The variation range of the quanta generation rate (q) and its average value in recent works studying COVID-19 transmission are discussed at the end of this section.

The original Wells-Riley model relies on the small size of particles [26] and is not able to quantify the infection risk of large droplets dispersion or close contact. However, researchers have used other in-depth approaches, such as numerical modeling, to predict the distribution of concentration of particles of various sizes and, finally, the quanta inhaled to be able to use the Wells-Riley model with more realistic inputs (numerical modeling will be discussed later). The original Wells-Riley model is based on other simplified assumptions as well, discussed above, and many real-world scenarios cannot be considered. The original Wells-Riley model considers that the ventilation rate is the only variable affecting indoor infection probability since the well-mixed condition is the first assumption [37].

Efforts have been made to improve the Wells-Riley model capabilities to cover more details regarding the airborne transmission of COVID-19. In addition to the original assumption that particles are being removed from the space through indoor ventilation, modified versions can also consider other ways that particles can be removed from airborne propagation. These removals are the natural inactivation rate of pathogens, the deposition rate of pathogens on surfaces due to the gravitational force, the virus inactivation rate by devices such as UVGI in the room, and cleaning the air with filters (e.g., air purifiers). Moreover, the effect of wearing masks by both infectors and susceptible people, social distancing and close contact, and the effectiveness of the air distribution provided by HVAC systems has been incorporated into the original Wells-Riley model (it is clear that different ventilation systems have different performances which change the air distribution). ASHRAE [38] has specified the effectiveness of the air distribution for various ventilation systems, ranging from 0.5 to 1.5, which can be introduced to the Wells-Riley model. In addition, the effect of air recirculation and its filtration has been considered in new versions. Instead of considering a well-mixed and a constant rate of the quanta concentration, the impurity of the well-mixed condition, as well as the temporal variation of quanta concentration, have been added to the Wells-Riley model. Recently, the capability of considering the spatiotemporal distribution of particles (instead of the random and evenly distribution of particles assumption) has been examined with the Wells-Riley model. Table 3a summarizes the new features added to the original Wells-Riley model and modified equations versions.

Similarly, several other papers examined the COVID-19 infection probability by developing a modified Wells-Riley model [4,32,42,43]. The modified versions take into account more details and are expected to produce more realistic estimations. The important note in Table 3b is that few authors have incorporated the multiple effects of these modifications in their work. Most of them just added one or two modifications to the original model. Based on our understating, more holistic works are required to develop modified models incorporating the effect of various combinations of these features and compare their accuracy with experimental data showing their accuracy.

| Num. | Ref. | Year | Capabilities added to the Wells-Riley model |
|------|------|------|---------------------------------------------|
| 1    | [27] | 2022 | ✓ △†  △‡  △§  △|| | |
| 2    | [33] | 2021 | ✓ △†  △‡  △§  △|| | |
| 3    | [37] | 2020 | ✓ ✓ △‡  △§  △|| | |
| 4    | [39] | 2021 | ✓ ✓ △|| | |
| 5    | [40] | 2021 | ✓ △|| | |
| 6    | [41] | 2021 | ✓ ✓ ✓ ✓ △|| | |

a Social distancing.
b Air distribution effectiveness.
c Simultaneous effect of airborne transmission and close contacts.
d Mask filtration.
e Pathogens deposition (on surfaces).
f Pathogens natural inactivation.
g UVGI virus inactivation.
h Air purifier fresh air.
i Air recirculation and its filtration.
j Impurity of well-mixed assumption.
k Temporal changes of quanta concentration.
l Spatiotemporal distribution of airborne particles.
animals or humans are imposed by the pathogen. To make it clear, for a group of test animals that are exposed to a certain dose of SARS-CoV-1 [34]. SARS-CoV-1 and SARS-CoV-2 share the same host cell receptor angiotensin-converting enzyme 2. These two viruses need to be known to create a dose-response relationship between a pathogen and its surrogates for SARS-CoV-2 airborne transmission risk assessment at the moment. Many studies [34, 47, 50] pointed out in each respiratory cycle, the virus concentration, as well as the deposition fraction of particles in the human respiratory tract can be efficiently k has not yet been identified for SARS-CoV-2.

The quanta concentration to which a susceptible person is exposed needs to be calculated using a dose-response model to quantify the COVID-19 infection risk. For example, the quanta concentration at time t can be calculated as (quanta person−1)

\[ n = n_0 e^{-\gamma R(t)} + \frac{ER_v \times I}{VRR} \times \left(1 - e^{-\gamma R(t)}\right) \]  

where \( \gamma \) is the removal rate of the infectious virus (1 h−1), \( n_0 \) shows the initial concentration of the quanta (at time t = 0) (quanta m−3), \( I \) is the number of infectious people, \( V \) is the indoor area volume (m3), and \( ER_v \) is the quanta emission rate (quanta h−1). The removal rate of infectious viruses depends on different items [53], such as the air change per hour (ACH) of the room, the deposition rate of pathogens on surfaces, the viral natural inactivation rate, and the removal of pathogens due to application of mitigation measures like wearing masks, filters, etc., as discussed in the previous section. As a more realistic approach for future studies, different deposition rates should be assumed for different particle size bins (particles are being omitted over a size range), and the deposition rate of particles can be calculated as:

\[ d = \frac{IVR}{AER \times c} \]  

where IVR is the indoor ventilation rate (1 h−1), AER is the air change rate via ventilation (1 h−1), and c is the particle deposition rate (1 h−1). In order to calculate the dose d over time T, several parameters such as the number of respirations, the amount of air that moves in/out in each respiratory cycle, the virus concentration, as well as the deposition fraction of particles in the human respiratory tract can be taken into account [47].

The quanta concentration to which a susceptible person is exposed needs to be calculated using a dose-response model to quantify the COVID-19 infection risk. For example, the quanta concentration at time t can be calculated as (quanta m−3) [34]:

\[ P = 1 - \exp \left(-\frac{P}{d} \lambda \right) \]  

where P is the infectious probability, d is the magnitude of applied dose reported in PFU, and k is a coefficient specific to each kind of pathogen (PFU), which has been estimated to be 4.1 × 105 PFU for SARS-CoV-1. It is also estimated that the parameter k can be between 10 to 104 PFU for coronaviruses, such as HCoV-229E, MHV-S, MHV-2, and HEV-67N [52]. However, the value for the coefficient k has not yet been identified for SARS-CoV-2.

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Variables:

- AER: Air change rate via ventilation; c: Quanta concentration (quanta m−3); x(t): Local particle volume fraction (−); cPAV: The viral load of an infected person’s respiratory fluid (copies mL−1); d: Particle diameter (μm); E: Ventilation effectiveness index (−); f: Fraction of HVAC system operation time (%); fUV: Infection particle filtration efficiency by filter (%); fUVG: Infectious particle natural inactivation (1 h−1); fUVGI: Infectious particle particle inactivation by UVGI systems (1 h−1); I: Social distancing index (%); q: Ventilation effectiveness index (−); r: Fraction of UVGI system operation time (%); q: Ventilation factor (−); \( \eta_{inactivation} \): Infectious particle inactivation rate by UVGI systems (1 h−1); rUV: Pathogen removal rate by filters (1 h−1) (e.g., air purifier); kUV: Pathogen inactivation rate by UVGI systems (1 h−1); P: Social distancing index (%); qPAV: Fresh air ventilation rate per person (m3 h−1 person−1); r: Pathogen removal rate (1 h−1); T: Time of exposure (h); TCID50: The dose of virus needed to infect 50% of the population (virions); k: Infection dose (virions); t: Time of exposure (h); V: Room volume (m3).

Superscripts:

- a: Airborne transmission; c: Close contact transmission.

3.1.2. Dose-response model

Dose-response models were previously used for infection risk quantification of hazardous chemicals and foodborne/waterborne pathogens. It is then extended to quantify the airborne transmission infection risk [13]. Infectious dose data are achieved when test animals or humans are exposed by the pathogen. To make it clear, for a group of test animals that are exposed to a certain dose of pathogens and 50% of them get the infection, this dose of the pathogen is called a 50% infectious dose [13]. The infectious dose data need to be known to create a dose-response relationship between a pathogen’s dose and the infection risk. A specific dose-response relationship for SARS-CoV-2 is not yet available [44]. There are many dose-response models developed previously, and among them, the exponential dose-response relationships have been widely used to assess the airborne transmission risk of pathogenic risks such as SARS-CoV-1 [34]. SARS-CoV-1 and SARS-CoV-2 share the same host cell receptor angiotensin-converting enzyme 2. These two viruses share similar profiles of cellular tropism, which shows similarities between the infectivity of SARS-CoV-1 and SARS-CoV-2 [45, 46]. Based on this similarity, the exponential dose-response model previously developed for SARS-CoV-1 is reasonable to be used as a surrogate for SARS-CoV-2 airborne transmission risk assessment at the moment. Many studies [34, 47–51] extended the model for the airborne infection risk of SARS-CoV-2 [34, 46–50], as shown below:

\[ P = 1 - \exp \left(-\frac{P}{d} \lambda \right) \]  

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\[ n = n_0 e^{-\gamma R(t)} + \frac{ER_v \times I}{VRR \times V} \times \left(1 - e^{-\gamma R(t)}\right) \]  

where IVR is the removal rate of the infectious virus (1 h−1), n0 shows the initial concentration of the quanta (at time t = 0) (quanta m−3), I is the number of infectious people, V is the indoor area volume (m3), and ERv is the quanta emission rate (quanta h−1), and t denotes time (h). The removal rate of infectious viruses depends on different items [53], such as the air change per hour (ACH) of the room, the deposition rate of pathogens on surfaces, the viral natural inactivation rate, and the removal of pathogens due to application of mitigation measures like wearing masks, filters, etc., as discussed in the previous section. As a more realistic approach for future studies, different deposition rates should be assumed for different particle size bins (particles are being omitted over a size range), and the deposition rate of particles can be calculated as:

\[ d = \frac{IVR}{AER \times c} \]  

where IVR is the indoor ventilation rate (1 h−1), AER is the air change rate via ventilation (1 h−1), and c is the particle deposition rate (1 h−1). In order to calculate the dose d over time T, several parameters such as the number of respirations, the amount of air that moves in/out in each respiratory cycle, the virus concentration, as well as the deposition fraction of particles in the human respiratory tract can be taken into account [47].

The quanta concentration to which a susceptible person is exposed needs to be calculated using a dose-response model to quantify the COVID-19 infection risk. For example, the quanta concentration at time t can be calculated as (quanta m−3) [34]:

\[ n = n_0 e^{-\gamma R(t)} + \frac{ER_v \times I}{VRR \times V} \times \left(1 - e^{-\gamma R(t)}\right) \]  

where IVR is the removal rate of the infectious virus (1 h−1), n0 shows the initial concentration of the quanta (at time t = 0) (quanta m−3), I is the number of infectious people, V is the indoor area volume (m3), and ERv is the quanta emission rate (quanta h−1), and t denotes time (h). The removal rate of infectious viruses depends on different items [53], such as the air change per hour (ACH) of the room, the deposition rate of pathogens on surfaces, the viral natural inactivation rate, and the removal of pathogens due to application of mitigation measures like wearing masks, filters, etc., as discussed in the previous section. As a more realistic approach for future studies, different deposition rates should be assumed for different particle size bins (particles are being omitted over a size range).
Various data used in previous works on the COVID-19 airborne propagation using risk assessment approaches.

Table 4

| Ref. | Building type | Model | Human Activity | Viral load (copies·mL⁻¹) | Quanta generation rate/emission rate (quanta·h⁻¹) | Particle diameter (μm) | Deposition rate (1·h⁻¹) | Pulmonary ventilation/inhalation rate (m³·h⁻¹) | Inactivation rate (1·h⁻¹) |
|------|----------------|-------|----------------|--------------------------|-----------------------------------------------|------------------------|-------------------------|-----------------------------------------------|-------------------------|
| [31] | E              | W-R   | B, S           | –                        | 5 to 25                                        | ≤10                    | 0 to 0.25                | 0.6                                           | 0.5                     |
| [32] | E              | W-R   | VC, S, V       | 10⁹                      | 29.6 to 142                                   | 0.8 to 5.5             | 0.24                    | 0.29, 0.96                                   | 0.63                    |
| [33] | E, O, P, H     | W-R   | B, S           | 10⁹                      | 492 to 610                                     | 0.3 to 1.1             | –                       | 2.5 to 3.0                                   | 0 to 1                  |
| [34] | P, H           | D-R   | B, S, Si       | 10⁷                      | 2.4 × 10⁻² to 1500                            | –                      | 0.24                    | 0.49 to 3.3                                  | 0.63                    |
| [41] | E              | W-R   | –              | 10⁴.⁸⁷                   | –                                              | ≤20                    | 0.24                    | 0.49 to 3.3                                  | –                       |
| [42] | E, O, P        | –     | B              | –                        | –                                              | –                      | 0.3 to 1.5               | 0.65 to 1.38                                 | 0 to 0.63               |
| [54] | E, O, P        | –     | B, S, V        | 3.75 10¹¹ to 3.75 10¹²   | 1.84                                           | 0.4212 to 1           | 0.44 to 0.91             | –                                            | –                       |
| [55] | P              | W-R   | –              | –                        | –                                              | 0.3 to 1.5             | 0.32 to 0.76             | 0.26 to 1.08                                 | –                       |
| [56] | P              | W-R   | –              | 10⁹                      | 142                                           | 0.24                   | 0.96                    | 0.64                                         | –                       |
| [57] | E              | D-R   | B, S           | –                        | 0.575 to 15.85                                 | –                      | 0.24                    | 0.54                                         | 0.63                    |
| [58] | E              | W-R   | B, W, S, V     | 10⁹                      | 58.6                                          | 0.8 to 5.5             | 0.24                    | 0.71                                         | 0.63                    |
| [59] | E              | W-R   | –              | –                        | 142                                           | –                      | 0.24                    | 0.96                                         | 0.63                    |
| [60] | E, O, P        | W-R   | –              | –                        | 14 to 48                                       | 0.25 to 1.00           | 0.21 to 0.63             | 0.3                                           | –                       |
| [61] | P              | W-R   | B              | –                        | 550 to 1510                                    | –                      | 0.3 to 1.5               | 0.65 to 1.38                                 | 0 to 0.63               |
| [62] | –              | –     | 10⁶             | 10 to 1000                 | 0.1 to 1000                                    | –                      | 0.45 to 1.56             | –                                            | –                       |
| [63] | E              | W-R   | –              | 970                      | –                                              | 0.24                   | 1                       | 0.63                                         | –                       |
| [64] | –              | –     | B, S           | 10⁵.⁸                | –                                              | 0.2 to 50              | –                      | 0.57 to 0.67                                 | –                       |
| [65] | E              | P     | B, S           | 10⁵.⁸                | 10 to 100                                     | –                      | 0.49 to 1.38             | 0.63                                         | –                       |
| [66] | –              | –     | W-R, D-R       | S, C                   | 2 to 100                                       | –                      | 0.3 to 2.0               | 0.64                                         | –                       |
| [67] | E              | W-R   | VC, S, V       | 10⁹                      | 31.16 to 61.16                                 | 0.3 to 3              | –                      | 0.3 to 0.6                                  | –                       |
| [68] | P              | W-R   | B, S           | 10⁹ to 10¹¹                 | 1 to 32                                       | –                      | 0.72 to 1.375             | 0.63                                         | –                       |
| [69] | P              | D-R   | –              | 10⁹                      | 0.8 to 5.5                                     | –                      | 0.6                     | 0.63                                         | –                       |

a Building types are: E (educational), O (office), P (public), R (residential), H (hospital).
b D-R is dose-response and W-R is the Wells-Riley model.
c Human activities are: B (breathing), S (speaking), Si (singing), W (whispering), V (vocalizing), VC (voice counting), C (coughing).

range). The following assumptions are taken into account to develop the above equation [34]:

i. The removal rate of the infectious virus is constant
ii. The disease latent period is greater than the model time scale
iii. Particles emitted are instantaneously and uniformly distributed in the room

Thus, the dose of quanta received by a susceptible person over a time interval of T can be written as:

\[ D_q = IR \int_0^T n(t) dt \]  \hspace{1cm} (15)

where in the above equation, IR is the inhalation rate (m³·h⁻¹) (previously introduced as the pulmonary ventilation rate). Another simplifying assumption here is that the parameter IR is assumed to be constant. In reality, the parameter IR can vary with time, which can be considered in future studies. Thus, the infection probability of the dose of quanta received (Dₚ) can be treated as:

\[ P = 1 - e^{-D_q} \]  \hspace{1cm} (16)

As discussed above, a dose-response model for SARS-CoV-2 is currently unavailable. Therefore, a validated dose-response model for SARS-CoV-2 needs to be introduced as a future work plan.

Various input data used in infection risk assessment models in recent works investigating COVID-19 propagation are listed in Table 4. Based on the table, the range of viral load considered is between 10⁶ to 10¹² copies·mL⁻¹, the majority of which are around 10⁹ copies·mL⁻¹. The quanta generation rate (q) approximately ranges from 1 to 1510 quanta·h⁻¹ with an average of 349 quanta·h⁻¹. It is observable that most studies have assumed the size of particles to be smaller than 100 μm. Moreover, the deposition rate ranges from 0 to 0.6 h⁻¹, most of which are near 0.24 h⁻¹, and most studies have set the viral natural inactivation rate to 0.63 h⁻¹ (a range between 0 to 10 h⁻¹ has been identified).

3.2. Numerical modeling

This section summarizes numerical approaches used to model the airborne dispersion of COVID-19, such as zonal and CFD models. The inhalation rate varies between 0.29 and 3.3 m³·h⁻¹, ranges from 0 to 0.6 h⁻¹, and most of which are near 0.24 h⁻¹. It is observable that most studies have assumed the size of particles to be smaller than 100 μm. Moreover, the deposition rate ranges from 0 to 0.6 h⁻¹, most of which are near 0.24 h⁻¹, and most studies have set the viral natural inactivation rate to 0.63 h⁻¹ (a range between 0 to 10 h⁻¹ has been identified).
simulations. CFD simulations are the most sophisticated approaches to predicting contaminants’ propagation. The main focus of this part is to review previous studies that adopted CFD simulations and potential future work plans.

3.2.1. Zonal modeling

Single-zone modeling is the simplest form of zonal modeling. A zonal model considers that the virus concentration is homogeneous in the zone. Then, the variation of concentration of contaminants inside each zone is evaluated over time. A single-zone model can be written as [70]:

\[
\frac{dC_i}{dt} = E_i - \beta C_i
\]  

(17)

Where \( C_i \) is the particle number concentration with size range \( i \) in the air (particles m\(^{-3}\)), \( E_i \) is the particle release rate from the infector with size range \( i \) (particles h\(^{-1}\)), \( V \) is the volume of the indoor space (m\(^3\)), \( \beta \) is the removal rate of particles (1 h\(^{-1}\)), and \( t \) shows the time (h). The emissions of particles can be assumed to occur from three different human respiratory activities: 1: breathing, 2: speaking, and 3: coughing. As discussed previously, the removal of pathogens can be related to indoor air exchange rate, deposition of particles on surfaces, removal of particles due to the implementation of mitigation measures such as air purifiers, filters, and wearing masks, as well as viral natural inactivation rate. A recent work by Aganovic et al. [71] used a zonal model to divide a single zone into several horizontal/vertical subzones based on the flow regimes of three ventilation systems, including insufficiently mixing ventilation, displacement ventilation, and protected zone ventilation. The model is capable of estimating the concentration in each subzone to show the spatial impact of airflow patterns governed by the ventilation on the infection risks in a single room space.

Multi-zone modeling can predict the airflow rates between rooms, corridors, and floors as well as the concentration of contaminants in each room of the building [72]. All zones are interconnected by the airflow between them. The airflow enters a zone or removes from it through doors, windows, cracks, and shafts. It should be noted that the wind pressure of the openings can be obtained through a CFD simulation [72]. This explains the connection between the multi-zone and the CFD blocks shown in Fig. 1.

The airflow rate from zone \( j \) to zone \( i \) can be calculated as:

\[
F_{ji} = f(P_j - P_i)
\]  

(18)

where \( F_{ji} \) shows the airflow rate from zone \( j \) to zone \( i \) (kg s\(^{-1}\)), \( f \) is a function, and \( P_j - P_i \) is the pressure drop along the path from zone \( j \) to zone \( i \) (Pa). Then, the mass of air in zone \( i \) can be calculated based on the ideal gas law:

\[
m_i = \frac{P_i V_i}{RT_i}
\]  

(19)

where \( P_i, T_i, \) and \( V_i \) are respectively the pressure (Pa), the temperature (K), and the volume (m\(^3\)) of zone \( i \). \( R \) is the gas constant for the air.

The contaminant concentration in zone \( i \) can be obtained by Refs. [73,74]:

\[
\frac{dm_{vi}}{dt} = \sum_j F_{ji}(1 - \eta_{ji})C_j - \sum_j F_{ji}C_i + G_i - R_iC_i
\]  

(20)

where \( m_v_{i} \) denotes the virus mass in zone \( i \) (kg), \( \eta_{ji} \) shows the filter efficiency of the airflow from zone \( j \) to zone \( i \) (-). Moreover, \( C_i \) and \( C_j \) are, respectively, the contaminant concentration in zone \( i \) and zone \( j \) (-), \( G_i \) shows the generating rate of contaminants in zone \( i \) (kg s\(^{-1}\)), and \( R_i \) shows the removal coefficient of contaminants in zone \( i \). It should be noted that the removal of contaminants due to chemical reactions between them can be added to the above equation as a general form of the model [74].

The zonal modeling presented above has been used in recent years to study the airborne dispersion of COVID-19 in buildings [72, 75–80]. The major assumptions for this multi-zone modeling are [74,81]:

i. Well-mixed zones: Each zone (or any room) in the building is treated as a single node in which the air has a uniform (well-mixed) condition. The well-mixed assumption is applied to temperature, pressure, and contaminants’ concentration, which means their local distribution cannot be accounted for

ii. Trace contaminants: Trace contaminants are those that do not affect the density of the air. For non-trace contaminants, the contaminant concentrations affect the density of the air

iii. Airflow: The airflow is modeled using either a power law or a quadratic relationship between the airflow and the pressure difference within the flow path. These relationships are models themselves with their assumptions

There exist other types of multi-zone approaches, such as the near-field far-field zonal model, which have not been adopted to study the airborne transmission of COVID-19. It should be mentioned that few authors have tried to use zonal modeling to study the airborne dispersion of COVID-19. However, multi-zone models can be useful when the virus transmission through the connected zones needs to be monitored, such as multiple interconnected zones in hospitals and high-rise buildings [72,75]. For example, Guo et al. [75] showed that a multi-zone model could be employed in order to obtain a satisfactory controlling strategy for the ventilation system in hospitals. In future works, more studies need to be carried out using multi-zone models to ensure the layout of indoor space, indoor pressure, and ventilation system design of inter-connected floors/rooms in built environments are safe concerning the dispersion of infectious particles. Finally, it has to be mentioned that multi-zone models are a fast approach to estimating the trend of aerosol concentration in...
the zones. However, due to the assumptions of the method, they cannot provide detailed distributions, and the accuracy is limited compared to CFD models.

3.2.2. Computational fluid dynamics (CFD)

CFD is another primary analysis approach to airborne transmissions. In order to capture the movement of particles inside the air, two different approaches can be followed: species transport modeling and the multi-phase approach. Many details, such as the non-uniformity distribution of particles, different exposure times for each person, different room/space geometries, and ventilation conditions, can be simulated using CFD tools.

3.2.2.1. Size of particles and their characteristics. Particles released when talking, breathing, or singing is mostly smaller than 10 μm in diameter [82]. However, a broader range of size of particles, 1 μm–2000 μm, can be released when people cough or sneeze (the majority of them are smaller than 100 μm) [83]. Findings show that the peak aerosol diameter for SARS-CoV-2 is around 0.25 μm–5 μm [84]. Larger particles deposit in a small area around their source due to the dominance of the gravitational force [85]. The water content of small particles (<10 μm) evaporates rapidly after their release (shorter than 1 s), while the water content of droplets larger than 100 μm evaporates after 1 min [86,87]. It should be noted that, although heavy particles deposit near their source, some recent studies have shown that they can possibly travel long distances depending on environmental conditions such as air velocity [88, 89]. Moreover, it has been argued that aerosol particles contain more viruses than droplet particles; however, those droplets carry more liquids emitted from the respiratory tract [90].

Most studies have considered respiratory particles smaller than 10 μm to study the airborne transmission of COVID-19 [60,91–96]. A major reason for this range is that the peak diameter of aerosols carrying SARS-CoV-2 is below 10 μm, as mentioned above. Although a massive range of particles’ size (1 μm–2000 μm) can be released, smaller particles have a significant share than heavy ones since there is a distribution of numbers of particles for different size bins. The Rosin–Rammler distribution can be used to determine the fraction share of particles against their diameters, as follows [97]:

\[ Y_d = e^{-\left(\frac{d}{\bar{d}}\right)^n} \]  

(21)

where \( Y_d \) is the fraction of particles in diameter \( d \), \( n \) is the shape or spread parameter, and \( \bar{d} \) corresponds to a particle diameter that yields \( Y_d \) equal to \( e^{-1} \).

Fig. 5 summarizes the critical attributes of particles based on their size. As it is observable, the size of particles released is a major characteristic and determines their behavior.

3.2.2.2. Species transport modeling. The movement of virus-carrying particles within the airflow is a multi-phase phenomenon. However, the virus-laden particles can be simplified as a massless tracer gas so that it can be simulated in a single-phase structure. The particles smaller than 5 μm can be assumed to be massless gaseous particles, and the effect of gravity can be ignored [77,98–101]. This technique is prevalent in studying the airborne transmission of particles via aerosols or droplet nuclei. Ai et al. [102] reviewed the popularity of simplifying the particles as a tracer gas for the investigation of viral airborne transmissions. To consider the deposition of particles, drift-flux model [103] is developed for the simulations using the species transport model.

The following assumptions are considered for species transport modeling of the viral airflow [101]:

i. The gravity force is generally ignored in the simple species transport method but can be simulated using an improved version of the model, the drift-flux model.
ii. Particles can be assumed to have a spherical shape
iii. The concentration of large particles and droplets cannot be simulated
iv. Virus-laden particles are treated as massless gaseous particles
v. Particles re-suspending from surfaces and their coagulation are not modeled
vi. The effect of particles on the airflow is ignored
vii. The deposition of particles on surfaces is often ignored, specifically when the ventilation rate is sufficient [104]. Meanwhile, the settlement of particles can be modeled using the improved tracer gas method (drift-flux method)

The Reynolds-averaged Navier Stokes (RANS) equations have been widely adopted to solve mass, momentum, and energy-coupled equations of the airflow indoors [105]. RANS models are reliable and widely used to simulate a single-phase fluid flow (their mathematical description can be found in the following reference [106]). Additional species transport equation is solved to obtain the concentration of contaminants [98]:

$$\frac{\partial (\rho C)}{\partial t} + \frac{\partial \left( \rho u_i C \right)}{\partial x_i} = \Gamma + S_c$$ (22)

In Eq. (22), t shows time (s), C is the particle concentration reported in the number of particles per cubic meter (#·m⁻³), ρ is the airflow density (kg·m⁻³), i is a counter for three-dimensional directions, x represents the spatial dimension (m), uᵢ is the average velocity of airflow in the i direction (m·s⁻¹). Moreover, Γ shows the effective particle diffusivity (Pa·s), and Sᵦ is a source term. Γ can be written as:

$$\Gamma = \rho (D + v_p) = \rho (D + v_t)$$ (23)

where D is the Brownian diffusivity of a particle (m²·s⁻¹), vₚ denotes the particle turbulent diffusion coefficient (m²·s⁻¹), which is considered equal to the air turbulence viscosity, v₁ (m²·s⁻¹).

The drift flux model is normally used to simulate the relative motion between the two phases, and it has been adapted to predict the distribution of particles indoors [107] as described in the following equation [108]:

$$\frac{\partial (\rho C)}{\partial t} + \nabla \cdot \left( \rho \left( u_i + u_{i}^s \right) C \right) = \nabla \cdot \left( (D + v_t) \nabla C \right) + S_c$$ (24)

where $u_{i}^s$ is the settling velocity of particles (m·s⁻¹). The Drift-flux model is to correct the species transport equation by adding the drift flux term, $\nabla \cdot \left( \rho \overline{V} C \right)$. This particle drift flux comes from the velocity difference of particles and air caused by the drag force and gravity. The drift-flux method has been recently used to predict the transmission of COVID-19 [109,110]. Few researchers have adopted the drift-flux method for the airborne transmission of COVID-19 and more research needs to be carried out.

3.2.2.3. Multi-phase modeling. The general approach in multi-phase modeling is to use the Eulerian-Lagrangian model to simulate the airflow (called the continuous phase) as well as the movement of every particle injected (called the discrete phase). In the Eulerian model, mass, momentum, as well as energy conservations are solved simultaneously. A steady form of the RANS model is commonly used to model the airflow indoors in this concept [111–113]; however, few authors have used the unsteady form of the RANS model [114,115].

General assumptions for the discrete phase modeling (trajectory of particles in the Lagrangian framework) in the scope of COVID-19 airborne propagation are [101,116,117]:

i. Particles are spherical in shape, and their density is equal to that of water [118,119].
ii. Resuspending of particles from surfaces or their coagulation is ignorable.
iii. A one-way coupling is accurate enough to couple the continuous and the discrete phases. This means that discrete phase patterns can be predicted based on a fixed continuous phase flow field. This is because it can be assumed that particles in the second phase have a negligible impact on the gas phase since the second phase volume fraction is pretty low (lower than 10⁻⁶) [120].

For modeling the movement of particles in the Lagrangian framework (discrete phase modeling or DPM), an unsteady simulation is performed to monitor the motion of particles. A balance of forces on particles to obtain their velocity is [106]:

$$\frac{du_p}{dt} = F_D (u_p - u_a) + \frac{g(\rho_p - \rho_g)}{\rho_p} + F$$ (25)

where u and ρ show the velocity (m·s⁻¹) and the density (kg·m⁻³), and the subscripts p and g represent the particle and the continuous phase (here is gas), respectively. Moreover, g is the gravity acceleration (m·s⁻²), F is the additional acceleration term per unit particle mass (N·kg⁻¹), $F_D (u_p - u_g)$ is the drag force per unit particle mass (N·kg⁻¹), and the term $g(\rho_p - \rho_g)/\rho_p$ is for both the gravity and buoyancy forces per unit particle mass (N·kg⁻¹). $F_D$ is calculated by Ref. [106]:

$$F_D = \frac{18 \mu C_p Re}{\rho_a d_p^2} \frac{\rho_p}{24}$$ (26)
where $\mu$, $d_p$, and $C_D$ show the molecular viscosity of the continuous phase fluid (Pa·s), particle diameter (m), and drag coefficient (−), which is calculated based on the relative Reynolds number. In some studies, the effect of the buoyancy force has not been incorporated, and the drag force effect has just been taken into account [117]. Thus, for this scenario, the term $f = (\rho_p - \rho_f) / \rho_f$ is simply reduced to $g$.

The term $F_{ij}$ on the right-hand side of Eq. (25) can incorporate other forces, such as the “virtual mass” force and the “pressure gradient force”, which can be when the density of the fluid is much lower than the density of particles ($\rho_f / \rho_p < 1$) [106]. Another two forces are the “moving reference frames” and the “thermophoresis” forces. In addition, the effects of Brownian motion can impose a force on submicron particles, which can be significant when the particle size is smaller than 1 μm and become less important when the size increases [14,111]. The “Saffman’s lift force”, a force that arises due to shear, can be included in the right-hand side of Eq. (25). A generalized form of the Saffman’s lift force can be written as [121]:

$$F_{ij} = \frac{2Ku^{0.5}d_j}{\rho_p d_i(d_i d_j)^{0.75}} (u_i - u_p)$$

(27)

In the above equation, $K = 2.594$, and $d_j$ is the deformation tensor. This force is recommended only for submicron particles [106]. The dispersion of particles due to turbulence of the fluid in the continuous phase can be taken into account using the discrete random walks (DRW) model. For more details, please see Ref. [106].

Finally, the trajectory of particles can be obtained when their velocity (Eq. (25)) is solved.

In order to mimic an actual injection path of particles, some studies have supposed that particles follow an expanding cone-like shape staring from the mouth. The mouth can be regarded as a circle [116] or rectangular [122,123]. Larger droplets can become smaller through evaporation (smaller particles are called droplet nuclei that can travel farther distances) [14]. A detailed mathematical description related to the evaporation of the water content of particles can be found in reference [106]. It should be noted that numerical studies focusing on the dispersion of heavy particles (droplets) have modeled the evaporation forces. In addition, the effects of Brownian motion can impose a force on submicron particles (0.1 μm as an average) is simulated, all of these particles do not evaporate. This means that if the evaporation for virus-size particles (0.1 μm) is assumed, all of these particles move along with their properties [88,89,112,124,125]. However, based on our review and observations, in most previous works, the characteristics of small particles ejected have been assumed to be similar to that of water. However, viruses are made of protein and do not evaporate.

### Table 5

| Ref. | Activity       | Number of particles | Particle size (μm) | Forces in the DPM and turbulent dispersion effects | Injection speed (m s⁻¹) | Mouth diameter (m) | Cone angle |
|------|----------------|---------------------|-------------------|-------------------------------------------------|------------------------|-------------------|------------|
| [10] | Talking        | –                   | 1.5               | ✓ ✓ ✓                                           | –                      | 0.04              | –          |
| [97] | Coughing       | –                   | 1 to 2000 (mean: 32.6) | ✓ ✓ ✓                                           | 5 to 15                | –                 | 20°        |
|      | Sneeze         | –                   | 1 to 2000 (mean: 17.5) | –                                                | 15 to 25               | –                 | –          |
| [113]| Sneezing       | –                   | 8.3               | ✓ ✓ ✓                                           | 50                     | 0.03              | 15°        |
| [114]| Coughing       | 3000                | 3 to 750          | – – – –                                         | 50                     | 0.03              | 15°        |
| [115]| Breathing      | 1000                | 10                | ✓ ✓ ✓                                           | –                      | 0.50              | –          |
| [116]| Talking        | 30 per second       | 1 to 10           | ✓ ✓ ✓                                           | 3                      | 0.03              | 30°        |
|      | Coughing       | 3000                | 1 to 50           | 0.69 and 0.76                                   | –                      | 0.53              | –          |
| [118]| Coughing       | 10800               | 0.15 to 150       | ✓ ✓ ✓                                           | 10                     | 0.02              | –          |
| [122]| Coughing       | 1000                | 5 to 300          | ✓ ✓ ✓ ✓                                         | 8.5                    | –                 | –          |
| [128]| Sneeze         | 95000               | 40 to 980         | ✓ ✓ ✓                                               | 6.3 to 14.3             | 0.014 to 0.03     | 3° to 43° |
| [129]| Talking        | –                   | 1 to 10           | ✓ ✓ ✓                                           | 2.5                    | –                 | 30°        |
| [130]| Coughing       | 1751                | 3 to 175          | ✓ ✓ ✓                                           | 11.7                   | –                 | 23°        |
| [131]| Talking        | 4000 per second     | 1 to 50           | – – – –                                         | 2.3                    | –                 | –          |
|      | Coughing       | 40000               | 1 to 50           | – – – –                                         | 11.2                   | –                 | –          |
| [132]| Coughing       | 3000                | 0.31              | – – – –                                         | 10                     | –                 | –          |
| [133]| Coughing       | 40000               | 0.5 to 12         | – – – –                                         | 100                    | –                 | 20°        |
|      | Sneeze         | 40000               | 5 to 300          | – – – –                                         | 8.5                    | –                 | 20°        |
|      | Coughing       | 1000                | 5 to 300          | – – – –                                         | 8.5                    | –                 | 20°        |
|      | Sneeze         | 1000                | 5 to 300          | – – – –                                         | 8.5                    | –                 | 20°        |

* The abbreviations are: D (drag), G (gravity), Bu (buoyancy), VM (virtual mass), PG (pressure gradient), BM (Brownian motion), SL (Saffman’s lift), and TDE (turbulent dispersion effects).
Table 6
Building, simulation, and mitigation information of COVID-19 airborne transmission simulations by multi-phase approach.

| Ref. | BTa | Dimension (m³) | Occupant (people⋅m⁻²) | VRb (ACH) | Simulation model (gas side) | Validation source | Recommendations regarding the COVID-19 transmissionc |
|------|-----|----------------|------------------------|-----------|----------------------------|------------------|--------------------------------------------------|
| [10] | P   | 8.3 × 17.5 × 3.1 | 0.62                   | 1.1 to 9  | LESd                        | [135,136]        | ✓                                                |
| [97] | –   | 8.0 × 4.7 × 3.0  | 0.02                   | 4         | SSR with k-ε RNG            | [137]            | ✓ ✓                                              |
| [113]| H   | 7.5 × 4.0 × 2.7  | 0.10                   | 2         | SSR with realizable k-ε     | –                | ✓                                                |
| [114]| H   | –              | 0.18                   | –         | URANS with k-ε RNG          | –                | ✓ ✓                                              |
| [115]| H   | 6.1 × 5.8 × 2.9 | 0.20                   | 31.6      | URANS with RNG k-ε          | [138]            | ✓                                                |
| [116]| E   | 7.0 × 5.0 × 3.0  | 0.60                   | 5.5       | SSR with k-ε                | [139]            | ✓                                                |
| [117]| E   | 8.0 × 2.5 × 4.0  | –                      | –         | RANS with standard k-ε      | [117]            | ✓                                                |
| [118]| E   | 6.0 × 8.0 × 5.0  | 0.96                   | –         | SSR with k-ε RNG            | [140,141]        | ✓                                                |
| [122]| –   | 1.5 × 1.5 × 20   | 1.30                   | –         | RANS with RSMf              | [142,143]        | ✓                                                |
| [128]| –   | 4.0 × 3.0 × 3.0  | 0.16                   | –         | LES                         | –                | ✓                                                |
| [129]| –   | 2.0 × 2.5 × 1.9  | 0.84                   | 47        | SSR with k-ε                | [140]            | ✓                                                |
| [130]| H   | 6 × 3 × 2.6      | 0.11                   | 12.3      | SSR with RNG k-ε            | [144,145]        | ✓                                                |
| [131]| H   | 6.5 × 3.0 × 2.8  | 0.10                   | –         | RANS with RNG k-ε           | [131]            | ✓                                                |
| [132]| H   | 9.1 × 5.5 × 4.3  | 0.12                   | –         | RANS with realizable k-ε    | –                | ✓ ✓                                               |
| [133]| –   | –              | –                      | –         | RANS with k-ω               | –                | ✓                                                |
| [134]| E   | 3.6 × 4.5 × 2.7  | 0.12                   | –         | RANS with k-ε               | –                | ✓                                                |

a Building type (BT): E (educational), P (public), H (hospital).
b Ventilation rate.
c Recommendations are (in order): CTP (controlling thermal plumes), OW (opening windows), IVR (increasing the ventilation rate), LEV (using local exhaust ventilation), BITE (using a bottom inlet and top exhaust air vents), or TIBE (using a top inlet and bottom exhaust air vents), AP (using air purifier), ISP (using individual seat partition), WM (wearing masks), and SD (social distancing).
d Steady-state Reynolds Averaged Navier Stokes (RANS) equations.
e Unsteady state RANS (URANS) equations.
f Reynolds stress model.
will be evaporated rapidly, and the airborne transmission via those particles cannot be studied. This is why most studies have not considered the evaporation of small particles in their simulation. Therefore, more studies need to be carried out to simulate the dispersion of small particles based on a realistic assumption of the properties of viruses.

To summarize the details in previous works regarding the COVID-19 transmission multi-phase modeling, Table 5 and Table 6 report comprehensive information. As it can be inferred from Table 5, the size range of particles considered in multi-phase modeling of talking, coughing, and sneezing activities are respectively 1.5–50 μm (mostly below 10 μm), 0.15–2000 μm (with average values between 32 μm and 80 μm), and 0.5–2000 μm (with average values smaller than for coughing). The total number of particles released is different among the previous works, and there is no conclusive range assumed. The range of the injection speed of particles for talking, coughing, and sneezing are respectively 2.3–3 m•s^{-1}, 5–22 m•s^{-1}, and 6.3–100 m•s^{-1}. Some authors did not model the injection of particles as an expanding cone-like shape; however, others have considered a wide range of angles from 3° to 43°. Moreover, some authors have treated the mouth as a circle with a diameter ranging from 0.014 m to 0.040 m, and some have treated it as rectangular. In the DPM modeling settings, the majority of studies have incorporated the effects of drag, gravity, and buoyancy forces, as well as turbulent dispersion effects. In addition, some studies have taken into account the effect of Saffman’s lift force, and a minority of studies have considered other forces (virtual mass, pressure gradient, and Brownian motion). Based on Table 6, it can be observed that different ranges of occupancy density and the air change per hour have been assumed, which is impossible for us to draw a conclusion. The majority of studies have adopted steady-state RANS with different kinds of k-ε or k-ω models to simulate the air phase, while the minority have used more complicated approaches such as unsteady or large eddy simulations (LES).

Bi et al. [126] simulated the human cough jet development in the indoor environment using LES. They argued that the LES simulations are able to monitor the temporal behavior of a human cough jet very accurately when compared to unsteady URANS methods based on experimental data. Moreover, Fabregat et al. [127] adopted more advanced methods, such as direct numerical simulation (DNS), to predict the distribution of particles for the cough activity, reporting improved predictions. Although LES and DNS methods are able to obtain more accurate results, few authors have yet to use them since a high computational cost is an inevitable part of these simulations. This means that most authors have preferred to use simpler approaches such as RANS and URANS models. Moreover, it has been shown that URANS models can obtain more accurate outcomes than steady RANS models, especially when the domain of study and conditions in the simulation are complex [115]. As mentioned above, different types of k-ε or k-ω models have been used as acceptable methods, and a general conclusion cannot be made for these models as both have satisfied the accuracy of the results based on the validations done.

Based on the information shown in Table 6 and our understanding, more studies need to be conducted to investigate the effect of a combination of transmission mitigation strategies in CFD simulations. In other words, at the moment, each research has concentrated on a few mitigation measures and did not focus on their combined effects. Therefore, it is hard to draw a clear conclusion about what type of mitigation can contribute more to reducing the airborne distribution of COVID-19, which in turn unable us to make a clear guideline regarding the future mitigation plans for diseases like COVID-19 that can disperse via the airborne route. Thus, there is a call to conduct in-depth studies on the combined effects of various mitigations and compare them with the effect of every single mitigation.

### Table 7

| Ref. | Research focus | Particles’ surrogate | Available data as a validation source |
|------|----------------|----------------------|---------------------------------------|
| [91] | Poorly ventilated areas | TG(C2H4) | LC of C2H4 |
| [93] | Using air purifiers | AG (using DHSA) | LC of aerosols |
| [110] | Using a laminar airflow system | Candle smoke | Particles number temporal evolution |
| [131] | Propagation of aerosols and regional concentration | AG (solute is DS’ and solvent is IS’) | LC of aerosols |
| [146] | Using a laminar airflow system | TG(N2O) | The vertical air velocity profile |
| [147] | Using DOAS® and ceiling fan | TG(SF6) | LC of SF6 |
| [148] | Using a displacement ventilation | TG(CO2) | The vertical air velocity profile |
| [149] | Effect of ventilation on airborne transmission | TG(CO2) | LC of CO2 |
| [150] | Evaluating the effectiveness of a modified W-R® model | TG(SF6) | LC of SF6 |
| [151] | Using air purifiers | AG (using DHSA) | Local and temporal concentration of aerosols |
| [152] | Effect of negative pressure on the airborne exposure level | TG(N2O) | LC of N2O from the patient nose |
| [153] | Effect of wearing masks and ventilation on airborne transmission | AG (atomizing olive oil) | Local and temporal concentration of aerosols |

- a = Tracer gas.
- b = Local concentration.
- c = Aerosol generator.
- d = Di-ethyl hexyl sebacate-atomizer.
- e = Diisooctyl sebacate.
- f = Isopropanol.
- g = Dedicated outdoor air system.
3.2.3. Measurements on COVID-19 airborne transmissions as validation source

Some studies have sought to investigate the airborne transmission of COVID-19 by means of measurements. These measurements can be used as a validation source (or evidence data) to evaluate the accuracy of numerical results in future works. Table 7 summarizes several experimental works along with their major information studying the airborne transmission of COVID-19 in indoor environments. In the majority of them, the temporal and or local concentrations of particles released are available as measurement data. These measurements are instrumental in evaluating the accuracy of numerical results. More experimental works need to be done to evaluate the effect of different HVAC systems on the concentration of aerosols indoors as well as their dispersion while the energy consumption of the ventilation system is monitored. Moreover, most researchers have sought to study the effect of mitigation measures using numerical methods. Therefore, it can be said that further and more comprehensive experimental works should be conducted to evaluate the effect of various mitigation measures.

3.2.4. Infection risk assessment using numerical results as inputs

Data obtained using numerical approaches (both zone and CFD approaches) can be used as inputs to infection risk assessment models. This means that in addition to numerical results, several post-processing calculations are required to assess the virus infection risk using risk assessment models.

When the numerical results are obtained, the domain is divided into discrete zones (or cells) with a history of numerically obtained results; therefore, the local particle concentration can be treated as [154]:

\[ C_j = \frac{\sum_{i=1}^{n} m_i \cdot d(i,j)}{V_j} \]

where \( C_j \) represents the local concentration of particles in zone number \( j \) (kg m\(^{-3}\)), and \( V_j \) is the zone volume (m\(^3\)). \( m_i \) is the mass flow rate of a particle trajectory obtained from the numerical simulation (kg s\(^{-1}\)), and \( d(i,j) \) shows the residence time of particle \( i \) in the cell marked as \( j \) (s). Eventually, the infection risk models are able to quantify the infection probability [155]. Similar approaches can be found in the literature [156–158].

3.2.5. Future works for numerical modeling of COVID-19 airborne transmission

Further studies are required to model the evaporation of small particles based on their real-world characteristics, not just considering their properties similar to that of water. Moreover, most studies have adopted a steady-state simulation for the continuous phase in the Eulerian framework. More research is still necessary to perform unsteady simulations for both the Eulerian and the Lagrangian frameworks since it has been shown that unsteady models are efficient and robust [125,159] and can obtain more accurate outcomes than steady ones, especially when the domain of study and conditions in the simulation are complex [115]. In many previous works, the movement of people has not been modeled in an indoor space. More investigations are required to model the effect of individuals’ movements. It is a fact that studying the movement of people requires re-generating the computational domain as well as re-conducting the simulation. This is why most authors have considered a fixed position for equipment and people. Guo et al. [160] are the pioneer in finding a way to assess and predict the infection risk indoors while people are not fixed in a position, without re-conducting CFD simulations for new positions of people. However, further studies should be done on this concept to predict the infection risk based on a flexible position of individuals while the computational cost is not increasing significantly.

Last but not least, it is a fact that numerical simulations can provide helpful information for engineering applications. However, the optimization process can be time-consuming. As a solution, coupling CFD simulations and machine learning is a feasible solution in the context of disease transmission when it comes to optimization.

4. Mitigation measures for COVID-19 airborne transmission in buildings

Various measures have been proposed in previous works to combat the airborne transmission of COVID-19 in buildings. The key mitigation measures are (1) occupancy control, (2) ventilation air adjustments, (3) using filters and air purifiers, (4) Ultraviolet air disinfection, and (5) social distancing and wearing masks.

4.1. Occupancy

The seating arrangement of infected and susceptible individuals in a room affects disease propagation. People sitting next to infectors have a higher exposure risk than others [161,162]. The number of virus-carrying particles removed from the indoor space increases when the infected individuals sit near the exhaust vents [129]. If the infected individual is near the supply stage, the supply air disperses pathogens and increases the risk of disease propagation [163]. Indoor objects or equipment arrangements can also affect the airflow field as well as the virus propagation. Virus-laden particles in such areas are prone to be accumulated, remain suspended, or be deposited more significantly [117,129]. In other words, the ventilation system can remove more particles from the space provided that people and indoor equipment are appropriately arranged [129]. In-depth studies need to be conducted to offer the best indoor layout and equipment based on building types and ventilation systems used. Currently, there is a lack of information, and general conclusions and guidelines cannot be made.

Furthermore, the density of occupants needs to be decreased to control disease propagation [164]. It should be noted that reducing occupancy is the fastest control measure among other measures that are costly or time-consuming to implement. Studies show that a 50% reduction of occupant density can result in an 18.8%–40.6% reduction in the infection probability, depending on the space type [37].
4.2. Ventilation

In general, a low ventilation rate increases the probability of occupants being infected [80,91,165] and vice versa [59]. A wide range of the ventilation rate has been assumed in previous studies from 0 to 37 ACH to investigate its impact on the COVID-19 infection risk [58,70,93,139,166].

Furthermore, as a potential limitation, increasing the ventilation rate increases the energy use of the HVAC system as a result [59]. This energy use growth significantly relates to the local outdoor weather condition [167]. The challenging is to balance the propagation risk reduction and the cost spent during the system operation. For example, a ventilation system that introduces sufficient fresh air can significantly reduce disease propagation [151,158], which will dramatically raise energy consumption. Kurntiski et al. [168] proposed a method to design the ventilation system through an estimation of the required fresh air ventilation rate to limit the infection risk according to the Wells-Riley model. This type of method should be considered for future building standards and codes to avoid unnecessary oversizing of ventilation systems.

Another challenge here is that although increasing ventilation can mitigate the infection risk, this can increase the risk of exposure in other connected rooms [169]. It can be inferred that just increasing the ventilation rate blindly, without taking care of the potential dispersion of aerosols into other rooms, increases the energy consumption of the HVAC system and can also increase the infection probability in those connected spaces.

Ventilation can be supplied via mechanical or natural means. An example schematic view of natural and mechanical ventilation is shown in Fig. 6 (inspired by Refs. [170,171]). Ventilation modes can be named mixed or displacement ventilation in mechanical systems. In mixed mode ventilation, inlet vents are mounted on the ceiling/near the ceiling, and the exhaust is near the floor, while in displacement ventilation, inlet vents are near the floor, and outlets are close to the ceiling.

One of the benefits of natural ventilation is that it reduces energy use and cost; however, this mode of ventilation is much less effective in controlling virus propagation than mechanical ventilation systems [30,58]. This means that natural ventilation is an alternative to reduce virus transmission in spaces where mechanical systems have not been installed previously nor costly-effective to work [40]. Natural ventilation will be increased by opening the room window(s) and door(s).

There exists a debate on whether mixed mode or displacement mode works better during the pandemic. Some concluded that displacement ventilation effectively mitigates the risk of exposure to the virus better than mixed mode [77,172]. However, a contradictory conclusion has been made by other authors [173,174]. Based on our understanding, displacement ventilation needs to be appropriately designed to effectively reduce the infection risk by maintaining a sufficient air exchange rate; otherwise, it cannot work effectively [172]. To support this, a relatively higher ventilation rate (3 ACH or more) should be maintained when displacement mode is implemented to ensure sufficient contaminated air movement is achieved [173].

Another ventilation mode studied is the personal ventilation approach, in which ventilation is provided for each individual. This type of ventilation is suitable for risky places and can be more efficient than displacement ventilation in reducing the infection probability [33]. Other ventilation strategies exist out there which have not been studied regarding COVID-19 propagation.

Furthermore, a combination of ventilation modes can be used to combat the virus propagation more effectively by having the benefits of each mode. For example, using a combination of mixed and displacement ventilation can result in lower contaminants’ concentration by 15%–47% than supplying the air from a ceiling or upper side of the wall [175]. This indicates that the same level of mitigation can be achieved with lower ventilation rates when mixed and displacement modes are combined.

We can see a lack of knowledge regarding various ventilation modes available to mitigate the infection risk. More studies are required to provide a clear understanding of the capabilities of various ventilation modes in reducing the infection risk while maintaining the energy consumption of HVAC systems as one of the targets. Moreover, it should be noted that in harsh weather conditions,
Table 8 COVID-19 airborne transmission mitigations based on different building types.

| Measure | Educational | Office | Public | Residential | Hospital |
|---------|-------------|--------|--------|-------------|----------|
| Occupancy | 2 times reduction in new cases for reducing the occupancy to 20% [197] Hybrid learning is recommended (partially online) [67] | Reducing the occupancy by the \( r \) factor reduces the new cases by the \( r^2 \) factor [164] 9.6% reduction in IR for 50% reduction in occupancy [37] | Avoiding overcrowding [91, 198] |  |  |
| Using MV\[^b\] | Greatly reduces the IR [32, 58] 2.5 times more efficient than NV\[^c\] [199] | Greatly reduces the IR and the reproduction number\[^d\] [30, 69] | An efficient strategy in such areas [79, 203] 3 ACH is recommended for DV [173] |  |  |
| Increasing the VR\[^e\] | Reduces the disease dispersion [201] To 5 ACH (54% reduction in IR) [4] To 5 ACH is more efficient than higher ACHs [94] 4 to 7 ACH is recommended [202] | 8 ACH is recommended [163] | 37% reduction in IR for doubling the VR [59] | 77% reduction in particles for doubling the flowrate [114] | 5 CH is less expensive than higher ACHs [94] 8 ACH is recommended [189] 3 times reduction in the IR for 9 ACH [204] |
| Increasing the FA\[^f\] | Increases the NV and decreases the IR [206, 207] Useful when there is no MV [31] 38% increase in the removal of particles [111] | Increasing the OWR\[^g\] increases the NV and reduces the IR [208] Efficient in such areas [209] | 100% FA reduces the IR very sharply [158] Greatly increases energy use [205] | 50% reduction in the IR for a 100% FA [99] 56% reduction in the IR [161] | 50% reduction in the IR for a 100% FA supplied [205] 56% reduction in the IR |  |
| Windows opening | Increases the NV and decreases the IR [206, 207] Useful when there is no MV [31] 38% increase in the removal of particles [111] | 10 times reduction in IR using HEPA filters [199] MERV 13 is more efficient than higher MERVs in terms of energy use [67] | 8 to 9 times reduction in IR using HEPA filters [199] Using MERV 13 filters equals 100% FA supplied [205] | MERV 12 or higher is recommended [112] 40% reduction in the IR [161] | Duct filtering is an efficient strategy [63] MERV 14 is recommended [179] |
| Filters | 10 times reduction in IR using HEPA filters [199] MERV 13 is more efficient than higher MERVs in terms of energy use [67] | 8 to 9 times reduction in IR using HEPA filters [199] Using MERV 13 filters equals 100% FA supplied [205] | MERV 12 or higher is recommended [112] 40% reduction in the IR [161] | 50% reduction in the IR for a 100% FA [99] 56% reduction in the IR [161] | Duct filtering is an efficient strategy [63] MERV 14 is recommended [179] |
| Air purifiers | Good options for poorly ventilated areas [210] The best is to be near infectors [183] 97% reduction in particles for its ideal location [134] 70%-90% reduction in IR [93] 61% reduction in particles [183] | 8 ACH is recommended [163] | MERV 12 or higher is recommended [112] 40% reduction in the IR [161] | 50% reduction in the IR for a 100% FA [99] 56% reduction in the IR [161] | Duct filtering is an efficient strategy [63] MERV 14 is recommended [179] |
| UV lights | Energy-efficient compared to increasing the FA [158] Useful in poorly ventilated areas [209] | 93.7% reduction in the IR [161] An efficient strategy for households [216] | An efficient strategy in such areas [63, 179, 211] | Greatly reduces the IR [166, 212] Maximizing the flow rate of the air purifier [213] |  |
| Masks | 3.6 times reduction in new cases [197] Using masks with 95% efficiency is recommended [202] Surgical masks are recommended [214] High-quality masks are the best measure among others [190] 6.5% reduction in particles in the outlet vents [163] | Surgical masks are recommended [214] High-quality masks are the best measure among others [190] 6.5% reduction in particles in the outlet vents [163] | 93.7% reduction in the IR [161] Maintaining the IR at low values [56] Wearing surgical masks [69, 214] All people should wear masks [215] | An efficient strategy for households [216] | Greatly recommended [115, 217, 218] 63% reduction in the IR [44] N95 masks are recommended [219] |
| SD\[^h\] | 2 m SD is insufficient [112] SD is insufficient protection without a mask [220] | 2 m SD is insufficient [173, 221] | 2 m SD is insufficient [173, 221] | The recommended SD is not sufficient [218] |  |
| Others | Using individual partitions [118] Using microphones and voice amplifiers for teachers (20% reduction in IR) [31, 222] A cubicle-style layout is recommended [223] | A cubicle-style layout is recommended [223] | Maintaining the water seal in the drainage system [224-226] Positive pressure in the bathroom [235] Avoiding family gatherings [203] | LEV\[^i\] is recommended [114]; Negative pressure in patient rooms [115, 227] Ideal patients’ bed orientation [228] Face shield recommended [44]; 75% reduction in |  |

(continued on next page)
the energy cost of ventilation can be high due to a significant temperature difference between indoors and outdoors. Thus, an optimized ventilation mode and rate should be selected to balance the disease propagation reduction and the energy cost growth.

4.3. Filters and air purifiers

One of the effective methods to reduce the dispersion of viruses indoors is to use filters in ventilation systems [112, 176]. ASHRAE guidelines recommend using filters with minimum efficiency reporting values (MERV) of 13 or higher to prevent COVID-19 dispersion. Filters with MERV 13 can capture up to 85% of particles with a size range of 1 μm–3 μm [179]. It should be noted that filters with MERV 8 have commonly been used before the current outbreak [178]. Another recommended filter type is HEPA-rated filters (high-efficiency particulate air) which can capture up to 99.90% of particles between 0.3 μm and 1 μm [179].

It should be noted that blindly implementing filters with higher MERV in HVAC vents does not necessarily result in an efficient reduction of the infection risk. The general trend is that by increasing the filtration efficiency in HVAC systems, the risk of disease transmission will be reduced [33, 169]. However, it has been argued that using filters with MERV 13 is more efficient than other filters with higher MERVs in terms of mitigation level reduction [180]. Using air filters in HVAC vents adversely increases fan energy consumption to compensate for the pressure drop in ducts [77, 181]. Thus, the challenge here is that it is required to consider both disease transmission mitigation and energy usage when upgrading filters. More studies should investigate the best compromise between energy cost and infection risk reduction.

Using indoor air purifiers is suitable when upgrading the HVAC equipment or ventilation air adjustments are either costly or infeasible. It is relatively inexpensive compared to upgrading the HVAC equipment, and multiple air purifiers can be utilized in one space. Air purifiers can significantly reduce the concentration of particles in the room [93, 182]. A wide range of infection risk reduction has been reported in different indoor areas using air purifiers from below 10% up to nearly 90%, with an average value of 30% [33]. It should be noted that the ideal position of air purifiers in the room significantly affects their performance [183]. Moreover, air purifiers must be used with caution since a high velocity of the air leaving air purifiers can adversely disperse contaminated particles [184]. Thus, the best position and location of air purifiers need to be examined before being used. Another important note is that air purifiers do not supply fresh air into the space; therefore, they should be used as an auxiliary means of mitigation strategies. Based on our findings, there is no comprehensive work to investigate the performance of air purifiers under different ventilation modes. Thus, further studies need to be conducted to offer guidelines regarding the best positions of air purifiers concerning the main ventilation system.

4.4. Ultraviolet air disinfection

Using ultraviolet (UV) instruments is an effective way of destroying viral, bacterial, and fungal organisms [185]. UV devices are energy-efficient and can be used in different environments, such as liquids and air [186]. The operational cost of using UV air disinfection is much lower than adjusting the ventilation system [187]. The Centers for Disease Control and Prevention (CDC) recommends using UVGI (Upper-Room Ultraviolet Germicidal Irradiation) in spaces that do not have mechanical ventilation, sufficient natural ventilation cannot be established, or they suffer inadequate ventilation [188]. Surprisingly, these devices are still effective even when the ventilation air is adequate [189]. These devices can reduce the infection probability of COVID-19 by around 60% [33, 41].

However, the use of UV air disinfection machines can be prone to generate secondary air pollutants (e.g., ozone). It should be noted that the by-products (secondary organic aerosols) may be more harmful than the ozone itself [190]. Moreover, it could be harmful to occupants when they are directly exposed to UV lights. Therefore, the operation and installation of UV instruments should be careful with the presence of the occupants in the room [191]. Thus, the design of UV air disinfection machines to reduce these harmful effects is needed for further studies.

4.5. Masks and social distancing

Masks are efficient measures to prevent COVID-19 airborne propagation [44] as they reduce both the number of infectious particles emitted and the number of contaminated particles a person can inhale. So, it is highly recommended that both infected and susceptible individuals wear a mask [56]. Masks first slow down the emission speed of particles from infectors [192] and second reduce the
cumulative dose inhaled by susceptible people [193], effectively mitigating the airborne dispersion of particles. There is a correlation between mask efficiency and the concentration of particles emitted [132]. This means that when the efficiency of masks reduces, the concentration of particles emitted increases. However, it should be noted that homemade masks are still effective, although their performance is not as high as surgical and N95 masks [194]. Moreover, N95 masks are found to be the best among others [41]. Based on the filter efficiency of masks, they can mitigate COVID-19 airborne transmission between 60% to more than 90%, as indicated in different studies [33,194,195].

Furthermore, social distancing is an important measure that prevents contaminants from reaching other people and reduces their exposure time. In general, a distance between 1 m and 2 m is recommended as a social distance. However, some studies have shown that a social distance smaller than 2 m does not protect people from exposure to airborne transmission of COVID-19 [48,173]. Blocken et al. [196] also discussed the pattern under a situation of movement during sports or walking. Social distancing is mainly a measure to avoid short-range transmission through the droplets generated by human activities, so other literature discussing the dispersion of droplets from human activity, such as breathing, talking, sneezing, and coughing, also may have provided important references for social distancing.

Table 8 summarizes the COVID-19 airborne transmission mitigation based on different indoor environments categorized as educational, office, public, residential, and hospitals. As can be inferred from the table, reducing the occupancy is recommended for different building types, which significantly reduces the infection risk of COVID-19. Using mechanical ventilation is recommended for different built environments since natural ventilation cannot mitigate disease dispersion to the desired extent, and increasing the ventilation rate is a safe recommendation in all indoor areas. Another measure is increasing the amount of outdoor air supplied; however, this approach can dramatically increase a building’s energy consumption. Upgrading filters used in the HVAC system is highly recommended. It should be noted that filters with MERV 13 and 14 are more recommended than filters with higher MERVs since they significantly raise the system energy use with no reasonable reduction in the disease infection risk. Opening windows (which can enhance natural ventilation), using air purifiers, and mounting UV lights are alternative measures for poorly ventilated areas or places that are not equipped with mechanical ventilation systems. Furthermore, complying with personal protective measures (wearing masks and social distancing) is highly recommended. It should be noted that a general social distancing of 2 m is insufficient in almost all building types and need to be integrated with other measures to be counted as a safe distance. It can be concluded that there is a lack of information regarding the combined effects of the implementation of mitigation measures on infection risk reduction. Other important issues that need to be addressed are to make a trade-off between the infection risk reduction and the building energy use growth and make an economic insight into selecting different measures over the long term.

4.6. Standard recommendations

In recent two years, standards have updated their recommendations providing a guideline to control the airborne dispersion of COVID-19. A list of airborne mitigation transmission policies suggested by different standards can be found in references [229–234]. Table 9 summarizes some standards’ recommendations related to the airborne distribution of COVID-19. Some authors have argued that current standard recommendations to prevent the airborne transmission of COVID-19 might not be sufficient [30,37,63,65,91,162]. Based on the table, increasing outdoor air ratio and ventilation rate, using energy recovery devices with precautions (avoiding leakages), and upgrading the efficiency of filters used in HVAC systems have been offered by the majority of standards to combat COVID-19 propagation in buildings.

4.7. Future works for indoor COVID-19 airborne transmission mitigations

A lot of efforts have been dedicated to the parametrization of the mitigation measures, while there are still a wide range of research gaps to simulate these different mitigation measures. For example, Yan et al. [235] have developed parametric descriptions of filters, masks, and UVGI measures (To be confirmed) in a multi-zone model. However, the assumptions are aggressive. Further validation of
the model should be conducted with considerable experimental tests. In addition, much effort is needed to overcome the limitations of multi-zone methods to capture the effect of different mitigation measures.

A conclusive guideline to offer the best ventilation system configurations with the lowest infection risk based on different indoor environments is not available. This means that still different modes and configurations of ventilation systems need to be examined in terms of airborne transmission reduction. Although there are also several studies discussing the impacts of different mechanical ventilation systems and natural ventilation on the level of mitigation, the interaction of the breathing behaviors with these ventilation modes should be further studied, and there are still difficulties in simulating and real-time predicting the infection risks in indoor areas, which can provide precise control strategies for ventilation systems. More cost-effective ventilation systems are needed to reduce energy consumption and secondary environmental impacts.

There are already studies discussing the social distancing effect, as mentioned in the last section. However, most of them focused on the local short-range transmission and the evolution of particle sizes \[236,237\]. While it is better to combine the social distancing studies with the occupancy of the room and consider the occupant behaviors in the simulation.

To the best knowledge of the authors, there is also a lack of solid methods to simulate the UVGI for the disinfection of the viral airflow. A model that can be incorporated with the CFD airflow models is needed. Based on previous works, the location and airflow rate of UV lights and air purifiers significantly affect their performance. There is no comprehensive work to offer the best condition and their combination with other measures. Therefore, further studies are required based on this knowledge gap. The cost analysis of different mitigation strategies has not yet been adequately performed.

Further studies are required to delve into the cost analysis of various mitigation measures and classify them based on an economic view. In other words, complying with mitigation measures needs to be economically reasonable. The environmental impacts of complying with different transmission mitigation measures have not been studied. Further studies are required to label various mitigation measures based on their potential environmental impacts.

Furthermore, although different mitigation measures have been offered for various building types, there is no conclusive work to report the effect of using a combination of them based on different indoor environments. Energy performance in buildings is an important issue that has not been paid enough attention to in most previous works. Further studies need to be conducted to offer different measures to mitigate the virus propagation while energy performance is regarded as an important factor. Limited mitigation scenarios are considered in most of the previous works, and more should be considered for the development of consistent guidelines. The study of comprehensive mitigation strategies and their energy impacts would be necessary during the post-COVID-19 era.

5. Conclusions

In this paper, the recent studies modeling the airborne transmission of coronavirus disease are identified and reviewed, covering straightforward approaches to more complicated ones. The modeling tools adopted in the latest papers are:

- Infection Risk assessment models: Wells-Riley and the dose-response models are broadly used to quantify the airborne transmission risk of COVID-19 based on several simplified assumptions.
- Numerical models such as zonal and CFD simulations: in numerical simulations, the destination of virus-carrying particles released is tracked, and finally, the concentration of viruses in different parts can be quantified, which allows an in-depth understanding of the distribution of viruses via airborne particles.

The main goal of the present paper is to review models used to assess the airborne transmission of COVID-19 in built environments. Comprehensive assumptions taken into account to simulate the virus transmission are presented, and a complete list of input data is summarized in informative tables. Moreover, experimental works performed studying airborne dispersion of the recent coronavirus disease are introduced, which can be used as evidence data for numerical simulation results.

Meanwhile, the COVID-19 transmission mitigation measures and their effects on the level of mitigation are identified and reported in classified sections. The mitigation approaches suggested found to be:

- Controlling occupancy
- Ventilation modifications
- Using filter and air purifier
- Installing UV air disinfection
- Personal protective measures such as wearing masks and social distancing

Moreover, the airborne distribution mitigation plans based on various indoor area types are reviewed. The classification of indoor environments is the educational, office, public, residential, and hospital. The ideas for future researchers based on the current knowledge gaps are carefully discussed in the paper concerning both the modeling and the mitigation measures. One of the limitations of the present work is that the review in this study is from a perspective of engineering and building-related studies. It may overlook some important studies from other disciplines, such as virology, microbiology, and epidemiology, which can be crucial to support and improve indoor transmission studies. Therefore, a multidisciplinary summary of the studies would be necessary for future research.

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.
Data availability

Data will be made available on request.

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