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The impact of indoor air quality on the **transmission of airborne viral diseases in public buildings**

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ABOUT THIS REPORT

Title: The impact of Indoor Air Quality on the transmission of airborne viral diseases in public buildings: a systematic review of evidence

Authors: Georgios Kokogiannakis, Leela Kempton, Paul Cooper and Matt Daly

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- Associate Professor Robyn Schofield, University of Melbourne

Contact details:

Sustainable Buildings Research Centre (SBRC)

Faculty of Engineering and Information Sciences

University of Wollongong, NSW 2522 Australia

Telephone: +61 (02) 4221 8111 Email: sbrc@uow.edu.au Web: sbrc.uow.edu.au

Executive Summary

The COVID-19 pandemic tested many aspects of Australia's systems including those associated with public buildings such as schools, higher education buildings, workplaces, hospitals, aged care, childcare facilities, etc. – all of which were significantly impacted by the COVID-19 pandemic.

This review project was commissioned by the Office of the Chief Scientist of Australia on behalf of the Prime Minister's National Science and Technology Council. The report was requested by the Assistant Minister for Health and Aged Care, the Hon Ged Kearney MP.

The purpose of the review was to synthesise the evidence relating to the impact of indoor air quality on the transmission of airborne viral diseases in indoor public environments, and strategies to reduce the transmission of airborne viral diseases in indoor public settings in Australia. This report provides a synthesis of evidence focused on the following areas:

1. The mechanisms involved in the transmission of airborne diseases in indoor public buildings.
2. Strategies to improve indoor air quality can reduce the transmission of airborne diseases in public buildings.
3. Whether indoor air quality monitoring can be used to support reduction in airborne disease transmission.
4. Impacts of these strategies to improve air quality for reduction in disease transmission on the energy efficiency of buildings.
5. Impact of the identified airborne diseases on the economy, and human health and wellbeing.

The scope of the report is centred around evidence regarding the role of indoor air in public buildings in relation to airborne viral disease transmission. Examples of topics that were outside the scope of the review are:

- Surface or fluid transmission of diseases in public spaces.
- Private stand-alone properties (e.g. houses).
- Influence on the risk of disease transmission from the use of Personal Protective Equipment (e.g. masks) or vaccines.
- Transportation vehicles (private cars, buses, airplanes, etc).
- Impact on mental and social well-being because of restrictions due to public health efforts to reduce the transmission of airborne viral diseases.
- Indoor air pollution (VOCs, radon, nitrogen oxides, etc).

- Recommendations to government.
- Publications based on expert opinion (e.g. some standards or guidelines) but without direct reference to original outputs from evidence-based research.

Summary findings from each of the five areas of review are provided below.

1. Mechanisms involved in the transmission of airborne diseases in indoor public buildings

SUMMARY FINDINGS

- The three main *stages* of airborne disease transmission are: i) generation and emission of infectious respiratory particles by an infected person, ii) transport of the infectious particles from the infected person to susceptible persons and iii) inhalation of these particles by a susceptible person and deposition in their respiratory tract.
- Transmission of airborne infectious particles can occur either within a *short range* of the infected person (close proximity) through direct inhalation of emitted particles, or at *longer range* beyond the region defined by the exhaled jet of infectious air and particles (i.e. without close/direct contact between the infected and susceptible subjects). An understanding of the processes involved will assist in identifying effective strategies to reduce the risk of transmission of airborne diseases in indoor public spaces.
- The main factors influencing the *transport* of infectious particles in air are: a) settling velocity and residence time in air, b) change in size during transport, c) survival of viruses that are carried by these particles and d) indoor environmental factors (air temperature, humidity, airflow pathways and ventilation rates).
- Transport of infectious particles by indoor air can also be categorised as occurring within a building space, between separate spaces, or through ventilation systems. The relative contributions of these three airflow pathways to the number of infected cases is not yet well understood.
- The risk of long range airborne transmission has been verified with PCR air sampling. However, while verification of the infectivity of viruses in these samples is challenging due to the nature of the measurements, a number of studies have confirmed the presence of viable viruses over long distances. Long range transmission cases have also been confirmed by a handful of high-quality studies that utilised epidemiological analysis (video surveillance records, contact tracing, etc.) and genome sequencing during well-documented COVID-19 long range transmission events.

- A limited number of studies have confirmed the presence of virus particles deposited on grilles, ducts and filters of mechanical ventilation systems. However, further research is needed on the assessment of the viability (infectivity) of various viruses during transmission through ventilation systems.

2. What strategies to improve indoor air quality can reduce the transmission of airborne diseases in public buildings?

SUMMARY FINDINGS

- There are four broad categories of indoor air quality strategies with potential to reduce transmission of airborne diseases in public buildings: i) installation of air cleaning technologies; ii) use of air disinfection technologies; iii) dilution of contaminated indoor air with cleaner air (through natural/mechanical ventilation), and iv) control of contaminated air dispersion. The aim of all these strategies is to ensure that there is clean air in the breathing zone of building occupants.
- Potentially effective air cleaning and disinfection technologies include HEPA air cleaners and Ultraviolet-C (UVC) lights, respectively.
- HEPA air cleaners have the potential to significantly reduce the concentration of infectious particles in healthcare settings (especially if combined with UVC lights). Their efficacy has been demonstrated in laboratory studies but the results of their in-situ effectiveness in non-healthcare buildings have been mixed, with both effective and ineffective findings reported. To mitigate the risk of airborne disease transmission, it is crucial to properly size and position HEPA air cleaners in relation to the number and location of both infected and susceptible persons. The expected location of the infected/susceptible persons is more likely to be known in healthcare environments, but more challenging in other types of public buildings. However, further research is needed to quantify the benefits of such systems installed in air-conditioning ducts.
- Larger spaces will typically require commercial/industrial scale HEPA air cleaners which can generate significant noise and lead to complaints from building occupants. While this might be tolerable in some public building settings, it is unlikely to be acceptable in noise-sensitive spaces such as classrooms. During this review no reliable evidence was found indicating whether distributing multiple portable smaller systems in a space will be sufficiently quiet and whether such an approach would yield comparable effectiveness in terms of air cleaning.
- UVC light systems have been shown to be effective in a range of scenarios. However, optimal sizing, positioning and design are of paramount importance for effective operation. Direct exposure of people to UVC light is dangerous and some types of louvres installed in these

systems for safety reasons were found to render them much less effective than otherwise. Some UVC lights have been reported to cause secondary chemistry effects by increasing particulate concentrations.

- The effectiveness of UVC systems for in-duct air-conditioning installations depends on the design and size of the system. Very large systems, in terms of UV radiation dosage and duration of exposure of the air, have been shown to be effective in disinfecting air in ventilation ducts, but further research is required to determine if transmission risk of airborne diseases is lowered.
- Both UVC light and HEPA air cleaner systems will generally have greater impact in reducing airborne transmission risk in situations where the mean air change rate, with respect to pre-existing supply of outdoor/clean air to a space, is relatively low.
- Diluting indoor air contaminants, and thereby reducing the risk of airborne infection, by providing fresh or cleaner air, to the breathing zone of occupants through mechanical or natural ventilation is an effective strategy. However, natural ventilation may not always be reliable due to its strong dependence on weather, building design characteristics, and human factors. Indirect issues such as noise or pollution from outside may also hinder the use of natural ventilation for indoor air dilution.
- The complex airflow characteristics of any indoor space play a major role in determining the concentration of disease/contamination in air in the breathing zones of susceptible persons in that space. The location, velocity and direction of each source of contaminated or clean air in a space will have a significant influence on how contaminants are spread, and mixed, within the space. The positioning of air supply and extract grilles relative to infectious and susceptible persons is therefore important, for both permanent ventilation systems and portable HEPA filter/fan units.
- Similarly, maximising the clean air flowrate to a space via mechanical ventilation and pre-existing supply grilles will not always lead to the most effective infection control, since this may change contaminated airflow pathways or enhance existing pathways due to the position of supply/extract ventilation grilles, and result in potentially greater exposure of occupants to air from an infectious person. Further research and guidance to practitioners is needed in this area.
- Controlling the dispersion of contaminated air and associated airflow pathways can be a potentially effective method to reduce airborne disease transmission risk. This approach can be particularly successful in healthcare environments, where the locations of infectious or potentially infectious persons are typically known. Techniques for achieving this include: placing physical constraints on airflow pathways; partitioning spaces that would otherwise be well connected; control of airflow direction by either providing dedicated supply/extract air grilles near infectious people or by applying a negative pressure to an infectious space.

- Alternative ventilation methods (as opposed to conventional mixing ventilation), such as displacement ventilation, theoretically help remove contaminated air from occupant breathing zones. However, further research on the effectiveness of these systems in practice is needed, especially considering dynamic factors such as air movement induced by occupant movement/activities, and obstacles such as furniture, etc.
- The implementation of indoor air quality interventions for airborne transmission prevention purposes based on human behaviour (e.g. knowledge of operation of technical interventions, complacency related to other precautions, etc) is an area where there is little research in the literature and value will be gained by doing further research to be able to make better decisions.
- Ultimately, the decision to implement any indoor air quality strategy should be made in a holistic manner, considering the geometric characteristics of the space, the air-conditioning system details, the way the space is ventilated prior to a potential intervention and relevant human/social factors including the anticipated location, activities and practices of the building occupants.

3. Whether indoor air quality monitoring can be used to support reduction in airborne disease transmission

SUMMARY FINDINGS

- Four monitoring methods were reviewed: direct air sampling for pathogens, measurement of background ventilation rates, carbon dioxide (CO_2) levels and particulate concentrations. Although these methods can provide some data that influence the risk of airborne disease transmission or provide feedback to enable risk reduction, none can measure risk directly. Pathogens are often present in small amounts in indoor air, which makes direct air sampling methods difficult and time-consuming and continuous direct monitoring of air exchange rates in a building is currently not possible. No studies were found that directly linked monitored levels of indoor air quality with reductions in airborne disease transmission. Nevertheless, further research into the development of real-time indoor air sampling bioaerosol sensors has been recently recommended and funding mechanisms commissioned internationally.
- CO_2 concentrations in an occupied space can provide an indication of the rate of outdoor/clean air dilution and can be used to trigger action to mitigate airborne disease transmission risk when measurements reach high threshold levels. However, the measurement of CO_2 alone is not always a reliable indicator of infection risk because CO_2 supply in the space by the occupants is generally not accurately known and CO_2 concentrations in a space may vary as a function of location or human activity unless the air is very well mixed, for example.

- Measurement of CO_2 as a direct proxy for airborne infectious particle concentration does not account for potential filtration/disinfection, deposition, infectivity and deactivation of various airborne pathogens. For example, air cleaning or disinfection systems purify or disinfect indoor air without affecting CO_2 levels. Similarly, CO_2 monitors alone do not capture the impacts of low occupancy during which the risk of infection will depend on multiple factors and may remain high.
- Particulate concentrations vary with human activity (breathing, talking, etc.) and thus can be linked to disease transmission to some extent. However, their measurement can be confounded by other sources of generation, such as indoor activities, combustion, cleaning sprays, smoking, outdoor pollution, etc. Accurate monitoring of particulate matter requires specialised equipment, and while handheld options exist, they can have accuracy and sensitivity issues.
- The effectiveness of monitoring airborne disease transmission can vary significantly depending on the specific disease. Calculations of actual disease transmission risks involve a significant degree of uncertainty, particularly in relation to factors such as viral load, relative susceptibility, and quanta generation. While significant advances have been made in understanding these factors for some diseases, more research is needed for quantifying such factors for new airborne diseases.

4. Impacts of strategies to improve air quality for reduction in disease transmission on the energy efficiency of buildings.

SUMMARY FINDINGS

- There have been relatively few studies of the impact on the energy efficiency of buildings serviced by HEPA air filtration units and UVC lights for disinfection. Whilst the energy consumption of individual units is relatively low, the number of units required to achieve sufficiently clean air will likely result in an increase in overall energy consumption of a building. Some examples for Australian classrooms and hospital spaces are provided in the relevant sub-sections in the main body of this report.
- Installation of UVC units will increase building energy consumption primarily due to the energy required to power the lamps.
- High-efficiency filtration (MERV-13, HEPA etc) units installed consume additional energy primarily due to electrical energy for fans required to move air through the filters.
- Heating Ventilation and Air Conditioning (HVAC) systems with variable speed supply air fans should be adjusted to compensate for the pressure drop caused by the addition of high efficiency filters by increasing fan speed so as to maintain the original supply air flow rates. This will consequently result in greater energy consumption.

- Some existing HVAC systems may only operate with fixed fan speeds, which will result in a reduced supply air flow rate if a higher airflow resistance filter is installed. This can have negative impacts on indoor air quality and the dilution of potentially contaminated indoor air. Installation of high-efficiency filters in ventilation systems with fixed speed fans may therefore not be a feasible retrofit solution in practice.
- In cases where fan speed control is possible, simulations for US buildings have reported increases of approximately 6% to 18% in the energy use of fans when upgrading to a MERV-13 filter, and an overall building energy use increase of less than 3%. HEPA air filters cause larger pressure drops with one US study finding a 12% increase in overall building energy requirements.
- It is important to note that the increase in energy use will depend on building characteristics, HVAC system type, climate, hours of operation of the HVAC systems and increased pressure drop from the upgrade to a higher performance filter. Further evaluations are needed that quantify the impact of filtration upgrades in Australian climates and building types.
- Increased use of outdoor air in HVAC systems for airborne disease dilution purposes will generally increase the energy consumption of the system, with the increase most notably seen in climates where there is a large air temperature (or enthalpy) difference between indoors and outdoors.
- The energy needed to condition additional outdoor air may be calculated from: the HVAC system efficiency, the amount of outdoor air, and the difference between outdoor and indoor air temperature/enthalpy.
- In some spaces, such as museums and art galleries, where humidity must be controlled within prescribed limits, introducing outdoor air may impose additional energy penalties.
- Strategies which control the dispersion of contaminated air are only expected to influence energy efficiency when mechanical interventions such as extract fans or personalised ventilation are installed. However, this may occur on an as-needed basis, for example during outbreaks at hospitals when converting wards from positive to negative pressure, and thus the long-term impact on energy efficiency may be of secondary importance.
- Energy efficiency upgrades to the building envelope or addition of renewable energy systems are generally not expected to significantly affect indoor air quality (in relation to airborne disease transmission). In terms of upgrades to HVAC systems, many modern HVAC systems aim to reduce the supply of air under part-load conditions for energy saving purposes. This may lead to an increase in airborne disease transmission risk due to reduced rates of clean dilution air supplied, depending on operational settings.

5. The impact of airborne diseases on the economy, and human health and wellbeing.

SUMMARY FINDINGS

- Significant direct and indirect socioeconomic impacts occur as a result of airborne disease transmission and outbreaks.
- Health and wellbeing impacts include increased morbidity and mortality, increased medical care costs, including costs to manage chronic effects from the infection (e.g. long COVID), and public health costs for resourcing the management of outbreaks and preventing their transmission to and within the community.
- Economic impacts have been reported in relation to reduced productivity, particularly due to absenteeism and presenteeism (lost productivity due to health reasons), declines in employee engagement, sick leave costs due to more absences from work, working errors and in some cases other impacts in relation to employment for specific parts of the population (e.g. reduced pay, retrenchment of workers, etc).
- The economic costs of school closures in response to pandemics have also been estimated in various countries and can be significant.
- A review of impacts of COVID-19 found learning loss or slower learning gain for primary school students, particularly for students of low socioeconomic background. An Australian study confirmed similar findings in terms of attendance rates of secondary school students in Tasmania. The cohort of students in this Australian study from high socioeconomic status (SES) backgrounds had similar school attendance rates before and after schools reopened during COVID-19, while the attendance rates dropped significantly amongst socioeconomically disadvantaged students.
- A study found that the risk of COVID-19 infection within Australian aged care homes was higher by more than 25% compared with the general Australian population. Additionally, high expenditures were recorded for managing COVID-19 infection risk in aged-care homes.

Table of contents

1 Mechanisms involved in the transmission of airborne diseases in indoor public buildings

1.1 BACKGROUND

Infectious disease transmission typically occurs through at least one of the following modes: exhalation and inhalation of airborne infectious particles, direct deposition of expelled infectious particles on the exposed mucosal surfaces of a susceptible person and contact (direct or indirect) between an infectious person or a surface where infectious particles have been deposited on it and a susceptible person [1–4]. *Airborne transmission* occurs when infectious particles are expelled and then inhaled by a susceptible person[5–7]. Airborne transmission of infectious particles can occur either within a short distance from the infected person through direct inhalation of emitted particles or at longer distances beyond the region defined by the exhaled jet of infectious air and particles[6].

Identifying appropriate indoor air quality strategies to prevent transmission of airborne diseases necessitates an understanding of the mechanisms involved in the transmission of these diseases. The three main stages of airborne transmission are summarised in Figure 1, which include the generation and emission of infectious particles by an infected person, the transport of these particles to a susceptible person, and the inhalation of these particles by the susceptible person (provided the infectious virus within these particles retains its infectivity throughout the three stages).

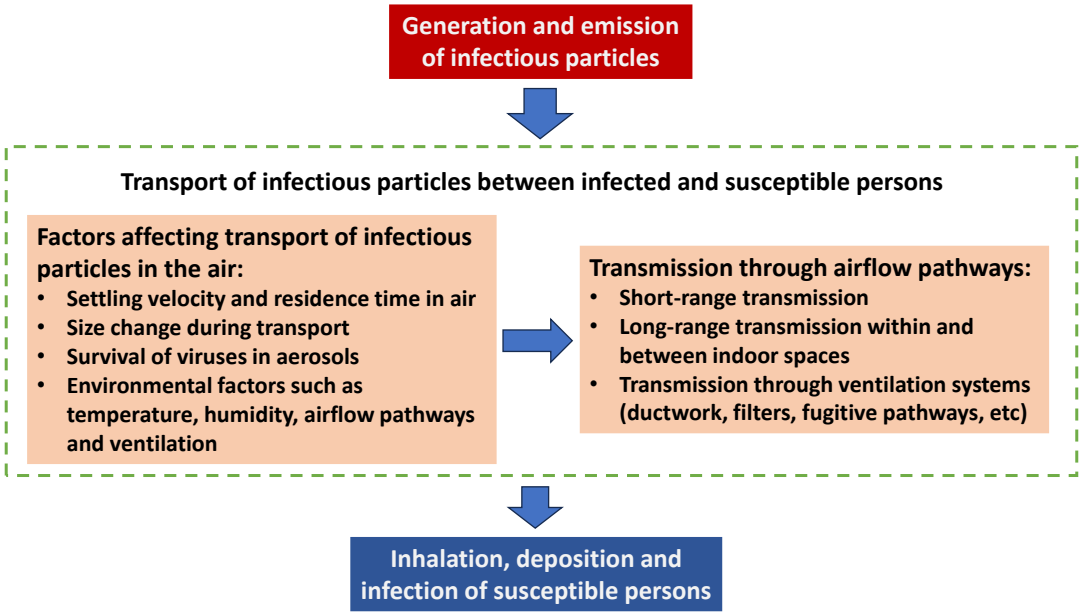

Figure 1: Overview of transmission process of airborne diseases from an infected person to a susceptible person.

1.2 GENERATION AND EMISSION OF INFECTIOUS PARTICLES

An infectious person will generate infectious particles from various sites in the respiratory tract due to activities such as breathing, talking, coughing, sneezing, etc[6,8]. The number, viral load, size, and velocity of these infectious particles depend on their origin within the respiratory tract[8]. Depending on the expiratory activity, the different mechanisms that cause the generation of these particles have been established and documented in the literature[5,9–15]. Infectious particles emitted from the lungs during activities such as breathing are smaller and aerosolised, while particles generated in the upper respiratory tract from activities such as coughing may be more likely to spread as both larger droplets and aerosols[16]. However, during breathing and speaking, 80–90% of particles are < 1 μm in diameter and are thus subject to aerosol transport[9]. Given that breathing and speaking activities occur more frequently than coughs and sneezes, the total number of particles released is likely to be greater than from other less frequent activities such as coughing. As a result, asymptomatic infectious individuals who spend prolonged periods indoors will emit a significantly higher number of infectious particles into the space around them.[6,16]

In the context of indoor public spaces, examples of high-risk activities from potentially infectious persons include singing (e.g. in pubs, theatres, churches), frequent coughing or sneezing (often in hospitals), loud talking (e.g. by teachers in educational buildings or restaurant customers) and heavy breathing (e.g. in gyms). However, while these activities increase the number of particles and quantity

of virus emitted, there are other key parameters that affect generation and emission of infectious particles. Asadi et al.[17], for example, showed with experiments that the rate of particle emission during normal human speech is positively correlated with the loudness (amplitude) of vocalisation, but at the same time a small fraction of the study participants (8 out of 40) were characterised as "speech super-emitters". These individuals consistently released significantly more particles than the other participants despite having the same phonic structures and amplitude of speech as the other participants. The authors suggested that unknown physiological factors may also affect the emission of infectious particles and lead to a higher number of subsequent infections. Similar observations regarding the variability in the number of expiratory particles between different individuals have been made by other researchers[18].

1.3 INHALATION, DEPOSITION AND INFECTION OF SUSCEPTIBLE PERSONS

Virus-laden particles can be inhaled by susceptible people and deposited in their respiratory tract leading to infection if sufficient quanta are absorbed. Air volumes inhaled by susceptible persons are strongly dependent on the activity they are engaged in (ranging from low volumes during sleep to high inhalation rates during intense physical activity). Wang et al[6] emphasised the importance of particle size in determining the deposition site in the respiratory tract. Several deposition mechanisms have been recognised including inertial impaction, gravitational sedimentation, Brownian diffusion, electrostatic precipitation and interception[19,20]. Infection occurs if the virus remains infectious at the deposition site and appropriate receptors are present[6]. While particles up to 100 μm in diameter can be inhaled, particles <5 μm may deposit anywhere in the respiratory tract including the lungs and alveolar lumen[6,21–23].

1.4 TRANSPORT OF INFECTIOUS PARTICLES BETWEEN INFECTED AND SUSCEPTIBLE PERSONS

1.4.1 Factors affecting transport of infectious particles in indoor air

In a comprehensive review of airborne transmission of respiratory viruses, Wang et al.[6] classified key factors influencing the transport of infectious particles in air as: settling velocity and residence time; size change during transport; survival of virus; and environmental factors.

1. **Settling velocity and residence time in air**. The residence time in air and the distance that infectious particles travel depends on their size, their initial velocity during exhalation, the indoor air velocity and the airflow pathways within and between building spaces[24]. The particle size, for example, can have a significant impact on the time these particles remain in air. For example, in perfectly still air it can be theoretically calculated that a particle of 100, 5, or 1 μm can take 5s, 33 min, or 12.2 hours, respectively, to fall to the floor from a height of 1.5 m [6]. However, while indoor air velocity in most indoor spaces is typically low, it will still be an important factor, together with air turbulence, that affects settling times of infectious particles.
2. **Size change during transport**. Expiratory infectious particles will change size over time due to evaporation but they evaporate more slowly than pure water because they contain non-volatile substances (proteins, etc)[25]. However, experimental measurement of the evaporation process of particles directly exhaled by humans is difficult and studies in this field have generally been carried out using modelling methods or with laboratory-generated droplets[26–29]. While significant uncertainties therefore remain in our understanding of the evaporation process of expiratory particles in real buildings, the modelling and laboratory studies have recorded significant changes in the morphology, viscosity, and pH of these particles during evaporation[6]. Such changes will affect the transport pathway of the infectious particles and the viability of viruses[30].
3. **Survival of viruses in aerosols**. The inactivation rate constant is a virus-specific constant used to define the decay rate of the concentration of infectious viruses. The inactivation rate constant is influenced by various environmental factors (e.g. temperature, humidity, exposure to UV radiation)[6,31,32]. It also depends on the chemical composition of the fluid from which the virus was aerosolised, which makes comparison of results across different studies difficult.
4. **Environmental factors such as temperature, humidity, airflow pathways and ventilation**. Studies that researched the impact of air temperature on the survival of airborne viruses are relatively scarce. Such studies have typically focussed on temperature ranges that are not common in indoor environments (e.g.[33,34]). Temperatures in indoor spaces are often controlled under relatively narrow ranges in order to satisfy thermal comfort requirements and no studies were found that have shown that temperature variations within these narrow ranges have significant impacts on the evaporation and survival of infectious particles in indoor spaces. However, variations in indoor air temperature within and between spaces is also a key

factor in defining air flow rates and pathways, which will therefore affect the trajectories of infectious particles.

Relative humidity (RH) affects the transport of particles and the viability of viruses in them[30,35–38], however, the relationship between relative humidity and virus viability also depends on the type of virus and its surrounding environment[6,36].

Additionally, air flows and associated air turbulence will influence the transport and dispersion of infectious particles and may slow the rate of particle gravitational settling[1].

It should be noted that, historically, many infectious diseases were thought to be only transmitted directly via direct deposition of expelled infectious particles from an infectious person to a susceptible person at close range. However, in recent years and particularly during the COVID-19 pandemic, it has been widely accepted that inhalation of airborne SARS-CoV-2 virus is a main transmission mode in spreading COVID-19 at both short and long ranges[6].

1.4.2 Transmission through airflow pathways

1.4.2.1 Short range transmission

Short range transmission is where virus-laden particles in the expired jet of air from an infectious persons respiratory tract reach the mouth or nose of a susceptible person in the very near vicinity[39,40]. There are a wide range of complex fluid dynamics processes and other phenomena involved in this mode of transmission, including the respiratory activities of the persons involved. While significant progress in our understanding has been made in recent years in this field, there are still many knowledge gaps to be filled, with researchers in the past reaching different conclusions for specific diseases on whether short range transmission is mainly caused by larger droplets or by aerosolised particles[7].

For example, using a simple mathematical, Chen et al.[41] modelled expired flows from potentially infected persons and droplet dispersion, deposition and inhalation, and concluded that unless the infectious and susceptible persons are close to each other (e.g. <0.2 m for talking), large droplet transmission is insignificant compared to aerosol transmission[41]. The infectious particles dominating short range transmission will typically be larger than particles in long range transmission and, while this is not easy to verify experimentally, it is expected that such large infectious particles will normally carry more viable virus particles[39].

In conclusion, whether short range transmission of infectious diseases is predominantly driven by larger droplets or aerosolised particles, both modes are not mutually exclusive. Preventing short range

transmission of infectious diseases will be unlikely with indoor air quality interventions as opposed to PPE, social distancing and physical barriers.

1.4.2.2 Long range transmission within and between indoor spaces

Long range presence of airborne infectious particles in the air has been verified with PCR measurements and indirectly with case studies where transmission was recorded without direct contact or short range interaction between index and susceptible persons.

In a systematic review of 24 studies where RT-PCR measurements for presence of SARS-CoV-2 RNA in the air were taken in hospitals, Birgand et al.[42] confirmed positive virus measurements in the air of most typical hospital spaces, near and distant from patient rooms. Approximately 17% of air samples within the same space of COVID-19 patients were positive. The route of transmission was not discussed but the percentage of positive samples in various hospital spaces was: 25% in the ICU, 11% in non-ICU wards, 24% in toilets, 8% in clinical areas (e.g. in IR), 12% in staff areas and 33% in public areas. Viability (infectivity) of the virus was measured only in 9 out of the 24 studies, and only two[43,44] of these 9 studies measured viable viruses. A similar finding on the difficulty of measuring viable viruses in the air despite being able to verify viral DNA or RNA in the air around patients was stated by another pre-COVID-19 review of respiratory viruses (seasonal and avian influenza viruses, MERS-CoV and RSV)[45]. However, the lack of viable virus measurements in air samples where virus RNA was found has been attributed the fact that common air sampler instruments can inactivate virions through their collection processes[44]. Using alternative instrumentation for air samples taken from 2 to 4.8 m away from two COVID-19 patients, Lednicky et al. confirmed that the air samples contained viable SARS-CoV-2 virions and matched them with genome sequencing to these patients[44].

Positive SARS-CoV-2 air samples have also been measured in non-healthcare public buildings. For example, a large study in Iran confirmed positive samples in the air of all five sampled shopping centres, in 4 out of 5 airports, in 2 out of 4 subway stations and in 2 out of 4 government offices[46].

In addition to the air sampling studies included in the above reviews, there are examples of transmission events where the reason for the recorded infections was attributed to long range airborne transmission. A thorough analysis of evidence of 18 long range airborne transmission events of SARS-CoV-2 is given by Duval et al[47]. However, only three of the 18 events were ranked by the authors as being of high methodological quality, primarily because long range airborne transmission

was verified with detailed epidemiological investigations (contact tracing, review of surveillance videos etc) and genome sequencing[48–50]. All 18 studies involved transmission between unvaccinated individuals. The three studies that were ranked as high quality and two other extensively referenced studies that occurred at the start of the COVID-19 pandemic in China (ranked as medium quality by Duval et al.) are briefly discussed below.

- A long range transmission event was recorded in a quarantine hotel in New Zealand where infection between two opposite rooms was verified and matched with genome sequencing. The infected persons had travelled separately and never came in direct contact with each other (verified with video records)[50]. Fomite transmission was also ruled out based on video analysis. Analysis of video records showed that the doors of the two rooms were left open at the same time on four occasions during the quarantine period for only a short period of time. A review of the air flows through the ventilation system as well as the pressure differences between rooms and corridors verified the likely airflow pathways between the two rooms.
- Transmission between one index person and two susceptible persons in June 2020 occurred at a restaurant. This was confirmed using genome sequencing and a detailed location tracking system that South Korea had in place at the time[48]. The index patient sat 6.5 m from one susceptible person for five minutes, and 4.8 m from the other susceptible person for 21 minutes. All three cases sat at different tables.
- In July 2020, a church choir member in Australia was a probable index patient who sung at four church services within a period of three days[49]. Twelve infected cases had sat in the same section of the church and between 1 m and 15 m from the index patient. Genome sequencing of the index and 10 infected patients showed a single genomic cluster, suggesting that transmission had occurred during the church services.
- A SARS-CoV-2 infection transmission was recorded between three families in a restaurant in Guangzhou, China at the start of the COVID-19 pandemic[51,52]. Video records from the restaurant showed no direct contact or fomite contact between the three families and there were no other records of infected customers or staff at the restaurant. Tracer gas measurements and simulations showed that localised airflow pathways favoured the transport and recirculation of infectious particles from the index patient to the tables of the other two families.
- Similarly at the start of the COVID-19 pandemic, 24 out of 68 bus riders in Eastern China were infected after travelling for approximately 100 minutes with an index patient who had

recent travel history to Wuhan[53]. The infected passengers were scattered around the bus, with some of them being seated 7 rows behind the index patient. The transmission link between the infected passengers was verified with RT-PCR or by viral genome sequencing, however, Duval et al. classified this study as not including details about genome sequencing.

Long range airborne transmission has also been documented for other highly infectious diseases such as measles[54,55].

1.4.2.3 Transmission through ventilation systems

The possibility of dispersion of viruses via the grilles, ducts and through filters of ventilation systems to different parts of a building has been investigated by a limited number of studies. For example, swab samples with positive SARS-CoV-2 virus were found on the exhaust grilles of the ventilation system in a dedicated disease outbreak facility in Singapore and also on grilles and in ducts of a hospital in Sweden[56,57]. Similarly, as a result of a COVID-19 outbreak in one of seven wards of a nursing home in the Netherlands, de Man et al.[58] found SARS-CoV-2 RNA on some grilles and filters of the ventilation system. The specific ward had a different ventilation system than the other six wards, which included air recirculation that follows a CO_2-controlled logic (i.e. use of recirculated air unless CO_2 exceeds a specific threshold). The positive swab tests and the large scale of the outbreak in that single ward during a period of low background prevalence of COVID-19 infections in the community indicates possible transmission through the ventilation ducts. However, no study was found during this review that provides evidence on the viability (infectivity) of viruses in the ductwork of ventilation systems.

2 Strategies to improve indoor air quality that can reduce the transmission of airborne diseases in public buildings

2.1 BACKGROUND

At the highest, or most fundamental, level the question at hand can be summarised as - what are the best methods by which risk can be reduced of a susceptible person becoming infected as a result of inhaling air contaminated with airborne infection disease particles emitted from an infectious person some distance away. Clearly a wide range of factors and processes influence the generation, transport and potential control and treatment of the contaminated air in such situations.

A schematic overview of these key factors and Indoor Air Quality (IAQ) strategies involved in response to the review question is provided in Figure 2. In terms of improvement of IAQ generally (i.e. for all types of contaminants) there are a number of fundamental ways by which to improve IAQ, including:

- Removal or mitigation of the contamination source.
- Cleaning, decontamination and/or disinfection of the air.
- Dilution of the contamination with cleaner air.

In the case of transmission of airborne diseases and mainly long range transmission, the primary technological IAQ strategies that decrease airborne disease transmission risk therefore include:

- Air cleaning or disinfection
- Dilution of the contaminant via ventilation with cleaner air
- Constraint and/or control of the movement of contaminated air from source to susceptible subjects (including air movement between different building spaces or within a given space).

In addition, there are a wide range of associated strategies that involve human factors such as day-to-day practices, susceptibilities to infection, activities, etc.

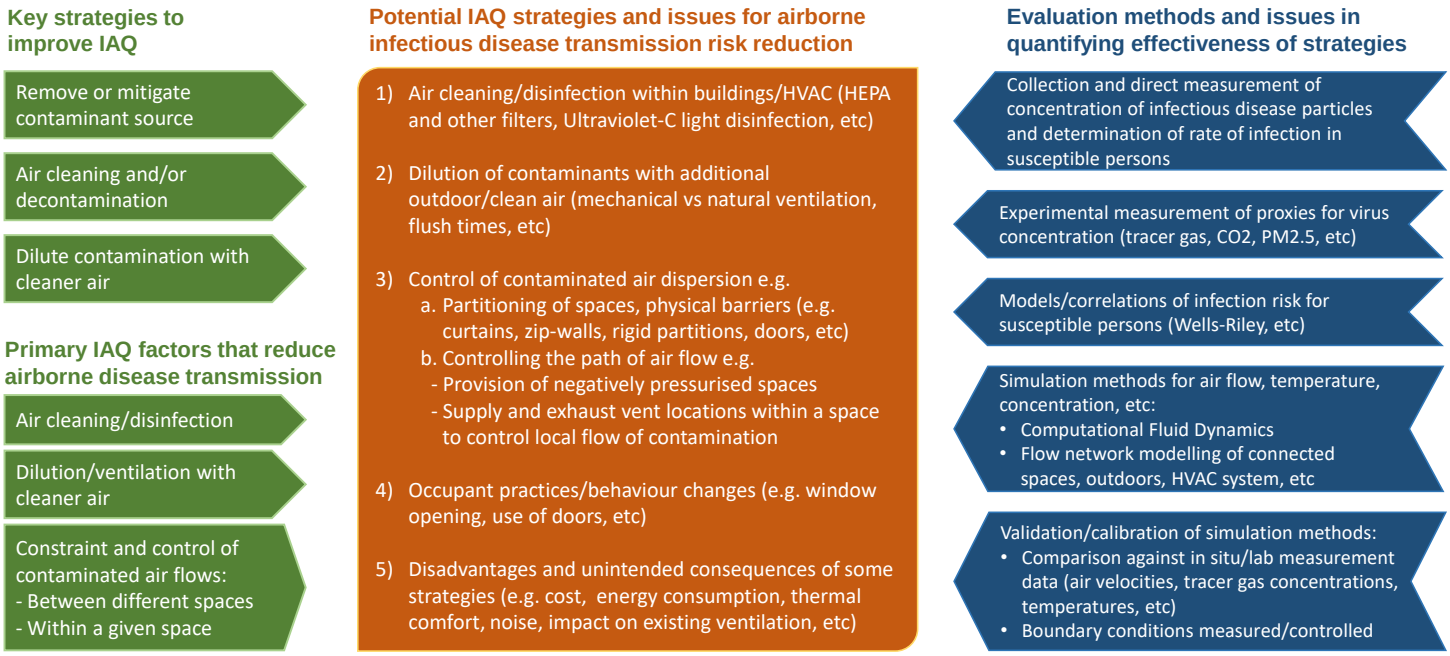

Figure 2. Schematic overview of the key Indoor Air Quality (IAQ) strategies and issues involved in response to the review question, "What strategies to improve indoor air quality can reduce the transmission of airborne diseases in public buildings?"

2.1.1 Key IAQ strategies/issues relevant to airborne disease transmission risk reduction

IAQ improvement strategies and associated considerations that are directly relevant to airborne disease transmission reduction risk reduction that have been considered under this review include:

1) Air cleaning and/or air disinfection within building spaces or HVAC systems. These two strategies are important from many points of view, and particularly to reducing quasi-steady exposure of susceptible subjects to risk, and to transient situations such as rapidly cleaning the air of a previously contaminated space. Technologies available for this process include:
   - HEPA filters
   - Standard HVAC air filters
   - UVC (Ultraviolet-C light) disinfection
   - Other cleaning (e.g. electrostatic)
2) Dilution of contaminant air with additional outdoor/cleaner air via
   - Mechanical ventilation
   - Natural ventilation
3) Control of contaminated air dispersion is heavily influenced by the complex fluid dynamics of air movement. Potentially effective IAQ improvement strategies include:
   - Partitioning and constraint of spaces
   - Control of air flow direction/destination
   - Provision of negatively or positively pressurised spaces
   - Alternative HVAC/ventilation configurations

2.1.2 Evaluation methods for effectiveness of strategies

There are many challenges facing researchers and other stakeholder seeking to establish the real-world effectiveness of IAQ strategies in reducing the risk of transmission of airborne diseases, particularly due to the multi-faceted and multi-dimensional nature of the complex processes involved. The authors have developed the schematic shown in Figure 3 to illustrate the interrelationships between a number (but not all) of key components that have been used to date to measure and model the key processes and factors that govern IAQ strategies and infection transmission risk.

Given the dependence of infection transmission risk on myriad factors and influences it has generally not been possible to achieve generalisable direct measurements of infection transmission risk (the scenario indicated in the dashed rectangle on the right side of Figure 3). Controlled cohort studies during periods when the number of infections in the community is high are of high value and are needed for evaluating IAQ interventions, but are difficult to commission. Rather, the approach to date has generally been to combine a number of the following elements that together provide an estimate of absolute or relative infection risk.

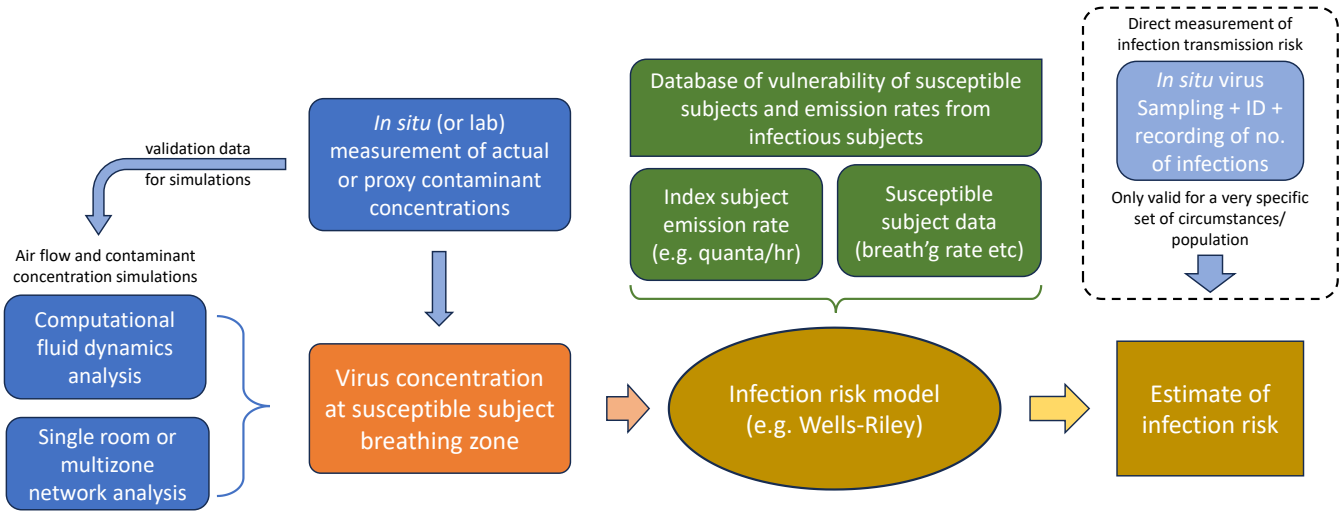

Figure 3. Schematic of a number of (not all) potential routes for evaluation of the effectiveness of different IAQ strategies in reducing airborne disease infection risk.

2.1.2.1 Infection Risk Models

At the heart of models of IAQ strategy infection risk effectiveness is an Infection Risk Model such as the widely used Wells-Riley Model[59] or the more recently published infection risk model for SARS-CoV-2 by the World Health Organization (WHO)[4]. While such models may be conceptually simple a very significant amount of data covering a wide range of independent variables is required

to quantify inputs, e.g. estimates of the virus emission rates of infectious subjects and details of susceptible subject's likely breathing rate. susceptibility to infection, etc[60]. Such data has been gathered from many studies to determine airborne disease emission rates and susceptibility from various populations of infectious and susceptible patients. One of the other key inputs to the Infection Risk Model is the local volumetric concentration of virus in the breathing zone of the susceptible subject(s), which may be estimated by a range of methods ranging from simple models of likely ventilation rates in a space, through complex Computational Fluid Dynamics (CFD) analyses, to direct experimental measurement of concentrations of actual virus or appropriate proxies[61]. In reality the concentration of contaminant in air within a given space will be non-uniform in both space and time, which has been accounted for in many studies[62].

2.1.2.2 Measurement of actual or proxy contaminant concentrations

1) Collection and direct measurement of concentration of infectious disease particles (in situ and/or in laboratory facilities), e.g. via impact collectors, cultures, visual/genetic identification can be carried out to determine impact of specific strategies (e.g. air cleaning/disinfection).
2) Experimental measurement of proxies for contaminant/virus concentration
    - Tracer gas air flow studies where point source release of a gas acts as a proxy for airborne disease emitted from infectious subject and proxy concentration distribution is measured spatially and temporally – this could inform spatially and temporally varying infection risk models as has been discussed by Li et al[62].
    - Dilution rate of contaminant estimated by measurement of CO_2 concentration in a room resulting from occupant(s) breathing. Several key assumptions required, e.g. CO_2 rate/person.
    - Aerosols/smoke particles as proxies for airborne disease vectors, and flow visualisation.
    - It must be noted that it is necessary to account for the limitations of proxies, e.g. some proxies will not reflect deposition and deactivation rates compared with actual airborne disease particles.

2.1.2.3 Air flow and contaminant concentration simulation techniques

- Computational Fluid Dynamics (CFD) has been widely used to estimate spatial contaminant concentration distribution. To date, CFD has been used primarily for flows within a single space/zone and is generally very sensitive to input boundary conditions. Ideally CFD simulations should be validated against in-situ or laboratory experiments close to real-world conditions.

- Flow network modelling of connected spaces, outdoors, HVAC system components, etc. These techniques generally assume full-mixed air within a given building space, but have the advantage of being suitable for modelling more complex multi-zone buildings and associated HVAC systems, and their interactions with outside conditions. However, they are not suitable for detailed predictions of non-uniform contaminant concentrations in a given room/space.

2.1.2.4 Agent based modelling techniques

Agent based models have been used to model disease transmission in various situations and at different scales (university campuses, cities, countries etc). Such models incorporate the actions and interactions of people (agents) across different locations and periods of time. These are event-based models where people are assigned specific attributes related to their movement, interactions and most commonly, their infection status; typically three infection status attributes are used: Susceptible to the disease, Infectious, and Recovered (SIR). While these models are useful to test the impact of infection control measures related to movement of people at larger scales (e.g. quarantine or social distancing), they generally do not incorporate the details needed to represent the local indoor environment and assess the indoor air quality interventions discussed in this report. A critical discussion on the limitations of these models to address building-level air flow characteristics by Mukherjee and Wadhwa[63] highlighted that agent based models do not typically model air flow and respiratory particle transport information. For example, air flow patterns and pathways are not considered or, less commonly, are defined by the user as a simulation input, and spaces in almost all cases will be considered to be well-mixed. On the other hand, rare examples of models with fully coupled high resolution air flow and agent interactions exist[64]. However, these models are computationally expensive, involve significant uncertainties (high number of degrees of freedom), and can output results for only a few minutes of physical time for presence in indoor spaces[63]. Additionally, the thermal domain of the building (e.g. simulations for predicting surface and air temperatures) is disregarded in agent-based simulations. As a result, temperature driven air flows (e.g. through openings between adjacent spaces, air stratification, etc) are not considered.

2.1.3 Literature review

The literature search strategy and search terms were developed to identify evidence on the effectiveness of such IAQ strategies. Using a replicable search process and sourcing additional references from the results of this process, 465 publications were retrieved from which over 380 were

reviewed in detail for the current version of this report. Through analysis of these 370 articles, there were 63 publications that were relevant to the specific review question here. The studies that were included would be categorised as of "High" or "Moderate" methodological quality against a grading system such the GRADE system used by medical researchers.

2.2 OPPORTUNITIES WITH HIGH POTENTIAL IMPACT

2.2.1 Air cleaning - HEPA air cleaners

High Efficiency Particulate Air (HEPA) air cleaners/purifiers can filter indoor air and remove the vast majority of airborne particles. HEPA systems are typically installed in buildings: i) most commonly as portable equipment that is placed in a given space to increase the effective rate of replacement of potentially contaminated air with cleaner air, or to simply exhaust air to outside; or ii) as fixed systems within air-conditioning systems to filter the supply air of the ventilation system.

Table 3 in Appendix 1 summarises the findings of 18 relevant reviewed studies. While the details and context of each study in Table 3 are important, the key findings are as follows:

- HEPA air cleaners in hospital wards with several infected patients were found to reduce the concentration of microbial bioaerosols in the air, particularly when combined in-line with UVC disinfection modules[65].
- While laboratory studies have verified the efficacy of portable HEPA air cleaners[66,67], clear conclusions regarding their effectiveness in non-healthcare spaces such as kindergartens cannot be drawn[68,69]. In one rigorous study, HEPA air cleaners were deployed in 10 kindergartens (control: 22 kindergartens) and the COVID-19 period prevalence rate per 1000 children over 6 months was higher in the HEPA air cleaners cohort than in the control group with no air cleaners[68].
- The size and the position of the HEPA air cleaners in relation to the infected and susceptible person(s) will determine their effectiveness in reducing airborne disease transmission risk. While air cleaners are typically beneficial in terms of reducing indoor aerosol concentrations in well-mixed spaces, there have been some simulation studies where increases in local contaminant concentrations were predicted within spaces[70,71]. In non-hospital ward environments where the positions of infected and susceptible persons cannot be known in advance, identifying the optimum location and size of HEPA air cleaners a priori would require multiple scenario analyses with advanced modelling techniques that quantify local

concentrations of aerosols within building spaces. Providing guidelines for the potentially optimal operation mode and positioning of these systems across various non-healthcare building geometries and occupancy scenarios would be beneficial.

- HEPA air cleaners were also shown to be effective in hospital wards when used to exhaust air to outside and create negative pressure to prevent transmission to anterooms or corridors.[72] In this case also, the context of the space (geometry, HVAC configuration, etc) in determining the capacity and position of the HEPA air cleaner needs to be carefully considered.
- Rigorous evaluations of the effectiveness of in-duct installations of HEPA air cleaners for the reduction of airborne transmission were not found in the reviewed studies.
- Noise considerations from the use of the HEPA air cleaners were raised in a number of studies[73–75] Larger spaces may require commercial/industrial scale HEPA air cleaners and thus their noise may not be acceptable to occupants. It is unclear from the literature whether this issue can be resolved by using several smaller systems and whether such an approach may have a beneficial or detrimental impact on air movement and removal of airborne particles in the room.
- It should also be noted that HEPA air cleaners are only filtering the air and are not a substitute of fresh/outside air supply.

2.2.2 Disinfection via Ultraviolet-C (UVC) lights

Another method for deactivation of airborne viruses is by exposing contaminated air to Ultraviolet-C (UVC) light (also known as Germicidal UV or UVGI), which can be generated using lights emitting short wavelength radiation (180-280 nm). UVC inactivates viruses by damaging the genetic material in their nucleic acids. However, UVC is harmful to humans and in potential applications in buildings UVC lights should be safely concealed. This would be typically done by deploying them in three ways: i) in ducts of ventilation systems; ii) in well-designed portable systems combined with HEPA filters, and; iii) in ceiling or wall mounted units.

Thirty studies assessing the effectiveness of UVC lights on the reduction of airborne transmission were reviewed and are summarised in Table 4 in Appendix 1. Key findings from these studies are:

- UVC light devices can be effective at reducing airborne transmission as long as they are sized and placed in spaces in an optimal manner[76–85]. Important parameters in optimising the effectiveness of such systems are: the intensity of the UVC energy, the duration of exposure

of air to UV light, the number of UVC fixtures, the use of one or more mixing fans in the space (typically ceiling fans), and the ventilation air exchange rate in the space[86,87].

- Upper room UVC light devices can be better utilised in poorly ventilated spaces as the slower replacement of air in these spaces would typically result in longer exposure times to UV radiation[79,88,89].
- For wall and ceiling mounted UVC systems, achieving uniform UVC intensity distribution in the room was shown to be also important for their effectiveness[90]. To achieve uniform distribution, several wall and ceiling mounted systems are required to be deployed across a space. Optimum positioning and ensuring uniform dosage distribution of UVC systems requires thorough design analysis to maximise their effectiveness without exposing the occupants to UV irradiation[2,91].
- Several laboratory studies have shown significant improvements to the efficacy of ceiling and wall mounted UVC systems after using a ceiling fan to create a well-mixed space[77,86,88,90,92,93]. However, one study found that careful analysis should be done on determining the optimum fan speed for achieving appropriate mixing of air[94].
- Louvres are often used in commercial ceiling or wall-mounted systems to prevent exposure of people to UV radiation. While louvres are important for safety reasons, some types of them significantly reduce the effectiveness of UV luminaires[88,95]. In one particular study, it was found that the efficacy of UVC systems dropped to zero with the use of louvres[95]. Far-UVC light (222 nm) was also found to be equally effective[77,96], but there were no safety experiments reported in these studies. Additionally, Far-UVC lamps at 222 nm have been found to produce significant amounts of ozone (O_3)[97] and OH radicals that oxidise indoor volatile organic compounds (VOCs) into more oxidized VOCs[98]. UVC lights in general were measured to cause significant increases in particle number concentrations (secondary pollution effects)[99–101].
- Combining UVC systems with HEPA filters in portable systems was shown to be effective in hospital wards with COVID-19 patients[65]. However, this is based on only one rigorous study which did not undertake a separate analysis on whether the measured benefits were attributable to the HEPA air filters or the UVC system. Given that exposure time of the air to the UVC light is a significant parameter for its effectiveness, it is more likely that the improvements observed in this single study were attributable to the HEPA filter.
- Two studies measured the effectiveness of in-duct UVC installations in ventilation systems of buildings[102,103]. While one of these studies was inconclusive in terms of measured airborne

concentrations[103], a large capacity (high dosage) commercial UVC system in the other study resulted in measured reductions in bacterial count by ~50%[102].

- In-duct installations have also been studied in test chamber experiments[104]. It was shown that while these systems can be very effective when air stream velocity is low and similar to velocities matching those in branch ducts of ventilation systems, they were ineffective when the air velocity increased to velocities closer to velocities of large supply ventilation ducts (e.g. ducts at the outlet of air handling units). A comprehensive review of designs and inactivation efficiencies of in-duct UVC systems for SARS-CoV-2 is provided in[105]. A design optimisation study was also undertaken by the same authors: it was found that all in-duct systems after optimising their design (lamp arrangement and UV dose) could achieve inactivation efficiencies >99% (>2 log reductions for all optimised designs), albeit their as-published inactivation efficiencies before optimisation varied from 70% to 100%. Overall, in-duct UVC systems have been reported to be effective against airborne transmission, but a design analysis should be considered prior to their installation in ventilation systems.
- UVC efficacy can decrease at high indoor relative humidity levels[82,87,90,92]. High levels of indoor humidity would also create discomfort and people will most likely act to improve such conditions (e.g. with Air-Conditioning), but nevertheless, UVC systems may prove ineffective in humid spaces such as indoor swimming pools.

2.2.3 Dilution of contaminated air with cleaner air (mechanical and natural ventilation)

A practical approach to mitigating the risk of airborne disease transmission indoors is provision of fresh air or cleaner recirculation air to the breathing zone of occupants with mechanical or natural ventilation. Several review studies have underlined the role of cleaner air supply for diluting indoor contaminants[106–108]. While the positive effect from mixing outdoor air or cleaner recirculation air to dilute potentially contaminated indoor air is obvious, there still remains the question on what the optimum amount of fresh/cleaner air would be for infection control purposes. Review studies on this topic remain inconclusive[107,108] and while some professional bodies have developed general empirical recommendations (e.g.[109,110]), the required amount of air for airborne infection control would depend on the geometry of the space, the occupancy level, the HVAC characteristics and the installation of any other air cleaning technologies (e.g. filtering). Further research is recommended to identify the optimum levels of airflow for diluting indoor air with outdoor or cleaner recirculated air. Outdoor air

in particular, does not often meet the thermal comfort needs of building occupants (i.e. too cold in winter and too warm in summer), and therefore any excess amount of outdoor air would lead to either thermal discomfort or increased energy usage.

Additionally, there appears to have been limited research done on whether increases in air flow supply at levels higher than the optimum levels may have an adverse impact locally within specific areas of a space. For example, the effect of increasing the supply flow rate of the mechanical ventilation system (a mix of outdoor and recirculated air) on the distribution of airborne particles emitted over time by a teacher in a lecture room was modelled using CFD[111]. The study predicted concentration rates locally around the classroom seats using discreet control volumes, but the thermal plume of individual occupants was not taken into account. Three important findings were reported:

1. The minimum ventilation rate resulted in the highest concentration of particles suspended in the air and the highest number settling out, as expected
2. The case with the maximum supply rate had a higher percentage of particles settle out and as a result, the maximum air flow supply rate did not have the best performance in terms of infectious particles removed from the space
3. Most importantly, while the overall number of particles suspended in the air decreases when increasing the supply air flow rate, at a local level in multiple control volumes in the space, the particle concentration increases. The authors speculate that the reason of this could be the asymmetric placement of the seats with respect to the diffusers and to the extraction grilles.

Similar conclusions to those as in the example above were drawn by other modelling and experimental studies[112,113]. For example in a CFD modelling study[113], it was found that the thermal plumes generated by people in large, densely occupied spaces influenced the patterns of indoor air flow. As a result, at the highest air flow rate modelled higher numbers of infectious particles were suspended in the air, and for prolonged durations, compared to lower air flows. In another study where Particle Image Velocimetry (PIV) was used for air flow field investigation and aerosol counter equipment was used to measure particle concentration in a large environmental chamber[112], the results showed that exposure to cough-released particles increased when supply flow rate was increased from 6 to 12 ACH. This implied that local air flow patterns are an important factor that governs exposure caused by airborne infectious particles and careful consideration should be made to identify the optimum supply flowrate of cleaner air for dilution of indoor airborne contaminants.

In terms of selecting the most effective strategy between natural and mechanical ventilation, supplying the amount of fresh air needed for infection control via natural ventilation (through

windows or other openings) would be more cost effective but is often unreliable (e.g. [106,114]). This is because natural ventilation is dependent on: highly variable outdoor wind velocity and air temperature, location and size of windows and on people keeping windows open (unless automatic window opening actuators are installed). Other potential limitations of natural ventilation are acoustic discomfort due to noise from outside entering through windows and in some cases the introduction of outdoor air pollution in building spaces. On the other hand, mechanical ventilation also has disadvantages in relation to capital cost, energy consumption (and thus running cost and carbon emissions), and the requirement for periodic maintenance.

In a relevant systematic review study, comparisons were undertaken between natural and mechanical ventilation to determine whether the ventilation used in hospitals influences microbial bioaerosol concentrations[115]. Out of 36 relevant reviewed studies, it was found that hospital areas with natural ventilation had the highest total bioaerosol concentrations, which were higher than for areas serviced by mechanical ventilation by up to a factor of 10 in terms of measured colony forming units per cubic metre (CFU/m^3). However, the authors advise caution in interpreting some study results and to only refer to the trends of their findings because the numerical estimates may be biased due to limitations of the reviewed studies (reporting gaps, sample sizes, etc).

Epidemiological studies, and particularly cohort studies, that have sought to establish the relationship between transmission of airborne infection, technological IAQ interventions and specific ventilation scenarios are extremely rare. However, one such study during the COVID-19 pandemic, as reported by Buonanno et al[116], involved a comparison of the numbers of clusters of infections in school classrooms in the Marche region of Italy. The total number of classrooms in the study was 10,441, of which 316 had been retrofitted with mechanical ventilation and/or filtration systems with a range of air delivery flowrates between 100 to 1,000 $m^3\ h^{-1}$ and with varying levels of filtration. The remaining 10,125 classrooms were naturally ventilated. Data on the numbers of students reported as infected in classrooms throughout the region was used to identify clusters of two or more students infected in a given classroom, and this metric was assumed to provide some measure of the likelihood of student-to-student transmission within a particular classroom. During the reporting period the number of infected students within clusters in naturally ventilated classrooms was 3,090, and 31 students in classrooms with mechanical ventilation. Results from the statistical analysis indicated that "… the relative risk of infection of students decreased at least by 74% compared with a classroom with only natural ventilation, reaching values of at least 80% for ventilation rates >10 L s^{-1} $student^{-1}$". In mechanically ventilated classrooms, infection transmission risk was also found to significantly

decrease with increasing air delivery flowrates from the mechanical ventilation systems. Field data from this article[116] was also successful used as a validation of the widely cited predictive risk infection model previously developed by three of the authors[60]. It should be noted that, as with many post hoc epidemiological studies, not all relevant data could be gathered, statistically analysed and reported - including matters such as details of the mechanical ventilation system configurations employed in different classrooms, differences and similarities between the settings (location, etc) and operation of the naturally and mechanically ventilated classroom cohorts, and measurement of actual ventilation rates in the naturally ventilated classrooms.

2.2.4 Control of contaminated air dispersion

The way that contaminated air disperses inside a building clearly determines, in part, the risk of airborne infectious disease transmission. Measurement and modelling of processes involved in indoor air contaminant dispersal are extremely complex and involve issues such as turbulent air flow interactions of infectious particles with moving air, movement and activities of people within buildings, etc.

In any real-world indoor space containing an infectious person, the concentration of infectious particles will vary in both space and time within the space – so the risk of infection of a susceptible person will depend on their location and the time spent breathing contaminated at the various locations. In addition, fugitive contaminated air will also disperse to other adjacent spaces via openings in the walls, floor and ceiling of the space (e.g. doors, windows, cracks, small openings and penetrations for water and electrical services, etc) or through ventilation grilles and ductwork systems.

There are therefore a number IAQ strategies that can be used to control such contaminated air dispersion and concomitant infection risks. These strategies can be categorised in terms of:

1. Physical constraint of airflow using barriers within a space or between spaces such as: curtains, partitions (for desks, floor-mounted, etc), semi-permanent closure of openings (zip-walls/doors), permanent rigid partitions, doors, anterooms, etc.
2. Control of airflow direction or destination, e.g. through provision of negative or positive pressurisation of a given space relative to other spaces, appropriate location of ventilation grilles for supply and extraction of air to/from a space.

3. Alternatives to conventional mixing ventilation in a given space, e.g. displacement ventilation, personalised local clean air supply, etc.

The deployment of such strategies will be influenced by the type of building concerned, particularly regarding the distinction between the following categories of public buildings:

a) Healthcare settings, such as hospitals and aged care facilities, where the locations of infectious subjects (and vulnerable/susceptible subjects) are usually known, and/or where specific rooms/spaces have been designated and configured for the accommodation of infectious people, and
b) Other settings where it is not known which occupants may or may not be infectious and therefore special accommodation is not provided (e.g. offices, hotels, etc).

Nine studies analysed the impact of constraining spaces or controlling the flow of air for preventing airborne transmission. Eight of these studies were for healthcare settings and one was for office spaces. The main conclusions from these studies are summarised below together with a brief discussion on alternative relevant ventilation systems.

2.2.4.1 Physical constraint of airflow

Healthcare Settings

- Curtains. The use of curtains may reduce contaminated air dispersion within a room to some extent, however, there is relatively limited evidence on this topic. In a study involving booth on-site sampling in COVID-19 hospital isolation wards and CFD modelling, curtains used as a partial-height partition to bisect a 4-bed patient wards so as to mitigate particle dispersion between adjacent patients were evaluated. The curtains were found to be effective in reducing the average particle concentration in the breathing zones of the two adjacent patients by 87% and 52% respectively, but would slightly increase the risk to another patient within the same curtained space[117]. It should be noted that this case study assumed an exhaust/return air grille was located behind the head of each of the four patients, which is not likely to be typical for Australian hospitals.
- Flow through permanent openings. Many existing hospitals have no doors between a ward or room and the adjacent corridor. There is typically a complex bidirectional flow at such permanent openings which plays an important role in bioaerosol transmission from an infectious space to other rooms[118]. The rate of escape and dispersion of contaminated air is dependent primarily on: i) any pressure difference between the ward/room and corridor (e.g.

due to HVAC/mechanical ventilation), ii) temperature differences between the two spaces and iii) the movement of people through the opening. A precise control of pressure of temperature differences between indoor spaces is difficult, and thus closing, or reducing the area, of the openings between spaces was recommended by [118] and is an obvious and effective strategy to reduce infection transmission risk (e.g. using a conventional door or temporary zip wall).

- Doors and zip walls for hospital rooms with infected patients can act as potential barriers for limiting the amount of infectious particles escaping to the corridor or neighbouring rooms[72,119].

Other public buildings

- There appears to be limited high quality evidence as to the effectiveness of barriers such as partial height desk partitions. A rapid review of a number of studies in this area indicated that such barriers are less likely to be effective in mitigating long range airborne transmission as opposed to close proximity transmission from expelled infectious particles[120]. In addition, there is some evidence that such partitions may actually inhibit mixing of cleaner air throughout a space and therefore lead to locally increased risk of infection at some locations in a space.

2.2.4.2 Control of airflow pathways

Healthcare Settings

- In general terms infection risk will be reduced if the local concentration of contamination is minimised in the breathing zone of one or more susceptible persons.
- Installing appropriately located supply and exhaust ventilation grilles for each patient in hospital rooms has been demonstrated to reduce the spread of infectious particles within multi-occupant rooms and between spaces[121,122]. Although such an approach may not be pragmatic in existing hospitals, it could be useful for new designs or retrofits of hospitals. To mitigate this risk, return air grilles/ducts should be placed within the infectious patient's room.
- Often the ventilation return air duct grilles are placed in corridors, as a result patient rooms are positively pressurised relative to the corridor. This will cause infectious particles to escape through openings or gaps around the door or zip wall into the corridor. If this situation cannot be easily rectified in existing buildings through modification to the HVAC/ventilation system, installation in the room of either one or more extract fans to outside ambient, or HEPA air

cleaners exhausting into the HVAC return air ductwork can create negatively pressurised rooms (-2.5 Pa has been recommended[72]).

- It should be noted that sizing of such depressurisation extraction fans should be such as to ensure they do not significantly interfere with the operation of existing ventilation and HVAC systems, or with the operation of doors, zip-walls, etc. It also important to recognise that although they carry a high cost penalty, purpose-built healthcare isolation rooms built to current standards will perform to much higher levels of isolation than general-purpose wards/rooms retrofitted for modest negative pressure.
- Depressurisation of rooms with infectious subjects will also serve to mitigate fugitive contaminated air flows through unintended paths, e.g. lift shafts, stairwells service penetrations through walls/floors/ceilings, etc).
- Opening/closing doors. Even with implementation of moderate depressurisation of rooms accommodating infectious subjects, it is likely that some contaminated air will escape into the adjoining space or corridor when a door is opened and person enters/leaves. Quantitative estimates of the volume of contaminated air released under various scenarios have been estimated from tracer gas laboratory experiments and CFD simulations[123]. The type of doors used has been shown to impact the actual volume of fugitive contaminated air. In laboratory experiments replicating a hospital situation and without ventilation (still air), sliding doors were found to result in less release of contaminated air (from 0.3 m^3 to 2.3 m^3) as compared to hinged doors (1.2 m^3 to 2.4 m^3). The passage of a person through the opening/closing door was also found to cause a significant escape of contaminated air (of order 0.4m^3)[124].

Other public buildings

In most other types of public buildings the location of potentially infectious occupants will not be known. However, many of the strategies used in healthcare settings will also be useful in other situations.

In the case of lecture theatres, classrooms and music rooms, for example, the location of supply and return air registers, or of portable air cleaning units may have significant impacts on infection risk as a function of position within a space containing a large number of occupants – as discussed in Section 2.2.3.

Hotels and other buildings with multiple rooms serviced with access from common corridors are suitable for depressurisation of rooms relative to the corridor, e.g. through utilization of en-suite

bathroom air extraction systems, provided that these are sized, designed and maintained appropriately.

2.2.4.3 Alternatives to conventional mixing ventilation

Traditionally the majority of air-conditioning systems have been designed to utilize fully mixed, or to close to fully mixed, conditions in a conditioned space. However, in recent times displacement ventilation systems have found favour in various situations, particularly those involving cooling. Here cooler/cleaner air is introduced at low velocity and low elevant in a space. Such systems bring about a stable thermal stratification in the space where potentially contamination or infectious particles are transported from breathing zone height to upper elevations in the space where the contaminant can be readily extracted by vents or fans. In a review of ventilation strategies this was found to be effective at reducing the exposure risk[125]. Personalised air supply and exhaust systems have been seen as having potential to reduce airborne disease transmission in situations such as open-plan offices[91]. However, they are generally complex and potentially expensive to install. Some studies have also shown that personalised ventilation can be effective at reducing risk for occupants at their workstations[126,127], but protection is not provided when they are away from their workstations.

Further research and evidence is required on the performance of displacement and other alternative systems in the field, particularly with respect to issues including: the impact of disturbances to the stably stratified space by movement of occupants, etc; blockage of clean air supply by furniture, etc; and the formation of potential stagnant regions in a space where contaminant concentrations are high.

2.3 OTHER STRATEGIES – RELATIVE HUMIDITY CONTROL

The impact of relative humidity of indoor air on airborne disease transmission risk is complex and multi-faceted – it affects several key aspects of the disease transmission pathway including: generation of infectious particles by an infected person, particle evaporation, viability, susceptibility of subjects, etc. However, there is significant variation in the degree of increase or decrease of overall risk for each of such factors relative to changes in indoor relative humidity and a clear relationship with transmission of airborne diseases has not been clearly demonstrated in the literature. The review paper by Bueno de Mesquita et al. covers at least 8 studies that discuss a number of these issues[106].

2.4 INFLUENCE OF HUMAN FACTORS AND PRACTICES

Many of the potential IAQ strategies for reduction in airborne disease transmission risk will be influenced by human factors and the day-to-day practices of people operating or occupying public buildings. It is also important to recognise that different classes of operators or occupants of public buildings will have greater or lesser agency in terms of controlling IAQ and airborne disease transmission in their location – a teacher has much greater agency than a student in a classroom, for example. While this review has found relatively little evidence directly relevant to this topic in the literature, a number of potentially important opportunities for, and barriers to, successful and effective implementation of strategies have been identified, a few of which are summarised below.

In both naturally and mechanically ventilated buildings, where operable windows are present their appropriate use can contribute to dilution of indoor air. A high proportion of school classrooms are naturally ventilated. for example, and generally it will be teachers who operate the windows. Window opening decision making by the teacher, as with other similar public educational building scenarios, will involve a complex balance of priorities including: thermal comfort considerations, perceived air quality in the room (e.g. stuffiness, odours, etc), noise, rain and pollutant ingress from the outside ambient, and potentially energy efficiency and infection risk. Notably, opening windows will generally improve IAQ in naturally ventilated rooms where outside ambient air has lower levels of CO_2 and pollutants - but this will be to the detriment to occupant thermal comfort when the outdoor air has a significantly lower, or higher, temperature than indoors, for example.

A modest body of good quality research literature exists regarding window opening practices in naturally ventilated buildings. However, most studies have focussed on issues of thermal comfort and general IAQ considerations, particularly in residential buildings. An exception is the work of Brager et al.[128] who studied the thermal comfort perceptions of occupants in a single large office building. However, there appears to have been very little research on the direct impacts of window opening decision making to reduce indoor airborne disease transmission risk.

Nevertheless, a study by Stabile et al.[129] has provided useful evidence and insights on this topic with respect to window opening and ventilation in schools. 16 Italian school classrooms were monitored for CO_2 and particulate concentrations during both heating and non-heating seasons and the impact of documented window opening by teachers on these concentrations examined. Other studies have highlighted the importance of educating teachers on good classroom ventilation practices and barriers that prevent optimal operation of windows and ventilation systems[130]. A Swiss study evaluated a human factor intervention whereby opening classroom windows during breaks were found to

significantly mitigate previously high CO_2 concentrations in 23 classrooms[131]. However, there is generally a lack of high quality studies on human factors that influence ventilation strategy effectiveness in reducing airborne disease transmission risk.

It should also be noted that a high proportion of public buildings, such as multi-storey offices, hospitals and hotels do not allow occupants control over window opening or other measures to control supply of outside air. By contrast, key stakeholders that do have influence on IAQ and airborne disease transmission risk in such buildings include architects, ventilation system designers, building facility management (FM) and maintenance staff.

2.5 LIMITATIONS OF EVALUATION METHODS

A number of limitations in the evaluation methodologies used to assess the effectiveness of the indoor air quality strategies discussed in this review question have been identified, some of which include:

- The source of infectious particles was often assumed to be in one location and the indoor environment effectively assumed as static. In other words, most studies assumed no movement of infected or susceptible occupants.
- Most studies assumed one source and type of particle emission and exposure to a number of different particles and their interactions was not discussed.
- The majority of the reviewed studies examined particle exposure but not necessarily disease transmission.
- Nebulizers in laboratory studies have been found not to provide good representations of particles exhaled by humans.
- Due to resource limitations, some in-situ field studies generally are not able to control, measure and report on all the key details that determine the effectiveness of a strategy or intervention as compared to the efficacy determined by modelling or experiment.

Nevertheless, the limitations above should not be seen as a reason for considering the strategies presented in this report as ineffective. This is because the strategies were often evaluated in terms of reductions of *relative* risk of airborne disease transmission, i.e. when compared to a business-as-usual situation. An ideal evaluation scenario for these strategies would require randomised clinical/epidemiological trials. However, such trials involving humans where their activities and health conditions are documented over long periods of time are financially prohibitive and they require careful design, execution, and strict compliance with ethical rules[106].

2.6 CASES WHERE IMPROVED INDOOR AIR QUALITY IS UNLIKELY TO HAVE SIGNIFICANT IMPACT

The strategies described in this report to mitigate airborne infectious disease transmission risk can be ineffective under some specific circumstances. Such circumstances include:

- High numbers of pre-symptomatic infectious (index) people in densely occupied spaces.
- Imperfect design/implementation of the intervention strategy (under-sizing, poor positioning of an air disinfection device, etc) that does not take into account the specific geometric characteristics of the space, the HVAC system characteristics and the expected activities of people within the indoor space.
- Poor maintenance practices. Although more research is needed to evaluate the effectiveness of ventilation equipment (e.g. filters) in terms of filtering infectious particles over long periods of time, it is expected that equipment will need periodic maintenance or replacement.
- In the case of natural ventilation, potential limitations in terms of reliability have been discussed in 2.2.3.
- Specific air cleaning equipment and ventilation infrastructure may require occupant training to ensure effective prevention of airborne transmission (e.g. operation of HEPA air cleaners, windows, fans, etc).
- Some air disinfection equipment technologies may have negative impacts on the quality and safety of indoor air.

3 Can indoor air quality monitoring be used to support reduction in airborne disease transmission?

3.1 BACKGROUND

Whilst indoor air quality monitoring has been widely used to monitor thermal comfort and minimise exposure to toxic or harmful environments, its role in supporting airborne disease transmission reduction has not yet been well established.

The aim of this review question was to investigate if indoor air quality monitoring methods could be used to support a reduction in airborne disease transmission. Within this question, the following sub-points were considered:

- What measures or proxies can be used as indicators for the likelihood of transmission of airborne diseases in public settings or triggers to initiate action to reduce the transmission risk?
- How might the reliability of these factors vary by disease type?
- What are the practical considerations around the feasibility, costs, reliability, frequency, and accuracy of these potential measures or proxies?

The review covers four relevant monitoring methods: direct air sampling for pathogens, background ventilation rate measurements, carbon dioxide (CO_2) concentrations and particulate matter.

3.2 MONITORING METHODS

3.2.1 Air Sampling

Sampling air for the presence of airborne pathogens has been previously used to monitor for the presence of various diseases[132]. However, there is a lack within legislation of formal standardised air sampling methods and strategies for any biological agents[132,133]. Air sampling is hampered by the fact that pathogens are present in very small amounts, requiring sampling of relatively large air volumes[134]. Additionally, there is a time-lag between the sampling process and the production of the test results, thus there are no current methods that will capture and detect in real-time the presence of

infectious particles. However, further research for the development of such real-time detection methods has been recommended by a recent technology foresight study published as part of the European HERA program[135] and funding mechanisms that aim to develop such detection technologies have been recently commissioned in the U.S. under the BREATHE program[136].

A comprehensive summary of the methods used for recovering and testing for airborne viruses has been provided in the literature[132]. The authors reviewed over 100 articles from as early as 1960, categorising the sampling devices used, considerations impacting their effectiveness and how they have been used for various airborne diseases. They identified that the most appropriate detection method may depend on the type of particle generated, and consideration of the particle size – from nanoparticle size to larger airborne particles. Challenges also exist in quantitative analysis, with sampling methods affecting the infectivity of the virus or causing damage to the virus. More recently, systematic literature reviews of air sampling methods used for SARS-CoV-2 detection were conducted by Borges et al.[134] and Silva et al.[137], analysing 25 and 76 papers with qualitative results, respectively. Of these 25 studies in Borges et al.[134], only 15 produced results with positive readings for SARS-CoV-2. It was noted by the authors that results from different methods will depend on the sampling process used, the bioaerosol being tested for, and environmental conditions[134]. In the review of Silva et al. [137], positive results were found across all sampling methods and in a majority of studies. However, only thirteen of the 76 studies assessed viral infectivity and only four detected viable viruses (i.e. by Lednicky et al.[44,138,139] and by Santarpia et al.[43]). The variance across all variables for the sampling methods including media type, air flow, duration etc. highlighted the need for a standardised protocol for air-sampling for SARS-CoV-2.

An overview of the types of air sampling methods employed is provided in Appendix 2 together with a generalised categorisation of these methods. This review has been restricted to studies that were connected with ventilation or indoor air quality monitoring, with a summary of the studies investigated included in Table 5 in Appendix 2. Most of these studies relate to hospital settings[140–142] with outcomes from one study[140] indicating higher concentrations in corridors outside patient rooms, where there is often lower ventilation and airflow. One of the challenges faced by studies investigating actual field measurements is that the presence of pathogens cannot be assured, with many studies having few positive results[133,142–144]. This limits the correlations that can be drawn between other measurement methods and pathogen sampling. We have not found any studies comparing the results of different sampling methods in the same environment to determine their accuracy.

3.2.2 Air exchange rate/ventilation potential

Monitoring air exchange/ventilation potential is a passive sampling method to assess the background ventilation potential of a room or building[112,145]. This monitoring method typically uses a tracer gas such as CO_2[145] or SF6[112] and is used to measure the impact of air flow patterns within a room to assess issues such as the potential risk of disease transmission in areas with minimal airflow leading to high concentration buildup. This can be done in a laboratory experimental setting[112] or in actual rooms[145].

Whilst overall, the air exchange rate has been shown to measure adequacy of ventilation, concerns have been raised from both studies investigated as to the distribution of air flow throughout a room. In the experimental study by Pantelic and Tham[112] it was identified that local airflow patterns were influential on the dispersion of cough particles and associated potential disease exposure. Their conclusion was that *"air change rate should not be used as the sole indicator of the air delivery system's ability to reduce exposure to airborne infectious droplets".* Similarly, Dacunto *et al.*[145] found that whilst increasing the ventilation rate lowered the overall concentration of tracer gas, it did not influence the zones of higher and lower concentration around the room. However, this method is useful for identifying potential areas of greatest risk in a room. In any case, while the methods used to assess ventilation using tracer gas decay will likely give different values for air changes per hour from typical HVAC flow measurements (e.g. using airflow hoods), it may be possible to reconcile the results from both measurements and draw useful conclusions for the ventilation rates of indoor spaces.

3.2.3 CO_2 concentrations (ventilation supply proxy)

Carbon dioxide (CO_2) monitoring has been used as a proxy for ventilation effectiveness for many indoor air quality studies. In many indoor settings, CO_2 levels are determined almost exclusively by anthropogenic metabolism, meaning that they are closely tied to occupancy and exhalation rate[146], in conjunction with outdoor air exchange from ventilation. However, it's important to note that CO2 levels in an indoor space can also be influenced by a range of other sources, such as combustion (e.g. gas cooking, wood-fired heaters etc, as well as from infiltration in areas of heavy traffic where outdoor air may contain vehicle exhaust). Interpretation of CO2 levels should therefore be setting dependent.

Indoor air quality guidelines and standards often include recommended limits for CO_2 concentrations indoors, with high CO_2 levels linked to occupant feelings of lethargy, poor concentration etc. For example, a recently published consensus document recommends specific CO_2 level thresholds[147], however, documents such as this are outside the scope of the present review which is focused on original outputs from evidence-based research.

Sensors for monitoring CO_2 are readily available, low cost and easy to install, and can provide real time instant monitoring. The use of CO_2 sensors for monitoring risk of airborne disease transmission has been less extensively studied. Although it is recognised that higher CO2 concentrations are an indicator of lower outdoor air ventilation and potential for increased risk of transmission, the levels at which the risk is assessed are highly uncertain, and do not generally consider the impacts of filtration, air cleaning and differences between pathogens[148].

The Wells-Riley model[59] was developed for estimating probability of infection from airborne pathogens. This was adapted to consider CO_2 measurements as a means of estimating indoor ventilation levels by Rudnick and Milton[149], however, in recent years many improvements have been proposed to this method including Peng and Jiminez[150], which considered removal rates of CO_2 and airborne pathogens. Further to this, Bazant et al.[151] extended this to consider a safety guideline incorporating aspects of facemask use, filtration, etc. Such models will often not incorporate issues such as spatial and temporal variations in indoor spaces and are sensitive to a number of other parameters as discussed in 2.1.2.1.

Studies investigating the adaption of CO_2 monitoring for measuring the risk of airborne disease transmission appear to be limited, with relatively little evidence provided to support the use of CO_2 as a proxy. Measurements of CO_2 levels ranged from using historical datasets[152], to short single time periods of a few minutes to a few hours[151,153], to multiple days[154–156]. The longest time period studied in the reviewed studies was 21 days[156], or the same time period but spread over 7 months[154].

Only one reviewed study investigated pathogen air sampling alongside CO_2 measurements but all air samples taken were negative for SARS-CoV-2[133]. A more recent study measured CO_2 levels over a period of 2 to 5 days across 100 classrooms in three buildings of a school and found a statistically significant correlation between hours of classroom CO_2 levels >1000 ppm and the annual incidence of SARS-CoV-2 infection[157]. However, one limitation of this study was that it recorded CO_2 levels for a short period (only 2 to 5 days) while keeping windows closed and correlated these measurements with positive COVID-19 cases for a period of a whole year during which ventilation practices, including window opening, between classrooms may have varied. A summary of the main reviewed

case studies where CO_2 monitoring was used for estimating infection risk is given in Table 6 in Appendix 2.

CO_2 monitoring may be useful in situations where high reading can trigger an intervention to improve ventilation, for example – manual operation of windows to increase natural ventilation. When CO_2 levels rise above a maximum threshold, it may be an indication that intervention is likely to be needed to reduce transmission risk.

Due to the availability and accessibility of measurement devices and interpretation of results, CO_2 monitoring has been accepted as a proxy for fresh/clean air supply. However, it is important to note that the interaction between CO_2 and airborne pathogen transmission can be impacted by a number of external factors including:

- Spatial variation of virus transmission in the space – CO_2 concentration is known to show wide variation across a room, with tracer gas tests demonstrating that concentration levels can build up within rooms in certain locations[145]. This implies that multiple sensors may need to be used for reliable results[155].
- Dependence on activity level of people in room and how this impacts measurements[152].
- Impacts of outdoor air concentration levels[152,154] and seasonal variation[155].
- The impact on pathogen transmission of removal mechanisms such as filtration (e.g. via facemasks), sedimentation and deactivation[151].
- Reliance on the assumption of well-mixed air in a room, and uniform distribution of aerosols[153].
- Only suitable in steady state situations and not for cases with high rates of movement or coming/going of people[153].

3.2.4 Particulate Monitoring

Particulate matter (PM) in the air is often used as a measure of air quality, as small particles from air pollutants can have harmful health effects particularly on the respiratory system. Particle levels are typically reported based on the size fraction of fine particles measured, such as PM_{10} (particles <10µm) or $PM_{2.5}$ (particles <2.5µm). Aerosol particles are also generated during human activities such as breathing, talking and coughing and can therefore be related to the transmission of respiratory diseases through dispersion of infectious particles[158]. The measure of particulate matter can therefore

be correlated with potential risk of disease transmission[146], with the level of particulate generation from talking found to be on average three times that of normal breathing in this study.

Studies have shown a link between increased particulate matter concentration from air pollution and SARS-CoV-2 infection and severity[159] particularly for PM2.5. Therefore it is useful to monitor particulate levels to ensure good indoor air quality and reduce risk from exposure to pollution levels. However, it is also recognised that outdoor particulate levels from pollution can negatively impact indoor levels, particularly when there is increased natural ventilation without filtering. Variations in outdoor particulate levels can therefore limit the usefulness of indoor PM levels as a measure of potential disease transmission from indoor sources[154,160].

A summary of the six studies identified in the literature review which have used particulate monitoring to identify risk of airborne disease transmission is given in Table 7 in Appendix 2.

Whilst particulate matter is important for measuring indoor air quality, the use of this monitoring to assess the potential for disease transmission is confounded by the influence of alternate sources of the particulate matter than human generation. This can include:

- People movement and clothing[154,161].
- Activities of occupants such as talking[146].
- Use of chalk on blackboards in schools, cooking from cafeterias and use of disinfectant sprays[154].
- Outdoor pollution[154,160].

3.3 RELIABILITY OF MONITORING FOR DISEASE TYPE

The majority of studies reviewed on the use of CO_2 as a proxy focused only on COVID-19. Although monitoring CO_2 has been used as a proxy for ventilation adequacy for a long time, the link to airborne disease transmission has only been utilised in recent years.

Applicability of monitoring to assess for particle disease risks can be highly dependent on the disease being monitored for. Actual transmission risk calculations involve considerable uncertainty regarding critical viral load, relative susceptibility and quanta generation[151]. Whilst uncertainty around some of these parameters can be reduced as understanding and experience around the disease increases, this will limit the applicability of these methods to new airborne diseases until more detailed information is known about them.

Assumptions in infection risk models (e.g. Wells-Riley) are applicable for airborne transmission (long range exhalation/inhalation of infectious particles), rather than short range direct deposition of expelled infectious particles on a susceptible person or surface contact[153]. For those diseases with multiple transmission pathways, CO_2 monitoring may not capture the full risk profile. However, there are not currently respiratory viruses where existing evidence suggests significant transmission via fomites and there is no clear evidence in recent literature that suggests short range direct deposition transmission is the primary mode of transmission for the most well-known viruses.

4 Impacts of strategies to improve air quality for reduction in airborne disease transmission on the energy efficiency of buildings

This chapter reports on the impact on energy efficiency of IAQ strategies identified that potentially reduce transmission risk of airborne diseases in indoor public spaces. It also includes a brief discussion on how actions to improve energy efficiency of public buildings can impact the risk of transmission of airborne diseases in these spaces.

4.1 IMPACT OF POTENTIAL INDOOR AIR QUALITY STRATEGIES TO REDUCE TRANSMISSION ON ENERGY EFFICIENCY

4.1.1 Portable HEPA air filters

Portable HEPA air filters can be viewed as additional appliances from the energy use point of view. While these systems will impose a slightly higher heat load on HVAC systems, they will not significantly affect the operation of the HVAC ventilation/air delivery system. The clean air delivery rate (CADR) of the HEPA air system, which would typically be dependent on the volume of the space it serves, will largely determine its energy use. For example, Uhde et al.[67] proposed the use of two portable HEPA filters, each consuming 55W of power at maximum speed (model: Phillips 300i) for a classroom roughly 34 m^2 in floor area. In another study of German kindergartens[68], a range of HEPA filter units (which also included UVC disinfection) were used depending on the size of the room, with an average power consumption of 0.9-1.35 W/m^2 (model: DEMA-airtech AP-1500). Whilst annual energy consumption per unit floor area of classrooms can vary depending on climate and building characteristics, an average energy intensity of 38 $kWh/m^2/yr$ has been found for existing Australian primary schools[162]. Using this average energy intensity value, a potential increase in the energy use of an average 75 m^2 classroom of 8.5% can be calculated for the first study (2x 55W system) and ~6% for the second study (1 W/m^2 system). Both calculations assume an 8-hour operation of the HEPA portable systems at maximum speed and for 40 weeks per year. A minimum 1 W/m^2 system also aligns with the guidance the Victorian government provides for the use of portable HEPA systems in schools (i.e. a 90 W system is recommended to be used in an up to a 90 m^2 class)[163].

In a healthcare setting, one study tested 2 x 60W HEPA filters (model Samsung AX5500K) for a 12.8 m^2 patient room[119]. This implies a 9.4 W/m^2 energy use, which is much greater than the previously mentioned systems for schools. Energy intensity of hospitals vary greatly between geographical areas and types of facility. Taking an approximate value of 400 $kWh/m^2/yr$ that is closer to the energy use of Australian hospitals in capital cities[164], and assuming that that the above 2 x 60W HEPA air cleaners are covering 12.8 m^2 wards and are running 24 hrs per day for the whole year, the energy intensity of this single room would increase by 20.5%. However, it is important to note that these portable HEPA devices would not be needed across the entire hospital.

4.1.2 In-duct filtration

Installing additional filters in existing HVAC system ducts or upgrading from typical filters to high-efficiency filters such us MERV-13 or HEPA, will increase the airflow resistance and the pressure drop through the filter. In order to maintain the same supply air flow rate, the fan speed will need to be increased and as a result the fan power consumption will increase. Some existing systems may not be able to increase the fan speed, and thus there will be a reduction in the supply air flow rate if a higher resistance filter is installed. In these cases, a lower supply of outside and recirculated indoor air will typically also imply lower supply rate of outdoor air. This may have detrimental impacts on some aspects of indoor air quality such as CO_2 and VOC concentration, even though the improved filtration efficiency will most likely reduce the concentration of particulates. On the other hand, for systems with no fan speed control, as the air flow decreases there will be less outdoor air supplied indoors. Upgrades to air filters for ventilation systems with no fan speed control may therefore not be a feasible option for practical implementation.

Example evaluations of filter upgrades in relation to changes in energy use are given in Table 1. It can be seen that most reviewed studies were done in US where a wide range of HVAC systems are common in commercial buildings. The results from these studies show that while fan energy increases by approximately 6% to 18% when upgrading to a MERV-13 filter, the impact on the overall building energy use would typically be less than 3%. Upgrading to HEPA air filters was investigated in one of these four studies and there was a significant energy penalty of 63% for the fans and 12% for the overall building. However, it must be emphasised that the increase in energy use for variable speed fan systems will depend on building characteristics, HVAC type, climate, hours of operation of the HVAC systems and the increased pressure drop resulting from the upgrade to a more efficient filter.

Further studies are needed that research filtration upgrades in the Australian context (climates and building and system typologies).

Table 1: In-duct filtration upgrade studies and associated changes to building energy requirements.

Ref.	Methodology	Filter upgrade type	Climate & building type	Energy penalty
[165]	Field measurements (pressure drop) & combination of simulations and field measurements (energy)	From MERV-8 to MERV-13, and MERV-14.	Austin, Texas, USA – retail stores	Replacing MERV8 with MERV13 or MERV14 in units with fan speed control can increase fan power draw during all modes by 11–18%. Changes to the energy use of the cooling system and the overall building energy use were minimal.
[166]	Simulations	From MERV-10 to MERV-13, and HEPA.	Denver, Colorado, USA (cold and dry climate) - office	Compared to MERV10, MERV 13 and HEPA filtration increased the total site energy consumption by about 3% and 12%, respectively. Fan energy used increased by 11.8% and 63% for the MERV13 and HEPA cases, respectively.
[167]	Simulations	MERV-8 to MERV-13	13 US cities (different climate zones) classrooms	Upgrade to MERV 13 filtration led to 6% increase in fan energy for all flow rates across all locations. Total annual HVAC electricity consumption with MERV 13 increased by 0.7–2.7%.
[168]	Simulations	MERV-9 to MERV-13 (assumed pressure drop increase of 100 Pa)	15 US Climates – US commercial building stock	On average, across the US commercial building stock: 0.8% increase in annual HVAC energy use, made up from a 1.4% increase in electricity, primarily from fans, and a 1% reduction in gas consumption for heating. The reduction in heating requirements is due to an increase in parasitic losses (waste heat) from the fans adding heat to the air stream.

4.1.3 Ultraviolet-C (UVC) lights

Similarly to portable HEPA air cleaners, the energy use of UVC light systems will depend on their size/rating. While sizing these systems for specific spaces is outside the scope of this review, effective air treatment may require multiple disinfecting devices in all occupied spaces. Noakes et al[79] calculated that the effectiveness of a 36 W wall-mounted system will vary depending on the area it covers. By way of example, when assuming a 36 W system in a 30 m^2 communal kitchen space of a hospital that consumes energy in line with the previously mentioned average energy intensity of 400 $kWh/m^2/yr$, the addition of one 36 W device that operates 24 hrs per day will result in a 2.6% increase of the energy intensity of the kitchen space. This value will be negligible if only one device is installed

across the whole hospital, but it will be representative of the hospital's energy use if all hospital spaces have the same UVC system installed in every 30 m^2 as per this example.

UVC disinfection has also been proposed for use in existing HVAC ducts to avoid potential risks from the use of in-room UVC units. The effectiveness of in-duct UVC is dependent on sizing, energy intensity, duration of exposure and ventilation air exchange rate in the space. The positioning of the UVC lamps in relation to the heating and cooling coils also impacts their effectiveness, as well the energy requirements of the unit. Building energy consumption will be impacted in four different ways: i) direct energy consumption for lamps, ii) increased cooling energy consumption as the heat from the lamps is dissipated in the air stream, iii) decreased heating energy consumption due to the added heat from the lamps, and iv) changes in fan power consumption due to changes in supply air temperature and additional pressure drop caused by the UVC system in the moving air stream[169].

The energy impacts of UVC disinfection methods are highly variable and dependent on the UV lamps used and their setup. One study[105] reviewed 24 different UV systems designed for in-duct systems and estimated their energy performances. Inadequate inactivation efficiencies were reported for a number of these systems. Of those with an inactivation efficiency greater than 99%, the UV dosage varied between 6.33 and 70.57 J/m^2, with the total annual energy consumption ranging from 613.2 to 120,428 kWh. There was no direct relationship between the UV dose and the energy consumption, as the dose was impacted by the reflectivity of duct internal surfaces and the lamp type/arrangement.

4.1.4 Dilution of contaminated indoor air with cleaner air - Mechanical and natural ventilation

Increasing the amount of outdoor air that is supplied into buildings can be achieved through natural ventilation (opening windows) or by increasing the supply of outdoor air in mechanical ventilation systems. Although there is no additional equipment requiring extra energy in either scenario, there is a significant impact on the energy consumption of the HVAC system, due to the additional energy required to condition the outdoor air to the required indoor comfort conditions (temperature and in some cases, relative humidity). The variables that define the additional energy needed to condition outdoor air are the HVAC system efficiency (or Coefficient of Performance), the additional amount of outdoor air (i.e. mass flow rate), and the difference between outdoor and indoor air temperature/enthalpy (which is climate dependent and varies with time).

In summary, increasing the supply flow rate of outdoor air can significantly increase cooling or heating energy consumption when the outdoor air temperature differs greatly from the room temperature setpoint. It may also lead to less satisfactory thermal comfort as most HVAC systems are not sized for higher outdoor airflow rates than those they were designed for. Specific examples from previous studies that have quantified additional outdoor air conditioning energy requirements with natural and mechanical ventilation are included in the following sections.

4.1.4.1 Increased supply of outdoor air – natural ventilation

The impact on building energy consumption of increasing fresh air supply to indoor spaces through natural ventilation will be highly dependent on the local climate of the building and the required indoor thermal environment. Natural ventilation is often regarded as a key strategy for improving energy efficiency, particularly for reducing cooling requirements in warmer or temperature climates, although it is less effective in heating dominated climates. A modelling study on university buildings in Brazil[170] noted that by maximising the use of natural ventilation and not enabling the cooling system while the temperature outside was less than 26°C, energy consumption was reduced by 7% to 9%. It should be noted though that this type of modelling studies typically assume optimal operation of windows during periods when outside conditions are favourable and may ignore any other external parameters that could affect their operation (outside noise, rain, distance of occupants from the windows, strong breezes, etc.).

However, the use of natural ventilation purely for increasing the amount of fresh air regardless of outdoor conditions can have a negative impact on either or both of the thermal comfort of the indoor environment and energy efficiency if the indoor air is to be conditioned by an HVAC system. Analysis of energy consumption across schools in Japan pre- and post-COVID-19 periods[171] found that energy use of HVAC units increased by between 50% and 340% in summer and 10% to 440% in winter as a result of changes to the way they were operated in concert with natural ventilation. Whilst part of this increase was due to increases in operating duration (which on averaged increased by 50% in both summer and winter), it was largely linked by the authors to the operation of the HVAC systems in simultaneous combination with natural ventilation, with the thermostat temperature often adjusted to meet thermal comfort requirements in the classrooms. This study concluded by recommending against the combined and simultaneous use of HVAC with natural ventilation due to the negative impact on energy use and thermal comfort. This was supported by another study from Japan[172] which found a 7% deterioration in energy efficiency across schools following the implementation of COVID-19 guidelines on the use of natural ventilation.

4.1.4.2 Increased supply of outdoor air – mechanical ventilation

There have been a number of studies investigating the energy penalty from increasing the fraction of outdoor air delivered by HVAC systems to rooms across a range of public buildings. The majority of these studies relate to educational buildings[173–175], while other studies have focused on office buildings[168,176–178]. Increasing outdoor air supply can impact the energy consumption of the HVAC system in two ways:

1. Increased fan energy if the total ventilation flow rate is increased, and
2. Increased energy for conditioning outside air to the required thermal comfort setpoint.

Most HVAC systems serving public buildings mix the required quantity of *outside air* with *recirculated air* from interior spaces - then condition (heat or cool) this mixture and return it as *supply air* to the spaces concerned. Increases to the energy consumption from increasing the ratio of outdoor air to total supply air will depend on the outdoor conditions at the building location. In an estimate of the impacts across six cities in USA[177] of increasing the outdoor air ratio from the baseline of 10% to 25% resulted in an increase in cooling energy demands ranging from 6% to 26%. With the outdoor air ratio increased to between 80% to 100%, the cooling energy demand for the buildings in various cities of the study increased by 29% to more than 215%.

Another study looking at the impact of various changes to ventilation systems of the commercial building stock in USA[168] found that using 100% outdoor air had the largest impact on annual HVAC energy consumption (24.5% increase of the total annual building energy consumption) when compared to other interventions such as the installation of higher efficiency filters. This impact varied significantly with climate, with cooler climates more substantially impacted. A similar comparison between upgrading filters versus introducing 100% outdoor air in the Colorado (USA) climate found that the outdoor air option would lead to a 54% increase in annual energy while upgrading to MERV or HEPA filters would lead to a 3% and a 12% increase, respectively[166]. Overall, the topic has been well-researched in American climates by utilising building energy simulations and other authors (e.g. [167]) found similar increases in energy use from the introduction of additional outdoor air to building spaces.

Mechanical ventilation systems offer a further advantage over natural ventilation as they present inherently more opportunity to be controlled. This has led to studies investigating the potential use of more specialised control systems such as ‘demand control ventilation’. Here indoor CO_2 levels are monitored and used to control the outdoor airflow required[174] to ensure that chosen CO_2 thresholds are not exceeded. Similarly, radiant cooling[177] and the use of heat recovery ventilation systems to

minimise the negative impacts of increased outdoor air supply has been investigated. However, demand control ventilation using CO_2 levels as a sensing parameter is not always an effective means of control for airborne disease transmission as discussed in Section 1.4.2.3, where an outbreak caused by such a system using only recirculated air during periods of low indoor CO_2 levels (<1000 ppm) is described.

4.1.4.3 Flushing before and after periods of occupation

In some cases, recommendations for operating HVAC/ventilation systems beyond occupied hours have been instituted to reduce airborne disease transmission risk, with a particular focus on 'flushing' of the air in the building for a 2-hour period pre- and post-occupancy. This approach will impact energy consumption directly due to the increased operational time required. One study on ventilation systems in the USA commercial building stock[168] found that operating the HVAC system with a 2-hour pre- and post-occupancy ventilation flush period resulted in consumption increasing by18.3% for gas and 4.3% for electricity. This was due to the energy required to condition the additional air, as well as the energy for operating the fans for an additional 4 hours per day.

4.1.5 Control of contaminated air dispersion

Strategies proposed for the control of contaminated air dispersion such as the use of partitions and curtains between spaces will have minimal impact on energy as there is almost no direct influence on the HVAC system. However, adding extract fans to convert spaces to negative pressure relative to their surroundings will increase energy use in a similar way to that of portable HEPA cleaning units discussed in Section 4.1.1. The size of these systems is important and will define their effectiveness and the energy use during operation. For example, in one study the use of portable HEPA filters exhausting to outdoor air were used to induce a negative pressure[72] within particular rooms. The units specified required 1118W of power for operation in a 25m^2 room. This is approximately ten times the energy of the smaller HEPA portable systems discussed in Section 4.1.1. In another study[179], personal suction ventilation was proposed at individual desk locations to remove pathogens. When this was compared to increased mechanical ventilation to achieve the same reduction in infection risk, it was found to reduce energy consumption by 30%. However, it was noted that this saving is highly climate dependent, with other similar studies in cold climates demonstrating increased energy consumption of between 61% to 268%, and studies from warmer climates experiencing energy savings of up to 51%.

4.2 IMPACT OF ENERGY EFFICIENCY STRATEGIES ON INDOOR AIR QUALITY AND AIRBORNE DISEASE TRANSMISSION

Energy efficiency retrofits of the building envelope and the integration of renewable energy technologies in buildings are generally not expected to affect indoor air quality (in relation to airborne disease transmission). However, modern HVAC systems may be controlled in ways that reduce the supply of air for energy saving purposes and in this case the risk of airborne disease infections will increase. Examples of such systems include temperature or CO_2-based demand-controlled ventilation and some Variable Air Volume (VAV) systems. In all cases, the control of these systems needs to be reviewed against the provision of fresh air supply during occupied hours.

Airtightness improvements can be another energy efficiency upgrade that will result in lower amounts of outdoor air entering building spaces. However, building spaces are not designed to be ventilated through uncontrolled leakages of air from the building envelope, but instead, they are meant to be ventilated using windows or mechanical ventilation systems.

5 The impact of airborne diseases on the economy, and human health and wellbeing

5.1 BACKGROUND

The aim of this review question was to investigate the impact of the transmission of airborne diseases in indoor public settings on the economy, health and wellbeing. It therefore covers the wider socio-economic impacts of airborne disease transmission in public buildings, particularly in high-risk settings such as: educational, healthcare, workplace, childcare, aged care, recreational and public transport buildings.

A key aspect that was specifically excluded from the scope of this review was the impact on mental and social well-being because of restrictions due to public health efforts to reduce the transmission of airborne diseases.

Given that the review question is very broad in scope, this chapter briefly reviews some of the key reported direct and indirect impacts across socioeconomic impact categories (Figure 4). The airborne diseases considered in the studies reviewed were SARS-CoV-2 (predominantly), as well as influenza, influenza A (H1N1), and SARS-CoV-1, resulting in a variety of disease symptoms, including influenza like illness (ILI), febrile illness, pneumonia, and COVID-19.

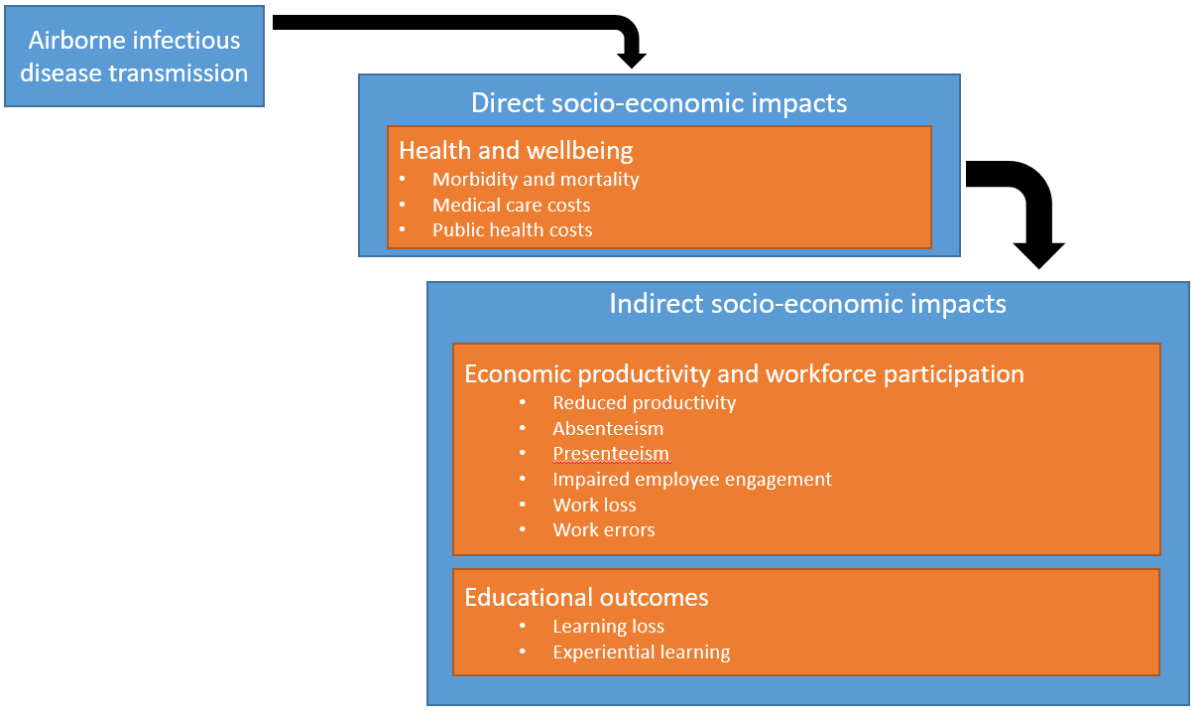

Figure 4: Framework for socioeconomic impacts.

5.2 IMPACT CATEGORIES

Impacts can be broadly categorised as either direct or indirect (Figure 4). Direct socioeconomic impacts focus on the health sector, particularly the healthcare and public health costs associated with disease from infections[180]. The other focus areas for this review question (economic productivity and workforce participation, and educational outcomes), are indirect impacts of disease outbreaks. Attributing these impacts to transmission in public buildings rather than homes or other personal settings is difficult. These impacts are therefore discussed under the general assumption that a proportion of airborne infections in the past have occurred in public buildings.

5.2.1 Health and wellbeing

5.2.1.1 Morbidity, mortality and associated costs

The primary health impacts from airborne disease transmission are the morbidity and mortality effects suffered by those infected. As an example, during a regular winter influenza season in Australia, between 5 - 20% of the population can become ill, however, this morbidity rate can rise to 30 - 50% of the population during severe influenza A epidemics[181]. Approximately 1,000 adults and children

die from influenza each year in Australia[181]. From 2010 through 2018 there were an estimated 964 influenza-associated respiratory deaths per year (4.03 per 100,000 population) [182]. This rose to an estimated 3024 deaths (13.57 per 100,000) in the severe influenza season of 2017[182]. These numbers were lower than those reported in another Australian study by Newall et al.[183] who concluded that influenza is responsible for a much higher number of hospitalisations and deaths of Australians aged ≥50 years than the deaths or hospitalisations that are formally reported as being caused by influenza. This was particularly evident in the age group ≥65 years where a significant association was found between influenza activity and circulatory mortality. The authors postprocessed data from the National Hospital Morbidity Database (NHMD) for the period July 1998-June 2005 and data from the National Mortality Database (NMD) for the period January 1997-October 2004 and estimated annual excess hospitalisations attributable to influenza of 33.3 (95%CI: 23.2-43.4) and 157.4 4 (95%CI: 108.4-206.5) per 100,000 for Australians aged 50-64 and ≥65 years, respectively. The annual excess all-cause mortality attributable to influenza was 6.4 (95%CI: 2.6-10.2) per 100,000 and 116.4 (95%CI: 71.3-161.5) per 100,000, for Australians aged 50-64 years and those aged ≥65 years, respectively.

Additionally, a study of the 2007 influenza epidemic in Hong Kong found that the average equivalent loss of days of perfect health per person per year was 10.7 days[184].

Between the start of the COVID-19 pandemic (11 March 2020) and 31 July 2023 there were 19,150 deaths registered and received by the Australian Bureau of Statistics (ABS) where people died with or from COVID-19, and COVID-19 was the underlying cause of death for 15,460 of these people[185]. The impact of COVID-19 on life expectancy was quantified in U.S. by the National Center for Health Statistics[186] for the most recent years. The analysis of death records from complete life tables (i.e. tables that include data for every single year of age) found that life expectancy in 2022 increased by 1.1 years compared to 2021 as a result of decreases in mortality due to COVID-19 (84.2% of the positive contribution). However, this increase was less than the loss of 2.4 years of life expectancy between 2019 and 2021 that was mostly attributed to increases in excess deaths due to the COVID-19 pandemic[186].

Vardavas et al.[187] summarised two studies that quantified the cost of lives lost due to COVID-19 during specific periods during the pandemic[188,189]. While the methodologies and results in both studies differ, the calculated costs of lives in both studies was substantial.

5.2.1.2 Medical care costs

Medical costs related to direct health impacts include ILI-related medical, inpatient, outpatient, physician office, emergency department, pharmacy, ancillary care utilisation and costs[180]. Between 2002 and 2004, upper respiratory tract infections accounted for more than 6 out of every 100 clinical presentations to GPs in Australia[190]. A US study from 2013 found that during influenza epidemics in the US the average per-patient influenza-related medical cost (ILI-related medical, inpatient, outpatient, physician office, emergency department, pharmacy, ancillary care utilization and costs) ranged from USD239 to USD301[191]. Examples where COVID-19 related medical costs have been analysed are summarised in the following paragraphs.

- Costs of the chronic impacts of COVID-19 were discussed in the following studies:
    - a comparison of monthly healthcare costs of approximately 170 thousand patients who contracted COVID-19 in Israel after splitting them into long COVID and non-long COVID cohorts[192]. It was found that the average monthly healthcare costs per person for the non-long COVID cohort increased slightly (7.5%) at the 12-month follow-up compared to pre-infection, whilst for the long COVID cohort, direct health care costs doubled (USD2,015 to USD3,989 per patient) compared with pre-infection. However, it should be noted that large standard deviations were recorded in this analysis, which implies a highly variable associated cost for specific patients that may not be purely associated with the contraction of a SARS-CoV-2 infection.
    - Based on an analysis of a database with records from approximately 470,000 patients in the UK, it was found that the annual incremental cost of primary care consultations associated with long COVID was £2.44 per patient[193]. This cost increase was about 44% higher than in patients without long COVID symptoms and it should be emphasised that this only includes consultation costs and it excludes any hospitalisation or other medical costs.
    - Medical costs at 1-, 3-, and 6-month intervals post-infection were found to be 46% to 82% higher for commercially insured COVID-19 patients in the U.S. compared to non-COVID-19 patients[194].
- Four relevant studies were also summarised in a review by Vardavas et al.[187]:
    - Medical costs among 145 hospitalised children with COVID-19 in Korea[195] were found to be more than €252k in total, with more than 60% of the total cost being

attributed to the 54 older patients of age 16 to 19 years (€2,903 on average for the 16-19-year-old patients for a mean hospitalisation period of approximately 10 days).

- An analysis of hospital costs related to approximately 174,000 COVID-19 patients in the U.S. found typical (first quartile-third quartile) hospital costs between USD6,309–USD25,361 and hospital charges to patients exceeded the hospital costs by a factor of three[196].
- A cost-analysis of COVID-19 patients in Turkey showed that the mean cost per ICU patient was €2,322 for mean hospitalisation days of 14.7 compared with €700 for nine mean hospitalisation days for non-ICU COVID-19 patients[197].
- Using Monte Carlo simulations at the start of the pandemic, when no vaccines were available, Bartsch et al.[198] estimated that if 20% of the U.S. population were to be infected with SARS-CoV-2 over the course of the pandemic (without accounting for reinfections), the total medical costs would have been €129.8 billion and reaching €170.3 billion when accounting for post-discharge costs after 1 year. The same metrics reached an estimated €519.4 billion, and €682.6 billion, respectively, if 80% of the U.S. population were to be infected.

- A review of 31 studies of COVID-19 hospitalisation costs globally by Gholipour et al.[199] (which did not include estimates from Australia) reported that total costs of ICU hospitalisation per patient varied significantly between countries from USD5,437 in Romania to USD100,789 in Germany. For hospitalisation in general wards, the highest total cost per patient was USD28,918 in a study from Saudi Arabia (assuming no use of Mechanical-Ventilator), while the lowest cost of hospitalisation was reported in Iran as USD1,640 per patient.

5.2.1.3 Public health costs

Previous studies have noted many impacts of the COVID-19 pandemic on health systems globally, including the reallocation of resources, conversion of facilities such as surgical intensive care units and wards to COVID-19 facilities, and increased risk of nosocomial transmission of the virus to patients[200]. This leads to reduced accessibility, quality and outcomes from healthcare. On a broader public health scale, measures taken to control the spread of COVID-19 included: lockdowns, closure of borders, restriction of free movement, travel bans, temporary shutdown of organisations, screening of workers and visitors, quarantining of workers, physical distancing measures, use of partition

barriers, infection control and disinfection of work areas, infectious disease-related training, provision of personal protective equipment and hand sanitizers, and surveillance[180].

5.2.2 Economic productivity and workforce participation

Reported economic impacts from airborne disease outbreaks are commonly related to impacts on the workforce. Reported impacts include: reduced productivity largely related to absenteeism and presenteeism, declines in employee engagement, sick leave costs to employers, and working errors. There are potentially many other broader impacts on the economy that are not discussed in this section, such as COVID-19 pandemic impacts on employment. These include reduced pay, employees being furloughed, and retrenchment of workers[180]. A summary of the economic productivity and workforce participation impacts of COVID-19, seasonal influenza, H1N1 and SARS-CoV-1 is provided in Table 2.

Table 2: Summary of some studies on productivity and workforce impacts from airborne diseases.

	Influenza (including H1N1)	**SARS-CoV-1 & SARS-CoV-2**
Productivity[180,201–213]	58% - 74% relative productivity loss[213]. In the US, Average work loss and flu-related productivity loss was US$137 per person[212], and US$42,581 per 100,000 health plan members.[191] In Hong Kong, lost productivity due to influenza was estimated at US$152.pp/yr.[184]	Many workers in different settings reported productivity decreases[204,206,207]. Estimated 49% productivity loss [180,201–211].
Absenteeism[212,214–225]	1.3 - 2.8 workdays missed[212,216]. Avg. 14.0 - 23.9 work hours lost per employee[218,219]. 800% increase in absentee rate during epidemics[225] 30% of people with influenza diagnosis have >1 day of work absence due to ILI[191]. 3.73 workdays missed (H1N1)[223]. Avg. 25 work hours lost per employee (H1N1)[218].	Increase absenteeism[220,222]. 4.9 cases of sick leave per 1000 workers (in Mar 2020) This is double the rate of sick leave in 2017, 2018 and 2019 (2.5 cases/1000 workers)[221]. Mean duration of absence 25.8 days for HCW in Greece[224]. 1.4 missed work days/100 staff days observed (SARS-CoV-1)[226]. Short and long term absences from work for 110,868 COVID-19 cases were costed approximately as €114m (€1029 per case)[227]. Permanent losses due to premature deaths were estimated at approximately €333m for 3926 deaths (€84,836 per death)[227].

	Influenza (including H1N1)	SARS-CoV-1 & SARS-CoV-2
Presenteeism[21,4,216,217,228,229]	Average of 2.5 hours lost per day with ILI symptoms[217], 4.8 hours total. Reduced effectiveness reported for 3.5 days following return to work after ILI[216]. Illness reported to have had an impact on their work by 73% of participants[216].	30% - 55% of healthcare workers, and 26% of university staff[229] reported presenteeism.
Employee engagement[204,230–232]	-	23% of workers doubted their medical vocation. 21%-65% had moderate to very serious considerations about leaving the workforce[204,230–232].
Work Loss (sick leave)[221,233]	Sick leave costs increased by 67% during influenza epidemic[233].	Increased sick leave translated to 40% increase in costs per worker[221].

Other economic impacts have been discussed in terms of school closures, particularly in relation to parents being unable to work to care for their children at home. Pre-COVID-19 studies on the economic costs of school closures in response to influenza pandemics estimated the costs to be from 0.2% to 1% of British GDP for a 12-week school closure period[234] and 6% of US GDP for a 26-weel closure period[235]. However, the results of these economic studies are strongly dependent on the assumptions made in the models used to derive them.

5.2.2.1 Reduced productivity

A large-scale review of socioeconomic impacts from airborne diseases found that across multiple industries workers became less productive and efficient at work[180]. This was quantified as a 49% reduction in productivity during the COVID-19 pandemic[180,201–211]. Impacts on healthcare workers were frequently studied, with similar findings.

Research focused on influenza in 14 zip code areas of the USA found it was significantly associated with workplace productivity loss over 7 to 17 days following the onset of symptoms in 1278 employed adults, with no significant difference between virus type/subtype or seasonal vaccine status[213]. Regardless of vaccination, participants with H1N1, H3N2, or B infection had the greatest mean productivity loss (67% to 74%), while those with non-influenza ARI had the lowest productivity loss (58% to 59%)[213].

Average costs of reduced productivity due to seasonal influenza have been calculated in 2013 at USD137 per person in the USA[191], and in 2008 at USD152 per person per year in Hong Kong[184].

However, these costs are highly variable and can be case-specific. More recent studies are needed to associate productivity costs with airborne disease infections.

5.2.2.2 Absenteeism

A key impact on economic productivity is absenteeism. Exposure to airborne diseases results in an observed absence of workers from their workplace[212,214–218,220,223]. Average workdays missed due to seasonal flu range from 1.3 - 2.8 workdays, whilst epidemic diseases had greater impacts on workforce participation than seasonal influenza[223,224,233]. During the H1N1 influenza epidemics, workdays missed increased to 3.73 due to ILI in Australia[223], whilst the overall labour supply decreased by at least 0.2% in Chile[225]. In Greece, workers who contracted COVID-19 missed an average of 25.8 days[224]. Research specific to Australia suggests that an association exists between the peak in seasonal influenza activity and absenteeism[181]. In 2000-2001, influenza was responsible for 9,825 hospital days, although this includes non-workers also[181]. In another study of national records of SARS-CoV-2 in Greece, 1332 healthcare workers exposed to COVID-19 patients had a mean duration of absenteeism of 7.5 days, and 252 healthcare workers who contracted COVID-19 had a mean duration of absenteeism of 25.8 days[224]. The total costs for the management of the two groups were estimated at approximately €1.7 m, with absenteeism accounting for approximately 80% of this cost.

Groenewold et al. specifically looked at absenteeism amongst occupational subgroups in the US at the start of the COVID-19 pandemic (April 2020), finding that the absentee rates amongst a wide range of occupations significantly exceeded their occupation-specific epidemic threshold[236].

Table 2 summarises data on absenteeism due to airborne diseases and the associated impact on productivity.

5.2.2.3 Presenteeism

Lost productivity can arise when workers are not working to full capacity in their workplace as a result of an injury, illness, or other impairment. This is also known as presenteeism and has been reported in multiple studies amongst workers during SARS-CoV-2, influenza and H1N1 outbreaks[214,216,228,229,237]. Details are provided in Table 2.

5.2.2.4 Employee engagement and wellbeing

Research on COVID-19 found healthcare workers, including those in surgery[201], neonatal[205] and oncology[231], found decreased motivation levels at work. Exposure to patients with COVID-19 has

also been reported as being significantly associated with higher burnout rates in physician trainees, with exposure to more patients increasing the burnout rate[238].

A 2020 survey of teachers in NSW found significant decreases in morale and efficacy during the pandemic, with participants feeling dispensable and unappreciated [239]. The teacher efficacy metric includes sub-categories on student engagement, instructional strategies and classroom management.

5.2.2.5 Work loss

Increased use of sick leave during the initial stages of the COVID-19 pandemic in Spain was estimated to cost on average USD4,374. per 100 affiliated workers across industries[221]. A comparison of sick leave costs in a US hospital during an influenza epidemic compared with a baseline found absenteeism increased by 70%, and sick leave costs increased by 67% during the epidemic peak[233].

5.2.2.6 Work errors

Quality of work can also be impacted, with 12% of 288 surveyed Californian healthcare workers reporting increased medical errors[205].

5.2.3 Educational outcomes

Studies reviewed on the impacts of airborne diseases on educational outcomes have predominantly focused on the COVID-19 pandemic, and in particular on the significant disruption to normal education processes, the impacts of school closures and the switch to online or at home learning, rather than direct impacts from the disease[240,241]. School closures are also noted to have occurred in the US during the 1918-19 influenza pandemic[242], and in reaction to seasonal and pandemic influenza at other times, e.g. between 2011 and 2019[243]. Reviews of empirical studies that measure the impact of COVID-19 on student learning in comparison to pre-pandemic data have found evidence of negative impacts on student achievement[244,245]. Patrinos et al. reviewed 36 robust studies and found an average learning loss of 0.17 standard deviations, which was approximately equivalent to a one-half years of learning[245]. Hammerstein et al. also found learning loss due to the COVID-19 pandemic in 9 of 11 reviewed studies[244]. However, in both reviews there were studies (or particular jurisdictions) that did not report learning loss[244] or countries which managed to limit learning loss[245], Key findings are summarised below in terms of primary, secondary and tertiary education.

A review of impacts of COVID-19 specifically on primary education found that these typically resulted in learning loss or slower learning gain, although there were uneven impacts in relation to existing levels of socioeconomic disadvantage[241]. Analysis of NSW primary schools when comparing

2019 to 2020 (year 1 of the pandemic) performance found no significant difference overall in mathematics or reading[246]. However, this was not uniformly the case when level of disadvantage was included as a factor. Year 3 children in least advantaged schools achieved 2 months less growth in mathematics, while those in mid-level of advantage schools achieved 2 months additional growth[246]. A follow up review by the same research team was conducted on 2021 performance (year 2 of the pandemic) in NSW primary schools. Overall, the study again found no significant learning difference between 2019 and 2021 cohorts, however, the lower socioeconomic band achieved three months learning gain in mathematics compared to the 2019 cohort[247]. The authors tentatively suggest this indicates additional preparations and funding during the pandemic were useful in mitigating learning loss after the first year, particularly for disadvantaged students.

In secondary schools, there was typically found to be decreased rates of learning among students, and learning loss due to extended school closures, again exacerbated by inequality and inequity[241]. An Australian study examined attendance rates amongst secondary school students in Tasmania. Students from high socioeconomic status (SES) backgrounds had similar school attendance rates before and during COVID-19, while there was a significant drop in attendance rates amongst socioeconomically disadvantaged students[247,248].

At a tertiary level, educational impacts appear to be more discipline specific. Training of medical students (including nursing and dentistry) was disrupted as clinical rotations were suspended and licensing exams interrupted[241,249]. Medical professionals in university hospitals also experienced disruption (e.g. cardiac surgical training[200]) for multiple reasons, including redeployment of trainees to front line work, reduced training to limit staff loads in health facilities with limited ventilation sites available to reduce nosocomial transmission, and quarantine guidelines for isolation from potential contacts[200]. The impact on educational outcomes is less well understood. A study in the UK of 76 cardiac surgical trainees found that 88% were anxious about the impacts of the pandemic on their training, and 71% thought they would require extra time in their training[250]. Experiential learning was disrupted in multiple disciplines, such as field study components in the sciences[241]. Educational delivery was also impacted, a study of university staff documented the impacts of COVID-19 on participation, with 7% of participants reporting sickness absenteeism, and 26% of participants experiencing presenteeism[229].

The long-term impact of school closures on educational outcomes was analysed through a historical review of the 1918 flu pandemic. This found no detectable impact on school attendance in 1920, nor on educational attainment and labour market outcomes in 1940, though the authors caution against

extrapolating these historical findings to the COVID-19 pandemic[242]. Psacharopoulos et al modelled the economic impact associated with school and university closures during the COVID-19 pandemic by mapping lost learning to the lifetime reduction of the earnings of graduates from 205 countries, estimating that the total economic impact of school closures was likely to lead to the equivalent of a 0.8% annual reduction in global economic growth rate[251].

A separate area in which there is less research is the impact of COVID-19 on student wellbeing. An initial investigation in Australia suggested that the impacts of school closures is likely to have had widespread, complex and worrying effects on student wellbeing[252].

5.3 IMPACTS OF TRANSMISSION OF AIRBORNE DISEASES ON LONG-TERM CARE FACILITIES

Long-term care facilities such as aged-care homes, psychiatric care facilities and long-term care hospitals have been reported as environments were rapid spread of respiratory pathogens such as influenza and COVID-19 can occur[253]. Shared living areas, close living quarters, and shared sources of air make airborne infection control difficult[253,254]. High rates of comorbidities amongst the elderly increase the risk of mortality. Amongst the elderly, exposure to influenza in long-term care facilities increases the relative risk of death due to respiratory causes[255].

Outbreaks of respiratory tract infection occur frequently throughout the year in aged care facilities. A longitudinal study of 5 Canadian nursing homes found respiratory outbreaks occurred during 9% of all resident-care days[256]. In Tennessee, USA, a retrospective cohort study of nursing home residents reported that influenza contributed to approximately 147 courses of antibiotics, 28 hospitalisations, and 15 deaths per 1000 person-years annually for residents with comorbidities[257].

An analysis of aged care facilities in Australia found that the resident risk of COVID-19 infection within homes was 1.27 higher than for the general population[258]. COVID-19 had a large cost burden for aged-care in Australia. Health-related aged care spending from 2019-20 to 2021-22 for COVID-19 was AUD2 billion[259]. This included AUD0.5 billion for aged care workforce, AUD0.2 billion for COVID-19 preparedness, and AUD0.06 million for Rapid Antigen Testing[259].

5.4 IMPACTS OF TRANSMISSION OF AIRBORNE DISEASES ON HEALTHCARE SETTINGS

The impacts of transmission and acquisition of infections in hospital and healthcare settings has been extensively studied[260–262]. Studies have typically considered all infection types, without a specific category for airborne transmitted diseases.

In the United Kingdom, a detailed modelling study of NHS hospitals found that respiratory tract infections (pneumonia and other respiratory infections) are responsible for 22.8% of healthcare associated infections (HCAIs)[260]. While not completely aligned, this study is the most relevant comparison to airborne infections, and would include influenza and other airborne infections.

The impact of all HCAIs across 12 months of 2016/17 was quantified in detail. Amongst patients, there were an estimated 653,000 HCAIs across 13.8 million adult inpatients (4.7%). Of these, 22,800 (0.17% of all inpatients) died as a result of their infections. This is estimated to account for 5.6 million occupied hospital bed days.

Within the workforce, there were 13,900 HCAIs across 810,000 frontline healthcare workers (1.7%), accounting for 62,500 days of absenteeism. In total, HCAIs were estimated to have cost the NHS £2.1 billion over the course of 12 months, of which 99.8% was attributable to patient management and 0.2% was the additional cost of replacing absent front-line staff with temporary or agency staff for a period of time[260].

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7 Appendix 1

Table 3: Air filtration (HEPA air cleaners) - evaluation methods, effectiveness and considerations. The table includes only studies that would be categorised as of "High" or "Moderate" methodological quality against a grading system such the GRADE system used by medical researchers.

Evaluation method	Effectiveness/efficacy	Considerations
In-situ virus/aerosol sampling and identification or trial that recorded infections[65,68,263]	• One HEPA/UVC unit (277 L/s) was installed in both a "surge ward" and a "surge intensive care unit (ICU)" at Addenbrooke's Hospital (UK), both fully occupied with COVID-19 patients during the study[65]: In the surge ward, while the air filter was OFF, SARS-CoV-2 was detected in the air on all sampling days over a 2-week period, but no detectable SARS-CoV-2 RNA was found when the unit was continuously ON for one week. However, no airborne SARS-CoV-2 in was detected the surge ICU when the unit was OFF but was detected in a single sample when the HEPA/UV filter was ON. This unexpected result was not verified in terms of other bioaerosol measurements in the ICU, i.e. in this case too, the use of the air filtration device significantly reduced the presence of microbial bioaerosols. The authors speculated that the differences in the measurements between the two spaces to the fact that patients in ICU were at a later stage of disease and may therefore had shed less virus[65]. Note: the system used in this study at Addenbrooke's Hospital was a combined HEPA and Ultraviolet radiation unit (UVC dosage: 2 X 18W UVC lamps). • Recorded COVID-19 cases in 10 kindergartens with portable HEPA air filters (combined with UVC) in all rooms and 22 control kindergartens over a period of 6 months[68]. The HEPA/UVC systems were sized to match the room size and positioned in a way that was considered as the most optimum for each room. The study found that the portable HEPA/UVC air cleaners did not prevent nor reduced COVID-19 transmission. The mean COVID-19 period prevalence of the control group was 186 per 1000 children and 372 per 1000 children for the intervention group. Opening windows was not monitored but self-reported data (by the school) showed that 20% of the intervention group kindergartens ventilated the spaces less frequently than the rest of the kindergartens from both cohorts (the authors speculate that this may be due to potential behavioural changes in the schools with the portable HEPA filters, but the study does not cover this aspect of the research). • Portable HEPA/plasma air cleaner in ICU in Turkey was compared against an equivalent control ICU room (intervention and control rooms were alternated after 2 months for another 2 months)[263]. System was set to 74 L/s (setting used delivered only ~1 ACH). CFU (Colony-Forming Unit) per m^3 decreased more rapidly during the first week when the air purifiers were	• Measures to prevent airborne transmission may be more important in conventional wards than in ICUs[65]. • Research is needed to determine if interventions in certain public spaces (e.g. kindergartens[68]) create a sense of safety among occupants, potentially leading them to neglect other preventative measures.

	installed in the ICUs than in the control ICU. CFUs were similar at the end of the first month in both ICUs. The microbial load decreased in the intervention ICU, while it increased in the control ICU, at the end of the second month. Mean CFUs in the air were by 22% and 47% lower in the ICU with the HEPA/plasma unit for the two 2-monthly phases respectively, however, large standard deviations were also noted that exceeded these percentage differences. • An 86 L/s HEPA air cleaner installed in a kindergarten in Poland (~1 ACH, volume of space is given as 300 m^3 but this may not have been reported correctly)[69]. CFUs were measured for 6 cold months with HEPA ON and OFF. Measurements were not taken sequentially and not in parallel, which may have imposed some bias in the results. CFUs were on average 18% less when the HEPA system was ON, but large standard deviations were noted in this study too.	
Virus measurements in a laboratory (test chamber) or other controlled space [66,67,264,265]	• Small scale (0.24 m^3) biosafety chamber measurements: SARS-CoV-2 virus capture ratios of HEPA air cleaner were 85.38%, 96.03%, and >99.97% at 1, 2, and 7.1 air volumes, respectively[66] • In-duct installation of HEPA air cleaner: retained more than 99.996% of actinophage but at 0.5 m/s air velocity[264]. Typical duct air velocities are significantly greater than 0.5 m/s. • HEPA air cleaner tested with 44 L/s setting in a 30m^3 chamber (equivalent to 5.3 ACH) and two of the same 44 L/s setting cleaners were evaluated in a 95 m^3 classroom (~3.3 ACH)[67]. o In the chamber, bacteriophages were reduced to 14% in 27 minutes. o The results from the real classroom did not demonstrate any significant improvements from the use of the HEPA air cleaners. The measurements in this case may have been confounded by the opening of windows or other local air currents. An interesting observation was that the combination of HEPA air cleaners and opening windows did not result in higher reduction of phage concentration than when using HEPA air cleaners with the windows closed. • 13.4 ACH portable HEPA air cleaner in a sealed clinical room tested by measuring virus aerosol exposure (bacteriophage PhiX174) on a healthcare worker wearing PPE (masks, gown etc)[265]: Virus counts were reduced when HEPA was operating. However, there was still significant virus contamination with the HEPA filter ON. HEPA filter reduced aerosols, but it did not fully prevent air contamination. The authors recommend to instead place HEPA filters using a hood configuration close to the infected patient.	• One article states that lab studies tend to use artificial nebulizer suspensions. However, artificial nebulizer suspensions, even artificial saliva, were found not to produce the same effect as natural suspensions (human saliva) on the infectivity and survival of airborne viruses and therefore these studies will not accurately estimate the survival of these viruses[266]. • Applying antiviral agents to HEPA filter did not increase its efficacy[66].
Computational Fluid Dynamics (CFD)[70,71,117]	• The concentration of virus in a space and the performance of the HEPA air cleaner was significantly affected by the position of the infected person[70]. In some cases, (i.e. for larger distances between the infected person and the air purifier), the HEPA air purifier appeared to have led to a higher concentration at various locations in the space. For the case where the infected person was closer to the assumed location of the HEPA cleaner, using the HEPA air cleaner led to higher concentrations up until between ~6.5 mins and ~18 mins (depending on location in the room) from the start of the initial aerosols' introduction in the space. After these times, the HEPA air cleaner reduced the load on aerosols efficiently. Mean concentration of the	• Selection of CFD numerical solvers for these types of evaluation is important.[70] Comparisons made between transient coupled air flow and particle transport in CFD (computationally expensive) with the approach of steady-state flow field for a transient transport simulation. For short timescales (~<30mins), the transient approach is recommended but

	virus in the modelled classroom reduced by 68% if the infected person is near the HEPA air cleaner, and only by 12% at the second position modelled further away from the HEPA (attributed to a relatively low convective transport of particles further away from the HEPA air cleaner)[70]. • HEPA air filtration reduced the total particle count by 46% in a 4-bed ward with 100 m^3/h (27 L/s, 60.5 m^3 ward -> 6.6 ACH)[117]. • The optimal location for a HEPA cleaner strongly depends on the geometry of the domain (space) and the flow parameters. Identifying the region where placing an air cleaner would yield a positive benefit and not a negative effect is critical. The location of greatest benefit is usually the area in front of the infected person. Placing the purifier farther away from the infected person reduces the effectiveness of the purifier and, in some cases, worsens the situation (in one of the positions modelled the number of airborne particles increased).[71]	for larger timescales and as the concentrations of particles decrease, both numerical methods gave similar outputs[70]. • Particle removal efficiency is an input to models (e.g. typically >99.97%).
Measurements of proxies for airborne disease concentration [70,72–75,119,267,268]	• Two domestic HEPA air cleaners (130 L/s each) in a hospital ward removed 99% of all proxy particles in 5.5 minutes, which represented a 67% reduction in removal time compared to having no air cleaners. They also reduced spread to other areas (hospital corridors)[119]. • Using breathing simulators to represent infection and susceptible subjects, two HEPA air cleaners (each of 120 L/s capacity) in a 176 m^3 space reduced total exposure to simulated exhaled aerosol particles by up to 65% without masking. The combination of the two HEPA air cleaners and universal masking reduced overall exposure by up to 90%. The best location of the HEPA air cleaners was close to the aerosol source[267]. • A mobile HEPA filter system performed better in terms of (visually tracked) particle counts as compared to the 'No ventilation' regime, for all settings and indoor locations, and for some settings, even better than all the tested mixing ventilation regimes[73]. Tested with air-filled soap bubbles exhaled by a dummy manikin head. • Placing a large HEPA air cleaner (416 L/s) to create negative pressures in an anteroom and a second cleaner in an adjacent isolation room (experimental set up), discharging air to outside and combined with a plastic barrier (zip wall) resulted in aerosol containment of more than 99%[72]. The effect of the HEPA filters without the barrier and excluding the impact of the negative pressure was not tested separately. Optimum room location for a single HEPA air cleaner: in the isolation space. Placing the HEPA in the anteroom alone resulted in an unwanted draw of aerosols outside the isolation room[72]. Two HEPA filters in the isolation room did not provide additional improvement and high levels of negative pressure created structural issues for the zip wall that separated the two rooms. • Measured particle concentration in a classroom: reduction by 70-90% within approximately 30 mins, if 6 Air Changes per hour are achieved by the HEPA air cleaner (334 L/s in 198 m^3 space)[70].	• Existing ward HVAC system alone could not effectively clean proxy particles in the ward (slow clearance rate even at 12 ACH)[119]. • Reported air exchanges and actual aerosol clearance from rooms do not correlate in a predictable manner possibly due to localised flows and flow recirculation[119]. • May require staff training to use air cleaners[119]. • Air flow patterns will vary on case-by-case basis. In the breathing simulators experiment[267] the room air was well mixed, which facilitated better transport of particles to the air cleaners. In rooms with potential stagnation zones, air cleaners might be less effective and additional measures may be required to ensure a well-mixed air space[267]. • If the flow rate of the air cleaners is much higher than the rate of the HVAC system, aerosols may not be able to exit via the return duct of the HVAC (flow will be dominated by the air cleaners)[268].

	• Measurements of particle concentration between two side by side occupied classrooms with and without HEPA air cleaner[74]: Four air cleaners were operated at a total volume flow rate of 285 L/s (5.5 ACH). Particle concentration decayed much faster in the room with the air purifiers (a decrease of more than 95% within 37 min following an initial exponential decay rate without purification). Measurements were taken at two different locations in the space and showed that the room was well mixed and the reduction of particles in the room was homogeneous. An infection risk model was then used (applicable only to small volumes and when air is perfectly mixed in the space). Estimated that the inhaled dose for a susceptible person of virus-RNA via airborne transmission was reduced by a factor of six after 2 hours of exposure when using HEPA air purifiers with an air exchange rate of 5.7 ACH. Significant assumptions that carry uncertainties were made in the model around the infected/susceptible persons and the air flow in the space. • Measurements of clearance rate due to HEPA portable air cleaners in an office (controlled space in a lab) and a hospital (using theatrical smoke)[268]: HEPA air cleaners of high flow rates (16.7 and 19.6 ACH) reduced the clearance time significantly. Complete clearance of proxy particles in a small office room was achieved four to five times faster (<12 min) with portable air cleaning devices than with the HVAC system alone (2.3 ACH). Lowest flow rate device tested had 8.3 ACH nominal air flow rate and it was also more effective than the HVAC system alone. Three times faster clearance rates (<10 min) were measured in a hospital room when using two HEPA air cleaning devices (25 ACH in total). • Long term performance of HEPA air cleaners was tested in two schools[75]: No decline in filter efficiency after six months of continuous use. All air cleaners could reduce the aerosol particle load inside the classrooms by 85-95% within less than 20 min. A control test of a household air purifier filtering outdoor air yielded a maximum decrease in filter efficiency of 15% after approximately 1900 h (80 days) of operation (equivalent to a year of operation in an office or school when assuming eight hours of use per day).	• Noise levels of large systems may disturb the operation of classrooms (e.g. see survey in[75]). • HEPA air cleaners should not replace conventional means of fresh air supply.

Table 4: UVC lights: evaluation methods, effectiveness and considerations. The table includes only studies that would be categorised as of "High" or "Moderate" methodological quality against a grading system such the GRADE system used by medical researchers.

<table>
<tr><th>Evaluation method</th><th>Effectiveness/efficacy</th><th>Considerations</th></tr>
<tr><td>In-

situ virus/aerosol sampling and identification or trial that recorded infections[65,68,102,103]</td><td>

Two studies with combined HEPA/UVC portable systems in hospital wards and in kindergartens were described in Section 2.2.1[65,68].
Installation of 1m long UVC tubes in the air recirculation duct of an open plan office (1130 m^3)[102]: Large capacity system (~190 W, 600 J/m^2 dosage) led to a reduction in bacterial count, by ~50%. A normalisation process was used for the measurements to account for variations of outdoor air measurements and spatial variations in the open plan office – the normalisation process was not described in the study.
Installed UVC in the ventilation systems (450 mW/cm^2 irradiating the cooling coils and drip pans) and took measurements of endotoxin and viable microbial concentrations in air of three office building with UVC ON and OFF[103]: Compared with UVGI off, operation of UVGI was associated with much lower airborne microbial and endotoxin concentrations in the supply airstream, and a non-significant reduction in airborne bacteria in the indoor office spaces. Although the use of UVC led to significant microbial contamination on surfaces, airborne microbial levels did not fall by much.

</td><td></td></tr>
<tr><td>Virus measurements at a laboratory (test chamber) or other controlled space[86,88,90,92,95,96]</td><td>

Measurements of bacteria S. marcescens and BCG in a room with ceiling and wall mounted UVC fixtures (UVC output: 10W and 5W. respectively)[86]. The following tables summarise the percentage reductions in particles in terms of using a mixing fan and deactivating the wall-mounted fixtures:

<table>
<tr><th>% particle reductions</th><th>S. marcescens 2 ACH</th><th>S. marcescens 6 ACH</th></tr>
<tr><td>Without mixing fan</td><td>46% (22-80%)</td><td>53% (40-68%)</td></tr>
<tr><td>With mixing fan</td><td>62% (50-78%)</td><td>86% (81-89%)</td></tr>
</table>
<table>
<tr><th>% particle reductions</th><th>BCG 6 ACH</th></tr>
<tr><td>Ceiling mounted only (10 W)</td><td>52% (11-69%)</td></tr>
<tr><td>Ceiling + wall mounted (15 W)</td><td>64% (51-83%)</td></tr>
</table>
</td><td>

The number of UVC fixtures, use of mixing fan, and air exchange rate significantly affected UVC effectiveness[86]. Very significant improvements to the effectiveness of UVC systems by using ceiling fans to create well-mixed air spaces were noted by several studies[86,88,90,92,93].
UVC effectiveness was reduced at temperatures lower than typical room temperatures (tests done between 4 and 25ºC)[86]. The reduced effectiveness of upper room UVC at lower temperatures may be caused by reduced UVC output from the lamps, reduced sensitivity of microorganisms at lower temperature, or a combination of both[86].

</td></tr>
</table>

Evaluation method	Effectiveness/efficacy	Considerations
	• The importance of having a well-mixed air on the effectiveness of wall or ceiling mounted UVC systems was confirmed in another two room chamber experiments[88,90]: e.g. in [90], effectiveness was reduced by almost 80% under wintertime warm air-supply conditions that led to thermal stratification of air in the space. • Experiments in a test room using two 15W wall-mounted UVC lamps:[95] UVC reduced concentrations of culturable airborne B. subtilis and M. luteus by 16-58% (at 2ACH). The average effectiveness of UVC was 57% for B. subtilis and 36% for M. luteus. Adding a louvre to a UVC lamp reduced its effectiveness to approximately zero. • The distribution of UV radiation within a room can have a significant impact on the UVC inactivation rate[90]. Even with well-mixed room air, in a chamber experiment, operating lamps on only one side of the room reduced the UVC inactivation rate by as much as 30% compared to operating lamps with the same total lamp power uniformly from all sides of the room. • The use of some louvres for preventing exposure of people to UV radiation significantly reduces the effectiveness of UV luminaires, however, their use is important for safety reasons[88]. • In an aerosol irradiation chamber, it was found that far-UVC (222 nm) can inactivate coronaviruses and it was stated that this wavelength is safer for humans than the more typical 254 nm UVC light[96].	• Same considerations around the use of artificial nebulizer suspensions as with the HEPA air cleaner studies apply also here[266].
Computational Fluid Dynamics (CFD)[94]	• CFD simulations of 4 corner mounted UVC lamps (36W each) and a fan at different speeds in a small (~43 m^2) chamber[94]: a high air exchange rate (with outside ambient) reduced the time air was exposed to the UV irradiation field. The ambient air exchange rate was an important factor in determining the effectiveness of UVC. However, the combined effectiveness of greater ventilation and UVC was always higher than that of UVC and low ventilation rate. Further, the UVC disinfection effectiveness improved with the use of a ceiling fan.	• In small rooms with UVC and ceiling fans there is a possibility of increasing the risk of airborne infection by using the fan when UVC is turned "off"[94]. • Ceiling fans could improve UVC effectiveness (especially for poorly or non-ventilated spaces) but optimum fan speed is not always at the highest speed setting[94].
Review studies (various methodologies)[2,87,91,105]	• The correct dosage and placement of UVC light can reduce airborne disease transmission[76–85]. • Upper room UVC light is likely to be more effective in poorly ventilated spaces[79,88,89]. • Airborne bacteria inactivation experiments in a test room (87 m^3), fitted with UVC (216 W top corner and ceiling-mounted systems, average upper zone UV irradiance 42±19 μW cm^{-2}), gave an effectiveness in terms of reductions of culturable airborne bacteria between 46-98%[81]. • Through high-fidelity CFD modelling it was shown that viral concentrations were reduced by 50-85% when using a top corner-mounted far-UVC (222 nm) compared to just using the room ventilation system (the room model was representative of a single occupancy hospital room).[77]	• Optimum positioning and ensuring uniform dosage distribution of UVC systems is not simple and should be carefully considered, particularly in ensuring that these systems are effective without impacting the safety of occupants from the UV irradiation[2,91]. • Two very important parameters in the germicidal effect of UVC systems are:

Evaluation method	Effectiveness/efficacy	Considerations
	• High levels of indoor relative humidity decrease the UVC effectiveness[82,87,90,92]. The exact amount of decrease depends on the virus type and UVC dosage. • A UVC lamp (0.73 mJ s^{-1} cm^{-2}) installed in the duct of an HVAC system inactivated fungal spores and bacteria by 75-87% at an air stream velocity of 2.2 m/s but were ineffective when the air velocity increased to 5.1 m/s[104]. The air velocity of the main HVAC supply duct would typically exceed 4-5 m/s, but smaller branch ducts can have air passing with velocities closer to 2-2.5 m/s. Thus, UVC lamps are likely to be more effective in smaller branch ducts than in the main ducts around the Air Handling Units. • A thorough review of inactivation efficiencies of in-duct UVC systems for SARS-COV-2 is provided in [105] and a further design optimisation was undertaken in the same study: it was shown that all systems after optimising the design could achieve inactivation efficiencies >99% (>2 log reductions for all optimised designs). Virus inactivation efficiencies before optimisation were estimated to be from 70% to 100%, however, the study does not provide a clear description on how such high efficiencies were calculated.	the intensity of the UVC energy and the duration of exposure[87].

8 Appendix 2

An overview of the types of air sampling methods as well as case studies relating to indoor air quality monitoring is provided in Table 5, with graphical descriptions of the collector types shown in Figure 5.

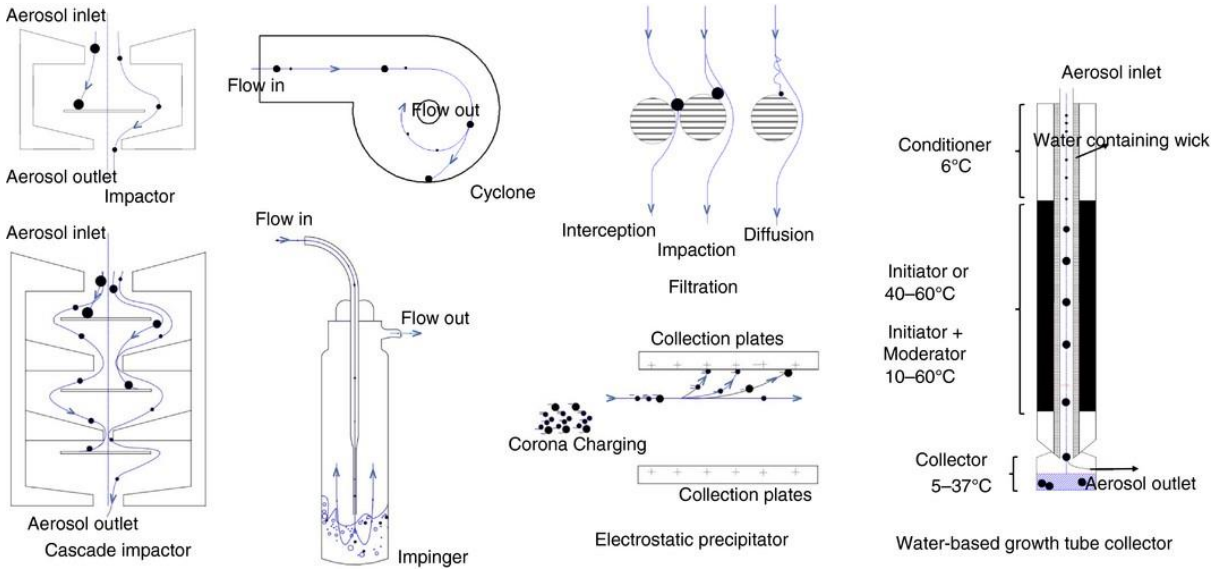

Figure 5: Air sampling strategies for airborne pathogen testing[269]

Table 5: Summary of air sampling methods and case studies

Type of Collector	Examples	Advantages	Disadvantages	Sampling methodology/ duration	Findings from case studies
Solid impactors	Cyclone separator[133] NIOSH bioaerosol separator Cascade impactor[270]	Can separate samples into size fractions. Efficient for large particles	Virus deactivation upon collection – unable to test for infectivity Low efficiency for small virus particles	Cyclone: 300L/min for 20/60min Cascade impactor: Air sampling at 5L/min over 5-20hours[270]	Authors of these studies have identified difficulty in cultivating viruses due to low concentrations in the samples and compromised integrity from impacting samples for collection. One study in a kindergarten found no positive SARS-CoV-2 samples[133]. In another[270], SARS-CoV-2 aerosol particles were mainly found in the two ranges: $0.25 < d_p < 1\mu m$ and $d_p > 2.5\ \mu m$. Concentrations were low across public areas of the hospital but highest in toilet areas.
Liquid impactors	Liquid impinger samplers[142]	Maintain viability of virus No extraction required for testing	Wall loss, inlet loss Low efficiency for small virus particles	Vacuum pump collects air at 1.5 L/min over 2 hours into 5mL viral transport medium[142]	A low positive rate of 2.5% was found from 24 locations inside a health centre[142.] The authors discussed possible impacts on the behaviour of the virus of temperature and humidity differences. Results were limited in that replicability and viability were not tested, nor was the air exchange rate of the rooms considered.
Filters	Aerosol filters collect particles at a filter through interception, inertial impaction or diffusion[140,143,144]	Efficient for particles 20nm to 10µm or larger Easy to use Can be used in combination with cyclone/impactor to remove large particles	Inactivation of viruses due to dehydration or extraction from filters	Air flow of 4.5L/min over 4 hrs drawing through PTFE membrane filter of 37mm diameter, 0.3µm pore size[140] Air flow of 0.3L/min over 1.5hrs drawing through a 47mm filter cassette with 0.22µm pore size[143] Air purifiers with HEPA filters with an air flow of 7CFM were sampled after 2-4 weeks[144]	One study in hospital areas found air sampling identified higher concentrations in corridors of the hospital than the rooms themselves[140], which the authors attribute to limited ventilation in the corridors compared to patient rooms. Concentrations in the ICU rooms and corridors were much lower than the other rooms, which was attributed to patients in the ICU being intubated and connected to respirators with filters on exhaled air. This study highlighted the importance of ensuring monitoring captures all areas, particularly those with minimal ventilation. Another study investigating a range of community buildings[144] found 8.33% of samples were positive for SARS-CoV-22, particularly in child

Type of Collector	Examples	Advantages	Disadvantages	Sampling methodology/ duration	Findings from case studies
					daycare centres. This study highlighting the potential use of low cost air purifiers and filters for monitoring diseases transmission. Likewise a study on public transport highlighted potential for low cost assessment of virus presence in public areas.
Other	Water-vapour deposition methods[141]	Cost efficient Easy to use	Efficacy not tested	Passive collection over 4-6hours (no air flow) [141]	Aerosol samples from several rooms showed much higher concentrations in non-ventilated rooms compared to those with continuous ventilation or with 1-2 windows open[141]. Changing operation of the windows to increase fresh outdoor air supply also demonstrated changes in the monitored results
	Electrostatic precipitators[271]	Size-dependent collection efficiency Consumes less energy and portable	Low efficiency for sub-micrometre or nanometre particles Ozone formation deactivates viruses	Air flow rates of 10, 20, and 40 L/min used for 90min[271]	The Wet-type Electrostatic precipitator[271] was found to have much higher collection efficiency than an impinger collector, but not as high as the gelatin filter-type sampler. It also exhibited lower noise levels. However, it was noted that the use of PCR testing will detect both live and non-infectious viral RNA so it may not be a good predictor of virus transmission.
	Natural sedimentation processes	Not aggressive Lower cost	Qualitative analysis Collection duration longer	N/A	N/A

Table 6: Summary of CO_2 monitoring case studies

Ref	Location	Method	Findings
[152]	Office United Kingdom	Uses Wells-Riley model, extrapolated to consider CO_2 rates, combined with pre-existing CO_2 measurements to calculate likelihood of transmission risk	The authors conclude that the risk of COVID-19 being spread by the airborne route is not insignificant and varies widely with activity level and environmental conditions which are predominantly determined by the bulk supply of outdoor air.
[146]	Experimental chamber Denmark	Experimental setup to test link between CO_2 and aerosol viral load for breathing and talking. Sensirion SCD30 used for CO_2	Both CO_2 and particle levels increased linearly over time, so CO_2 can be used as a proxy for airborne exhaled particles, however, CO_2 production was not dependent on the human activity (talking or breathing), in the same way that particle count was.
[272]	Office India	Extech EA80 IAQ meter/datalogger used to measure CO_2 R-Event calculated from curve fitting as a function of CO_2	The risk of infection (R-event) was most highly correlated with occupancy, followed by CO_2 levels. This study only looked at natural ventilation of an office space with sedentary workers and did not account for human activity.
[154]	Secondary school and Universities Toledo, Spain	Two classrooms at secondary school and two classrooms at university CO_2 monitored with portable non-dispersive infrared (NDIR) sensor (Testo) indoor and outdoor, 3 days per week, once per month over 7 months	The difference in CO_2 levels between indoor and outdoor was used to estimate the potential risk of airborne transmission. Whilst the CO_2 levels measured were all below required thresholds, the risk of transmission was found to be low to medium for most classrooms, and medium to high where the average ΔCO_2 levels were higher. Mechanical ventilation with filtration reduces risk by ensuring sufficient clean air and dilution.
[155]	Schools United Kingdom	Monitored CO_2 data in 45 classrooms in 11 schools for two five-day periods in January and July. Used Wells-Riley model to calculate probability of infection.	The authors found that there was significant seasonal variation in the risk of infection, with expected levels of infections in winter nearly double those of summer. This variation is only due to changed ventilation and occupant behaviours. They also found that varying the quanta rate did not change the qualitative results.
[151]	Office and Classroom Massachusetts, USA	Atlas Scientific EZO-CO_2 Embedded NDIR CO_2 Sensor Measured over a single time period for each room.	Allows safety guidelines and mitigating factors to be accounted for when calculating disease transmission risk. Limited application but has investigated the impact that mask-wearing can have on transmission risk.
[153]	Hospital Japan	Non-dispersive infrared CO2 recorder, TR-76Ui. Measure for single day over 8-180min time period	Model was able to predict transmission with an acceptable accuracy when compared to actual results. Maximum allowable CO_2 levels could then be predicted for various scenarios based on mask wearing etc.
[156]	School Italy	NoseC non-dispersive infrared CO_2 sensor 11 classrooms monitored for 3 consecutive weeks	Surveillance activity used to evaluate effectiveness of ventilation response protocols with real-time feedback of CO_2 levels used in operation of

Ref	Location	Method	Findings
			ventilation (windows etc). In most cases, following ventilation protocols was successful in maintaining acceptable risk levels, however, in some cases, it was not enough to reach safe levels.
[273]	School Italy	Portable dual NDIR detector. Monitoring conducted over 3 consecutive days.	Monitored results used to calibrate the estimated infection possibility. Authors identified issues such as the natural fluctuation of the CO_2 signal when being used to control variables, and uncertainty.
[274]	Experimental USA	Air sampling and CO_2/particle monitoring conducted over a 60 minute period for various activities/ventilation conditions. CO_2 monitoring using Onset HOBO MX1102A.	Compared aerosol viral load in near and far field from COVID patients with CO_2 concentrations, under varying ventilation rates. Authors found that an increase in ~128 PPM of CO_2 concentration corresponds with approximately doubling of the viral load.

Table 7: Summary of particle monitoring case studies

Ref	Location	PM instrument	Findings
[143]	Public transport - Subway train Mashhad, Iran	EPAM-5000 Haz dust model: PM_1, $PM_{2.5}$ and PM_{10},	Particle levels were compared with air and surface RNA sampling, however, limited positive results hindered analysis. There were no statistically significant differences between particle levels and air/surface sampling results for the results obtained.
[146]	Experimental – airtight chamber Denmark	TSI Incorporated OPS 3330: PM_{10}	Particle generation from talking was found to be 2.98 times higher than that from breathing, with substantial variation in aerosol particles seen.
[154]	Secondary school and Universities Toledo, Spain	Kanomax handheld laser particle counter for $PM_{0.3}$, $PM_{0.5}$ Aeroqual portable laser sensor – $PM_{2.5}$, PM_{10}, resolution 1 $\mu g/m^3$	PM formation was mostly found to come from indoor sources, though mean values measured were low. Mechanical ventilation with partial filtration was found to reduce particle levels.
[274]	Experimental – environmental chamber USA	TSI AeroTrak 9306 particle counter, PM_1, $PM_{2.5}$, PM_{10} and PM_{25} Verified against RNA air samples.	A positive relationship was found between viral load in near field aerosols and particles for PM_1, $PM_{2.5}$ and PM_{25}, but not for PM_{10}. A positive relationship was also found between viral load in far field and $PM_{2.5}$ levels only.
[160]	Primary schools Cyprus	PurpleAir sensors: PM_1, $PM_{2.5}$ and PM_{10}	Indoor particle levels were correlated with the corresponding outdoor levels for PM2.5 and PM10, as well as positively associated with opening windows
[161]	Public transport – buses, trams and trains Brunswick/Hanover, Germany	Sensirion SPS30 optical particle sensor, PM_1, $PM_{2.5}$ and PM_{10}, resolution 1$\mu g/m^3$	PM_{10} was strongly correlated with dynamics of people getting on and off, not occupancy.
[275]	Public spaces: Gym, Train, Office spaces, Airport, Restaurant Netherlands	Fluke 985 handheld particle counter, $PM_{0.3}$, $PM_{0.5,}$ PM_1, $PM_{2.5}$ and PM_{10},	Validated handheld particle counter against laser diffraction for a single person coughing. Aerosol persistence times in spaces found to be short due to adequate ventilation. Exposure risk from measured particulate levels found to be low.