MINISTRY OF EDUCATION
TE TĀHUHU O TE MĀTAURANGA

The Impact of Natural Ventilation During Winter on Thermal Comfort

A Systematic Literature Review

May 2022

Authors

This report was written by:

Alexis Sutherland	Victoria University of Wellington
Dr Aniebietabasi Ackley	Ministry of Education
Professor Robyn Phipps	Victoria University of Wellington
Dr Ian Longley	National Institute of Water and Atmospheric Research (NIWA)
Scott MacKenzie	Ministry of Education
Professor Mark Jermy	University of Canterbury
Dr Jason Chen	University of Canterbury
Renelle Gronert	Ministry of Education

For any information regarding this report please contact: ventilation.mailbox@education.govt.nz.

Foreword

The New Zealand Ministry of Education's approach to addressing ventilation in schools, as part of its response to the COVID-19 pandemic has been informed by an evidence-based approach which includes this literature review.

In November 2021, the Ministry, in collaboration with the National Institute of Water and Atmospheric Research (NIWA) carried out a ventilation study, which confirmed that an efficient way of achieving good ventilation and reducing the transmission risk of COVID-19 is by opening doors and windows (i.e., natural ventilation).

In March 2022, the Ministry's Ventilation Programme in collaboration with the research institutes above carried out the next phase of targeted studies. These studies are: a control room study conducted at Epuni School and two literature review studies. The review in this report summarises the current research on the impact of natural ventilation during winter on thermal comfort.

The findings from these studies have informed our approach on managing ventilation improvements in schools.

Sam Fowler

Associate Deputy Secretary - Property Delivery

Contents

Executive Summary

The COVID-19 pandemic has highlighted the importance of ventilation as a transmission mitigation strategy. However, there is a widely-held concern that a drop in outdoor temperatures during wintertime may impact thermal comfort in the context of naturally ventilated classrooms. This concern has not been widely investigated by peer-reviewed empirical studies. The aim of this paper is to review the available literature on the impact of natural ventilation during winter on thermal comfort.

Using the replicable search processes of a systematic literature adopted from medical research practice, 142 articles were retrieved from four search databases (Science direct, Scopus, PubMed, and Google Scholar) for this review. Analysis of these articles revealed that most studies have focused on the assessment of ventilation conditions, especially in non-naturally ventilated spaces.

There were only five suitable articles identified that empirically investigated the impact of natural ventilation on thermal comfort during winter. This demonstrates that there is a significant gap within the existing relevant literature. The key findings from these five articles were that:

- Natural ventilation is most effective in winter due to buoyancy driven air flow. However, when the outdoor temperature equals the indoor temperature, there is no natural draught pressure due to temperature difference. This means that only wind will move air. High ceilings are also required for effective buoyancy driven air flow.
- Partly opening windows in classrooms can achieve adequate air flow on cold days above 12 ^{o}C and maintain acceptable temperature levels depending on space usage. However, only opening windows during lunch breaks is an ineffective strategy for wintertime ventilation.
- At temperatures below 12 ^{o}C, a ventilation strategy using the opening and closing of windows or limiting the number of open windows should be established. This strategy should be complemented by the installation of CO_2 monitors.
- Wintertime ventilation can be improved through clerestory windows to assist with the removal of hot air, due to the stack effect. This approach also maintains adequate indoor thermal comfort.
- In colder climates and in the presence of individuals infected with COVID-19, combined interventions (natural ventilation, masks, and portable air cleaners) is a highly effective strategy.
- Windows should be completely opened at temperatures above 12 ^{o}C, if the risk situation is high.
- A temperature of ±3 ^{o}C around the optimum minimum comfort temperature levels of ±18 ^{o}C may still be tolerable to children. This is because children generally prefer conditions to be a few degrees cooler due to their higher metabolic rate and activity levels over the course of a school day.

Summarily, there is a significant literature gap for survey-based thermal comfort investigations in naturally ventilated classrooms during winter months in a comparable climate to New Zealand. Hence, the need for further research on the impact of natural ventilation during winter on thermal comfort.

1.0 Introduction

People spend approximately 90% of their time indoors; for children a large portion of this time is spent within a school classroom (EPA, 2021; Ackley et al., 2017). This clearly illustrates the importance of indoor air quality, particularly in classrooms where physical distancing is more difficult to achieve. This importance is further boosted because the central route of Covid-19 transmission is airborne.

Most of New Zealand's classrooms are naturally ventilated by opening windows and doors (MoE, 2022). Natural ventilation is the optimal way of reducing the risk of airborne transmission of COVID-19, when considering capital and operating costs as well as occupant comfort (Bhagat et al., 2020; Melgar et al., 2021; NIWA, 2022b).

However, a drop in outdoor temperatures of up to 14 ^{o}C during the winter adds complexity to the reliance on natural ventilation due to the implications for thermal comfort and the likely increase in energy usage (Melgar et al., 2021; Navaratnam et al., 2022; NIWA, 2022a; Rencken et al., 2021; Stabile et al., 2017). Defining exactly how colder outdoor temperatures impact the performance of natural ventilation in classrooms is vital because it allows the Ministry of Education to make informed, recommended measures for schools so they can maintain adequate indoor air quality and thermal comfort.

Current guidance from the US Centers for Disease Control and Prevention recommends that classrooms bring in as much fresh air as possible. If temperatures get too cold, heating should be increased (Centers for Disease Control and Prevention, 2021). The UK Chartered Institute of Building Services Engineers (CIBSE) suggest that:

- windows should be open more than is usual
- classrooms should be purged for 15 minutes before classes begin, and
- in cold temperatures, clerestory window usage should be prioritised. Partial opening of windows can help maintain thermal comfort (CIBSE, 2021).

Similarly, the United Kingdom's Health and Safety Executive (HSE) suggest that partially opening windows and doors can still provide adequate ventilation with a rate of 5-6+ air changes per hour (ACH) during winter. They further recommend that opening clerestory windows can mitigate draughts. HSEa also recommends relaxing dress codes, increasing heating and regularly purging the room (Health and Safety Executive, 2022).

The World Health Organisation provides the specific recommendation of 10L/s/person for indoor ventilation (World Health Organization, 2021). Based on this, Australia's Commonwealth Government recommends that air flow should be optimised in schools by opening windows and doors (Australian Health Protection Principal Committee, 2021).

The Canadian Federal Government's guidance suggests moving as much outdoor air into the space as possible during the winter season (Government of Canada, 2021). However, they also noted that doing this intermittently will have minimal impact on indoor air temperature and further recommended regular refreshing of the indoor air (Government of Canada, 2021). Though these guidelines encourage natural ventilation, they lack detail on the adequate indoor air temperature for classrooms and how to balance this with the occupants' thermal comfort.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) suggests that classroom environments should be approximately 22°C (ASHRAE Epidemic Task Force, 2020). CIBSE suggests that school classrooms should not exceed 21°C (The Chartered Institution of Building Services Engineers, 2015). As a minimum standard, the National Education Union of the UK states that classrooms should not be below a temperature of 18°C (National Education Union, 2019).

For the USA schooling sector, the Regional Education Laboratory suggests that classrooms should be kept between 20°C – 24°C during winter months and 23°C – 26°C during summer months (Regional Educational Laboratory Program, 2018). Similarly, the National Joint Council of Canada suggests that comfortable indoor temperatures are between 20°C – 26°C (National Joint Council, 2011). However, these recommendations are generally based on findings from workplaces.

In New Zealand, the Ministry of Education recommends a temperature of 19°C (+/- 1°C) for learning spaces in its Designing Quality Learning Spaces requirements (MoE, 2021). Naturally ventilated classrooms differ in performance because of design, climate, and occupant behaviour, which means that there is no globally accepted guidance for their temperature regulation or protocol (Kapoor et al., 2021). This means guidance for naturally ventilated classrooms needs to be provided through a context-specific lens.

Table 1. Recommended classroom temperatures.

Institution	Minimum classroom temperature	Average classroom temperature	Maximum classroom temperature
ASHRAE		22 °C	
CIBSE			21 °C
National Education Union of the UK	18 °C		
Regional Education Laboratory USA	20 °C (winter) 23 °C (summer)		24 °C (winter) 26 °C (summer)
National Joint Council of Canada	20 °C		26 °C
Ministry of Education NZ	18 °C		25 °C

Mitigation of COVID-19 transmission is one of the most pressing issues globally. Though large strides in knowledge have been made in the last two years, there are still many unknowns regarding best practice for risk reduction measures in schools. When proven measures such as increased levels of natural ventilation clash with thermal comfort goals during winter months, new techniques are necessary to deal with these new issues. In order to address these issues, a thorough understanding of the factors at play and how they interact is crucial.

There is a general concern that during cold days, opening windows and doors to achieve adequate ventilation to reduce the risk of Covid-19 infection will negatively impact the thermal comfort inside classrooms. Though this concern is undoubtably valid, the question of whether a balance between natural ventilation performance in winter and thermal comfort can be achieved is yet to be established.

The aims of this study were to:

- Review the available literature on the impact of winter temperature on the effectiveness of natural ventilation in classrooms.
- Propose measures that can be taken to improve this.
- Answer the following two research questions:
    - *What is the impact of natural ventilation during winter on thermal comfort?*
    - *What is the impact of winter temperatures on the effectiveness of natural ventilation?*

2.0 Literature Review Methodology

The methodology for the selection of publications followed the process outlined in Figure 1 below.

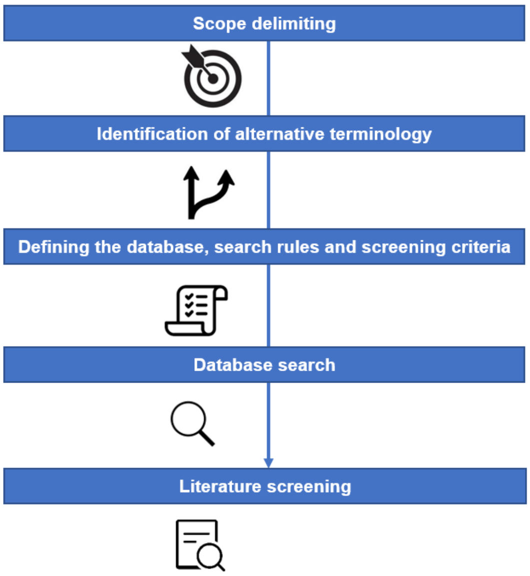

Figure 1. Literature review process

This provides a replicable process for future related literature reviews and studies. Note we used Mendeley as the reference database software for this study.

2.1 Inclusion Criteria

The central purpose of this literature review was to investigate the impact that winter conditions, including temperature, humidity and wind, have on the effectiveness of natural ventilation in New Zealand classrooms, as well as how this relates to the airborne transmission of COVID-19. We also used the literature review to identify any potential mitigation measures that could reduce the airborne transmission of Covid-19.

Taking these purposes into account this review focused on:

- School classrooms. However, other relevant spaces such as non-teaching spaces in schools, university teaching and non-teaching spaces, and office spaces were considered.
- The impact of low outdoor temperature on indoor thermal comfort where the space was using natural ventilation.
- The comfort and behavioural consequences of these effects. This included uncomfortable thermal conditions or changes to window opening behaviour.

2.2 Identification of Alternative Terminology

After the scope of the literature review was established, a matrix of alternative terminology was created.

Table 2. Keywords and alternative terminology

Natural Ventilation	School	Temperature	Effectiveness	COVID-19	Measures
Displacement ventilation	Classroom	Cold	Performance	Sars-cov-2	HEPA filter
Cross-ventilation	Study room	Winter	Efficacy	Virus	Air cleaner
Ventilation	School room	Heating season	Value	Aerosol	Fan
Buoyancy driven flow	Teaching space	Low	Review	Transmission	Heat recovery
Convection	University	Weather			Assisted natural ventilation

2.3 Defining the Literature Databases Used and the Search Rules and Screening Criteria Employed

The databases that were used were: PubMed, Scopus, Science Direct, and a general search on Google Scholar. These databases were chosen based upon their science, architecture, engineering, and disease transmission coverage. In terms of search rules, both peer reviewed and grey literature were considered on an individual basis. This is due to the fast-evolving and urgent nature of this area of research. Further limitations were that we used only papers that were available in English. Though the year of publishing was not a limitation, priority was placed upon literature from 2020 onwards, due to the importance in this context of the COVID-19 pandemic.

2.4 Database Search

The database search was conducted during the months of February and March 2022, using the search phrase and keywords noted above. From the initial search using the primary search phrase, 4,010 sources were found (see fig.1 below).

These searches included duplicates which were removed when identified throughout the screening process. These results were initially screened by their title to establish suitability, which resulted in 174 relevant papers. These papers were then screened through their abstract, which resulted in 113 relevant papers. From these 113 papers, 70 were deemed relevant after a full text reading.

2.5 Final Screening

From the final 70 papers, a second search process was conducted through the original sources' reference lists. These papers were screened through their title and then a reading of their full text. This resulted in 72 additional papers (see fig.2 below).

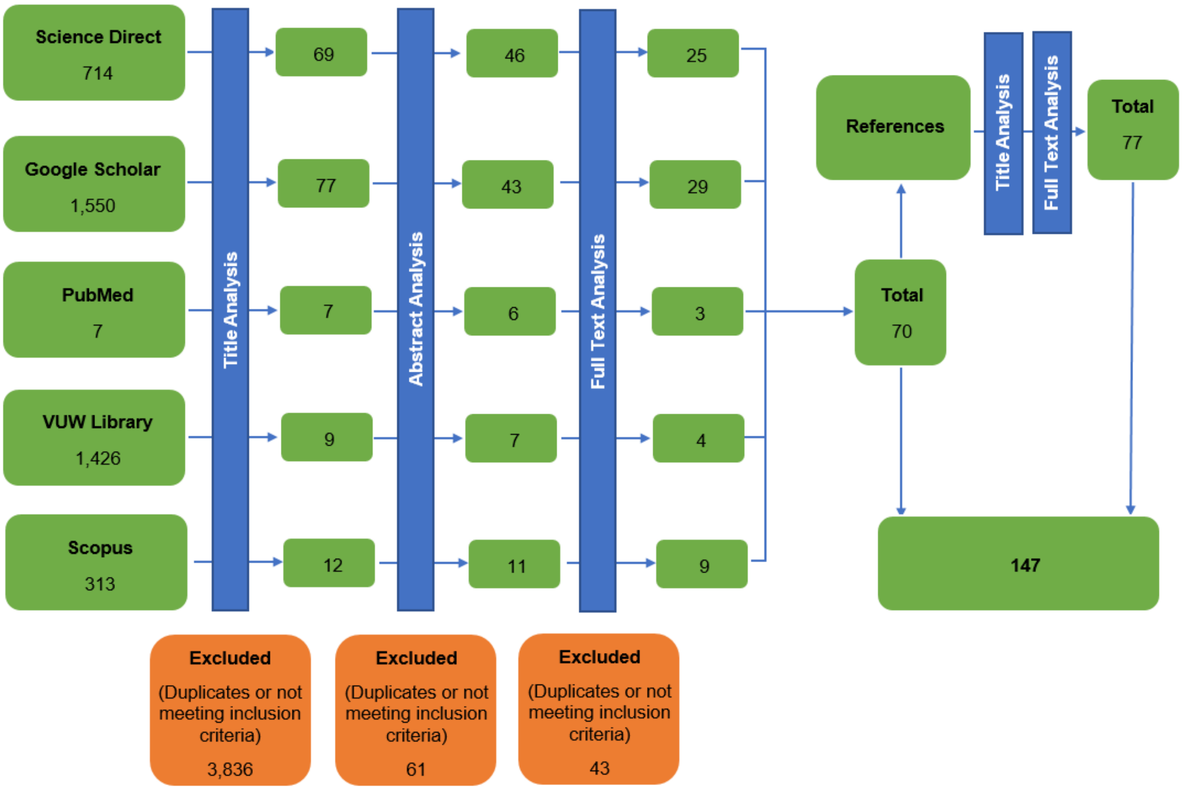

Figure 2. Figure sourcing diagram

2.6 Literature Analysis

A range of literature was explored in order to provide a comprehensive review on the impact of winter temperature and wind on the effectiveness of natural ventilation. This section provides an overview of the literature based upon its type, geographical distribution, and publishing date. The types of measurements used will also be discussed.

The types of literature found comprised experiments, simulations, guidance, and reviews. A few studies used a combination of real-world experimentation and mathematical simulation. 53% of the literature reviewed was an experimental study, with reviews being the second most common, followed by simulations and guidance respectively (see fig. 3 below).

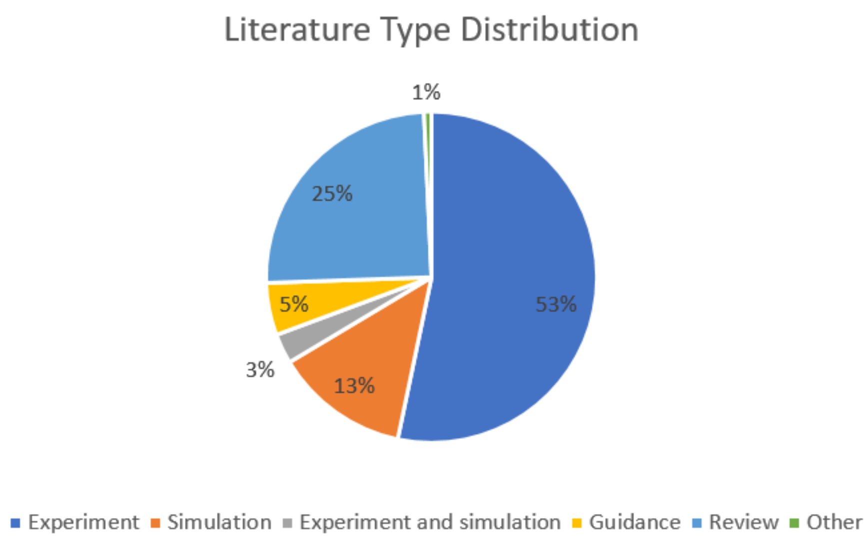

Figure 3. Literature type distribution

Geographical distribution was analysed on a continental basis. Most of the relevant studies were of European origin, followed by studies based in Asia and North America respectively (see fig. 4 below). Seven percent of the studies were not based in, or had no focus on, a particular geographical region. These studies took an international approach and were either literature reviews or guidance documents.

New Zealand has a complex climate ranging from warm subtropical to severe alpine conditions (NIWA, 2022a). This is reflected through six distinct climate zones used within the New Zealand Building Code (Ministry of Business Innovation & Employment, 2021). This range of climactic conditions means that certain geographical studies may be relevant to certain parts of New Zealand during certain seasons. The geographical distribution appears to reflect New Zealand's climactic conditions.

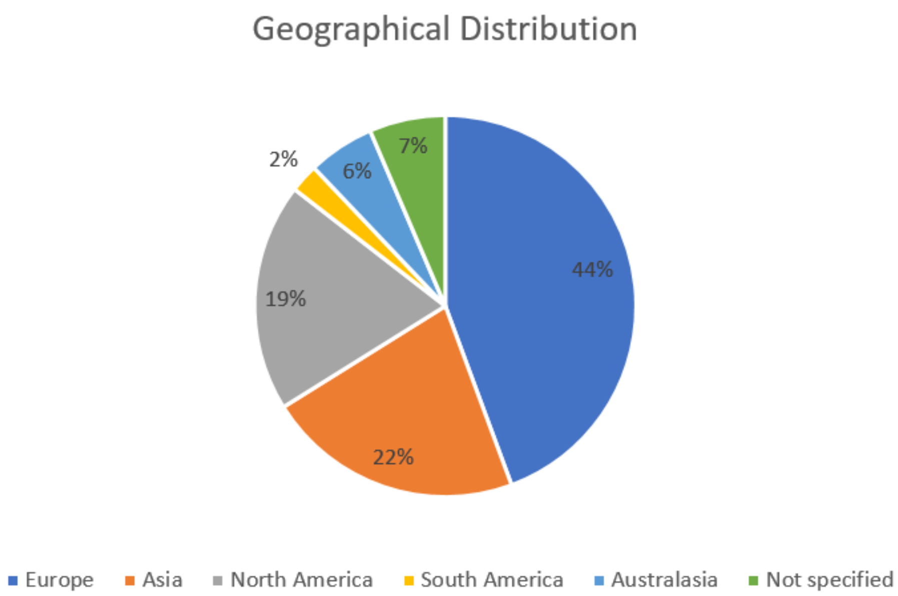

Figure 4. Geographical distribution

The study's relevance to the COVID-19 pandemic is reflected in the distribution of publishing dates, with 81% of the literature published after December 2019 (see fig. 5 below). However, some studies prior to December 2019 were also suitable because COVID-19 relevance can be inferred.

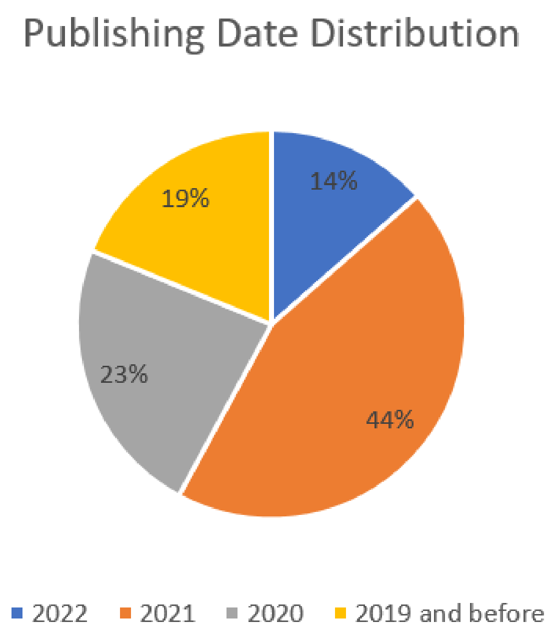

Figure 5. Date of Publishing Distribution

The purpose of the literature is reflected within the distribution of investigated building typologies, with over half of the literature directly investigating school classrooms (see fig. 6 below). Approximately 30% investigated indoor spaces of buildings in general, with the remainder made up of university classrooms, offices, hospitals, public transportation, gymnasiums and residential spaces.

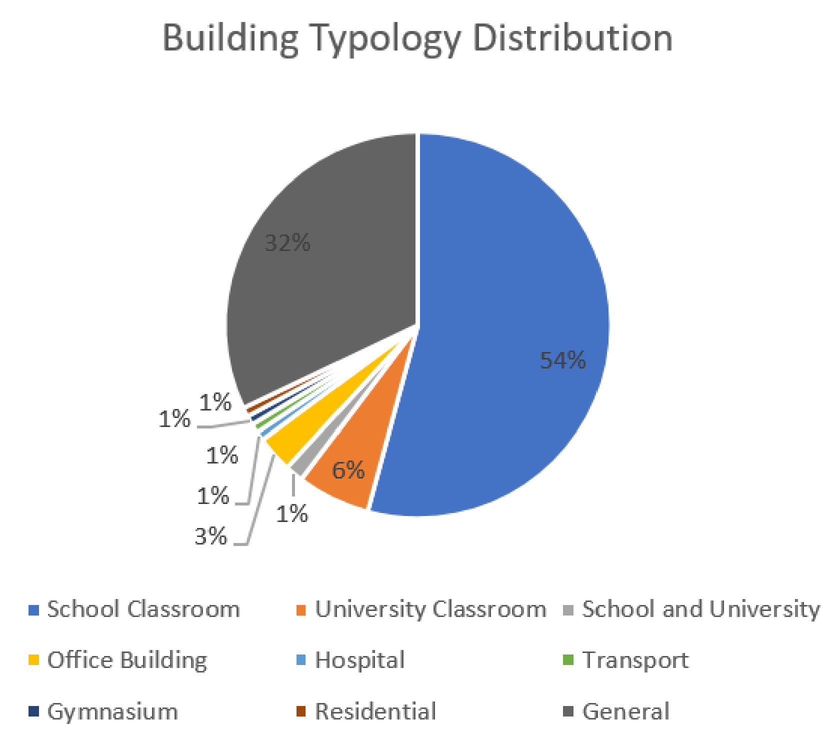

Figure 6. Building Typology Distribution

Overall, the literature found within this systematic process provides a comprehensive representation of the current knowledge and can inform balanced conclusions and guidance.

2.6.1 Literature Ranking

The final body of literature was then reviewed and ranked on a scale of 1 to 5. The purpose of this ranking is to further define the relevance and quality of each study.

Within the ranking scale a ‘5’ is used to represent an empirical study that was closely related to the research questions and provided clear results. A ‘4’ is used to represent an empirical study that was not as closely related to the research questions or reviews that directly address the research questions.

A ‘3’ was used to represent other literature that had a direct relationship with the research questions. A ‘2’ was used to represent literature that had an indirect relationship to the research questions. Finally, a ‘1’ was used to represent guidance documents and grey literature.

3.0 Literature Review

The sections below present the discussion on the two reseaech questions related to naturally ventilated classroom performance during winter months.

3.1 What is the impact of natural ventilation during winter on thermal comfort?

From the 142 papers reviewed, only 5 papers empirically investigated the impact of natural ventilation on thermal comfort during winter.

In Spain, Alonso et al., (2021) analysed the effects of the COVID-19 pandemic on thermal comfort and CO_2, in winter. They carried out in situ measurements of air temperature, relative humidity, and CO_2 concentration before and during the pandemic, in two primary school classrooms. The mean outdoor temperatures were 7 ◦C, while indoor temperatures ranged between 17 ◦C–24 ◦C, with an average temperature differential of 8 ◦C. The openable areas represented 30.6% percent of the south classroom’s envelope and 22.7% of the north classroom’s envelope.

The study found a reduction of 400 ppm when the schools were naturally ventilated during all teaching hours, and that over 60% of hours had thermal discomfort conditions (greater than 25.5 ◦C and less than 18.5 ◦C). However, their findings were limited to an approximation of thermal models and the authors noted that “further analysis in terms of mean radiant and operative temperature should be conducted to represent thorough thermal comfort evaluation”.

In Cyprus, Heracleous & Michael, (2020) evaluated the impact of natural ventilation on the indoor thermal environment in both winter and summer. The mean operative temperatures during winter varied from 19 °C to 21.7 °C. The outdoor temperatures varied from 8.5 °C to a peak of 18.7 °C, with a mean diurnal fluctuation of 5.7 °C. The area of openable windows ranged from 1.75–4.75 m^2.

The study found that for the winter period, students felt neutral or slightly cool, with mean wind chill values of − 0.07, and approximately 30% of students were dissatisfied with the thermal comfort provided. However, the classrooms remained within the comfort zone when heating was used. They concluded that indoor thermal comfort conditions were significantly improved through cross-ventilation strategies. Using both the main openings and clerestory windows assisted with the removal of stale air whilst limiting draughts at the occupant level.

In Switzerland, Vassella et al., (2021) carried out an intervention study to verify whether indoor air quality requirements can be achieved by following reasonable ventilation regimes that are also suitable for countries with cold winters. In 100 primary and secondary classrooms, they measured CO_2 levels in classrooms without any ventilation intervention and compared the effectiveness of natural ventilation during breaks, in the winter season.

Their rationale for performing ventilation exclusively during breaks was to avoid discomfort from cold drafts. They assumed that in Swiss classrooms, ventilation is often inadequate, particularly in winter because of discomfort due to low outdoor temperatures. They hypothesised that ventilating during breaks in the cold season solves the thermal comfort problem. Outdoor temperatures were below 15 ◦C with a median temperature of 3.1 ◦C, and indoor temperature was around 22 ◦C, with the openable window areas ranging from 1.2 – 13.8 m2 with a median of 5.8m2.

The study found that fully opening the windows for 10–15 min every hour reduced the average CO_2 concentrations to the values that would be obtained if the windows were kept constantly open, whilst maintaining the indoor temperature of the classroom at appropriate levels. They concluded that though the average CO_2 levels were reduced from 1600 ppm (control group) to 1097 ppm (intermittent window opening), spontaneous natural window ventilation in countries with cold winters could lead to high CO_2 levels. They recommended that whenever possible, further measures such as intermittent ventilation during class in conjunction with wearing masks should be applied. No distinction was made between secondary and primary schools within this study, presenting a limitation by not acknowledging contextual differences between the two environments.

Another study in Spain, by Miranda et al., (2022) examined how COVID-19 ventilation measures interfere with the thermal comfort of occupants depending on their clothing and the type of activity carried out in a higher education examination centre. The average indoor temperatures were around 21 ◦C. Data was grouped according to whether the average external temperature was up to 6 ◦C, between 6 and 12 ◦C, or above 12 ◦C. Openable window areas ranged from 0.68m2 – 3.85m2.

The study found that when the windows were open and outdoor temperatures were above 12 ◦C, the CO_2 concentration levels were very close to 500 ppm and comfortable thermal conditions were achieved. A significant influence on thermal comfort was observed when implementing natural ventilation when exterior temperatures were below 6 ◦C. However, in the range between 6 and 12 ◦C, factors such as occupancy determined the comfort/discomfort conditions.

The authors recommended completely opening wndows at temperatures above 12 ◦C if the risk situation is high. This is because thermal comfort will not be significantly compromised. When external temperatures drop below 12 ◦C, a ventilation strategy using the opening and closing of windows or limiting the number of open windows should be established. This strategy should be complemented by the installation of CO_2 monitors.

However, the findings of this study are limited to a predictive assessment of thermal comfort, and not actual perceptions of the occupants, e.g. by using questionnaires. This study was also carried out in a university environment. While this bears similarities to school classrooms, the findings of thermal comfort will likely differ for younger students. This is because university students do not remain in the same room for the entire learning day as is common in primary schools.

On the range of wintertime temperature acceptability, Jiang et al., (2020) developed a thermal comfort assessment model which emulated different ventilation conditions in primary and secondary schools in China. They found that the comfortable temperature range for 90% of the pupils was 13–18 ◦C with an average clothing insulation value (CLO) of 1.5.

This temperature comfort range is significantly lower than many of the thermal comfort models used in other studies. This may be explained through the low daytime outdoor temperature of -2.4 ◦C, leading to potential climactic adaptation, or the high CLO value. These results suggest that low outdoor temperatures and high CLO values in naturally ventilated classrooms can lead to a wide range of acceptable thermal conditions, some of which are far below the recommended ranges for school classrooms.

Besides the real-world experiments reviewed above, Villers et al., (2021a) simulated a 160 m^3 classroom model containing one infectious individual to explore the effect of interventions (natural ventilation, face masks, portable air cleaners, and their combinations) on the concentration of virus particles. They also calculated the cumulative dose absorbed by exposed occupants.

For winter, they simulated an outdoor temperature of 5°C and indoor temperature of 22°C. They found that “the most effective single intervention was natural ventilation through the full opening of six windows all day during the winter, and that partly opening two windows all day or fully opening six windows at the end of each class was effective as well”. They did not recommend only opening windows during lunch breaks because this was the least effective intervention.

Their experiment also found natural ventilation to be the most effective in winter and that the fresh air flow rate for single-sided natural ventilation is proportional to the difference between outdoor and indoor temperature. However, they stated that when outdoor temperatures are too extreme, there is too much noise or the outdoor air is too polluted, natural ventilation is inadvisable. This prompted their investigation of alternative strategies (such as portable air cleaners) to reduce virion concentration. Their overall conclusion was that combined interventions (natural ventilation, masks, and HEPA filtration) were highly effective in the presence of an individual with COVID-19.

Thermal comfort is a subjective assessment by which people consider themselves to be satisfied with their indoor environment. Studies (Cheng & Brown, 2020; De Dear et al., 2015) indicate that children may be more sensitive to higher temperatures than adults. This is because they generally prefer conditions to be a few degrees cooler due to their higher metabolic rate and activity levels over the course of a school day.

This is an important consideration because the adult teacher will most likely have the most behavioural impact on the thermal conditions of the space, such as window opening. In reality, what feels comfortable is not just related to air temperature, but also to other factors including:

- relative humidity
- surrounding radiant temperatures
- air movement
- occupant activity levels, and
- clothing worn.

‘Comfort’ inside naturally ventilated buildings will need to adapt accordingly to the occupants’ experience of external temperature.

For example, a study by Yao et. al., (Yao et al., 2010) found that occupants of naturally ventilated spaces were less thermally sensitive than those occupying air conditioned spaces. This finding was supported by a further study Lau et. al., (Lau et al., 2019) showing that people in naturally ventilated buildings tend to have a wider range of thermal acceptability than predicted in a predicted mean vote (PMV) model.

The personal thermal comfort parameters such as clothing, operation of fans, and intake of hot beverages were observed to be taken advantage of in a naturally conditioned environment. This indicates that behavioural adaptation can be used as a mitigation for occupants’ thermal sensitivities (Yao et al., 2010).

The impact of cold outdoor temperatures also helps people to adapt to colder indoor temperatures (Cao et al., 2011). In the survey carried out by Heracleous & Michael, (2020) despite the fact that the classrooms had temperatures lower than the adaptive comfort minimum level of 18 °C, the majority of students showed a high tolerance and felt comfortable during winter. De Dear & Brager (“Developing an Adaptive Model of Thermal Comfort and Preference,” 1998) support these findings through suggesting that a much wider range of thermal acceptability is achieved in naturally ventilated buildings due to psychological adaptation in the form of shifting expectations.

Given the variation in New Zealand’s climate, thermal comfort will generally change from one geographical location to the other according to the local climate, built environments, and occupants. Occupancy heat gains and solar heat can also significantly contribute to temperature goals in colder seasons.

However, despite this adaptivity, measures to reduce the impact of thermal non-uniformity and draughts from displacement ventilation in classrooms requires careful consideration. Most studies carried out so far in this field have particularly focused on the assessment of ventilation conditions, especially in non-naturally ventilated spaces. This review has shown that there are limited studies that take into account thermal comfort conditions for teachers and students when natural ventilation is used in winter.

3.2 What is the impact of winter on the effectiveness of natural displacement ventilation?

From the 142 papers reviewed, only 13 papers effectively discussed the impact winter conditions have on the performance of natural ventilation.

During the winter season in New Zealand the mean radiant temperature drops well below the range of human thermal comfort, leading to a disparity between the outdoor temperature and indoor classroom temperature (Melgar et al., 2021; Navaratnam et al., 2022; Rencken et al., 2021; Stabile et al., 2017). Due to the relationship between air temperature, air density, and buoyancy, warmer air will rise above cooler air (Fan et al., 2022).

When natural ventilation is used within classrooms during winter, it leads to a thermally non-uniform environment, which has implications for occupant comfort. This is due to heat convection (also known as the stack effect) and air flow. However, this non-uniformity can improve natural ventilation capacity through buoyancy driven air flow.

A simulation study by Henriques et. al. concluded that for a particular ventilation scenario in a small waiting room, natural ventilation was approximately twice as effective in winter as it was in summer (Henriques et al., 2022). This finding was supported by the Villers et. al. study which concluded that natural ventilation in winter was more effective than in summer, with six windows opening having a 1.8 fold decrease in cumulative dose of sars-cov-2 in summer and a 2.1 fold decrease in winter. However, they did note that a high ceiling is required to aid this thermal buoyancy driven flow (2021b).

This study also corroborated an analytical approach of air changes per hour being proportional to temperature difference (Henriques et al., 2022). This 'displacement ventilation' typically produces a laminar flow, meaning that air follows a smooth path with little mixing, though this can be heavily influenced by wind conditions (Lipinski et al., 2020).

Humans contribute to this temperature difference through emitted body heat and the temperature of exhaled air and aerosols. These warm air plumes can significantly affect the movement of air in rooms. This is more pronounced when people and air movement are limited and when the ambient temperature is low (He et al., 2021; Rencken et al., 2021).

Cross-ventilation is seen as being a crucial design element for schools in the wake of the COVID-19 pandemic (Saeed et al., 2021). However cross-ventilation can present its own issues. Although it can provide the impression of ventilation, it can also carry contaminants horizontally (Rencken et al., 2021).

Vertical displacement ventilation can provide a better solution for COVID-19 mitigation. However, although natural displacement ventilation can be more effective in winter, it can also cause major heat loss, because natural displacement ventilation makes use of warmer rising air to maintain adequate air flow. This heat loss can subsequently decrease the effectiveness of thermal displacement driven natural ventilation because of the decrease in temperature differential (Zivelonghi & Lai, 2021). This heat loss has consequences in terms of thermal comfort and energy demands (Melgar et al., 2021).

Thermal displacement offers effective strategies for the reduction of COVID-19 exposure risk through the removal of warm, SARS-CoV-2 aerosol-containing air travelling from breathing height to the ceiling height of a room (Bhagat et al., 2020). However, a balance must be found between the effectiveness of displacement ventilation for indoor air quality and viral exposure risk, and thermal comfort and heating demands.

In conclusion, this review has provided indications that:

- Natural ventilation is most effective in winter due to buoyancy driven air flow. However, when the outdoor temperature equals the indoor temperature, there is no natural draught pressure due to temperature difference. This means that only wind will move air. High ceilings are also required for effective buoyancy driven air flow.

- Partly opening windows in classrooms can achieve adequate air flow on cold days above 12 ◦C and maintain acceptable temperature levels depending on space usage. However, only opening windows during lunch breaks is an ineffective strategy for wintertime ventilation.
- At temperatures below 12 ◦C, a ventilation strategy using the opening and closing of windows or limiting the number of open windows should be established. This strategy should be complemented by the installation of CO_2 monitors.
- Wintertime ventilation can be improved through clerestory windows to assist with the removal of hot air, due to the stack effect. This approach also maintains adequate indoor thermal comfort.
- In colder climates and in the presence of individuals infected with COVID-19, combined interventions (natural ventilation, masks, and portable air cleaners) is a highly effective strategy.
- Windows should be completely opened at temperatures above 12 ◦C, if the risk situation is high.
- A temperature of ±3 ◦C around the optimum minimum comfort temperature levels of ±18 ◦C may still be tolerable to children. This is because children generally prefer conditions to be a few degrees cooler due to their higher metabolic rate and activity levels over the course of a school day.

Summarily, there is a significant literature gap for survey based thermal comfort investigations in naturally ventilated classrooms during winter months in a comparable climate to New Zealand. Hence, the need for further research on the impact of natural ventilation during winter on thermal comfort.

4.0 Acknowledgements

The Ministry would like to thank the following people for reviewing this document:

Dr Manfred Plagmann	Building Research Association of New Zealand (BRANZ)
Dr Mikael Boulic	Massey University

5.0 References

Ackley, A., Donn, M., & Thomas, G. (2017). The Influence of Indoor Environmental Quality in Schools A Systematic Literature Review. In M. Schnabel (Ed.), *The Next 50 Years, (51st International Conference of the Architectural Science Association (ANZAScA))* (pp. 625–634). Architectural Science Association.

Alonso, A., Llanos, J., Escandón, R., & Sendra, J. J. (2021). Effects of the covid-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a mediterranean climate. *Sustainability (Switzerland)*, *13*(5), 1–17. https://doi.org/10.3390/su13052699

ASHRAE Epidemic Task Force. (2020). *Ashrae Epidemic Task Force. SCHOOLS & UNIVERSITIES*. 2021.

Australian Health Protection Principal Committee. (2021). *Australian Health Protection Principal Committee (AHPPC) Statement on the Role of Ventilation in Reducing the Risk of Transmission of COVID-19*.

Bhagat, R. K., Davies Wykes, M. S., Dalziel, S. B., & Linden, P. F. (2020). Effects of ventilation on the indoor spread of COVID-19. *Journal of Fluid Mechanics*, *903*. https://doi.org/10.1017/jfm.2020.720

Cao, B., Zhu, Y., Ouyang, Q., Zhou, X., & Huang, L. (2011). Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing. *Energy and Buildings*, *43*(5), 1051–1056. https://doi.org/10.1016/j.enbuild.2010.09.025

Centers for Disease Control and Prevention. (2021). *Ventilation in Schools and Childcare Programs*.

Cheng, W., & Brown, R. D. (2020). An energy budget model for estimating the thermal comfort of children. *International Journal of Biometeorology*, *64*(8), 1355–1366. https://doi.org/10.1007/s00484-020-01916-x

CIBSE. (2021). COVID-19: Ventilation. In *Version 5*.

De Dear, R., Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in Australian school classrooms. *Building Research and Information*, *43*(3), 383–398. https://doi.org/10.1080/09613218.2015.991627

Developing an adaptive model of thermal comfort and preference. (1998). *ASHRAE Transactions*, *104*, 145–167.

Fan, M., Fu, Z., Wang, J., Wang, Z., Suo, H., Kong, X., & Li, H. (2022). A review of different ventilation modes on thermal comfort, air quality and virus spread control. *Building and Environment*, *212*(January), 108831. https://doi.org/10.1016/j.buildenv.2022.108831

Government of Canada. (2021). *COVID-19: Guidance on indoor ventilation during the pandemic*.

He, R., Liu, W., Elson, J., Vogt, R., Maranville, C., & Hong, J. (2021). Airborne transmission of COVID-19 and mitigation using box fan air cleaners in a poorly ventilated classroom. *Physics of Fluids*, *33*(5). https://doi.org/10.1063/5.0050058

Health and Safety Executive. (2022). *Ventilation During the Coronavirus (COVID-19) Pandemic*.

Henriques, A., Mounet, N., Aleixo, L., Elson, P., Devine, J., Azzopardi, G., Andreini, M., Rognlien, M., Tarocco, N., & Tang, J. (2022). Modelling airborne transmission of SARS-CoV-2 using CARA: Risk assessment for enclosed spaces. *Interface Focus*, *12*(2). https://doi.org/10.1098/rsfs.2021.0076

Heracleous, C., & Michael, A. (2020). Thermal comfort models and perception of users in free-running school buildings of East-Mediterranean region. *Energy and Buildings*, *215*, 109912. https://doi.org/10.1016/j.enbuild.2020.109912

Jiang, J., Wang, D., Liu, Y., Di, Y., & Liu, J. (2020). A field study of adaptive thermal comfort in primary and secondary school classrooms during winter season in Northwest China. *Building and Environment*, *175*(19), 106802. https://doi.org/10.1016/j.buildenv.2020.106802

Kapoor, N. R., Kumar, A., Meena, C. S., Kumar, A., Alam, T., Balam, N. B., & Ghosh, A. (2021). A Systematic Review on Indoor Environmental Quality in Naturally Ventilated School Classrooms: A Way Forward. *Advances in Civil Engineering*, *2021*. https://doi.org/10.1155/2021/8851685

Lau, S. S. Y., Zhang, J., & Tao, Y. (2019). A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus. *Building and Environment*, *148*(November 2018), 579–599. https://doi.org/10.1016/j.buildenv.2018.11.032

Lipinski, T., Ahmad, D., Serey, N., & Jouhara, H. (2020). Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings. *International Journal of Thermofluids*, *7–8*, 100045. https://doi.org/10.1016/j.ijft.2020.100045

Melgar, S. G., Cordero, A. S., Rodríguez, M. V., & Márquez, J. M. A. (2021). Influence on indoor comfort due to the application of Covid-19 natural ventilation protocols for schools at subtropical climate during winter season. *E3S Web of Conferences*, *293*, 01031. https://doi.org/10.1051/e3sconf/202129301031

Ministry of Business Innovation & Employment. (2021). *Outcome of consultation: Building Code update 2021*. *November*.

Miranda, M. T., Romero, P., Valero-Amaro, V., Arranz, J. I., & Montero, I. (2022). Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with Mediterranean climate. *International Journal of Hygiene and Environmental Health*, *240*(October 2021), 113910. https://doi.org/10.1016/j.ijheh.2021.113910

MoE. (2021). *Indoor Air Quality and Thermal Comfort*. *September*, 1–8.

MoE. (2022). *COVID-19 Ventilation Programme*. Ministry of Education, New Zealand. https://temahau.govt.nz/covid-19/advice-schools-and-kura/ventilation-schools#classroom-ventilation-study

National Education Union. (2019). *Cold weather and classroom temperature (England)*.

National Joint Council. (2011). *Permanent Structures and Safe Occupancy of the Workplace (Use and Occupancy of Buildings)*.

Navaratnam, S., Nguyen, K., Selvaranjan, K., Zhang, G., Mendis, P., & Aye, L. (2022). Designing Post COVID-19 Buildings: Approaches for Achieving Healthy Buildings. *Buildings*, *12*(1). https://doi.org/10.3390/buildings12010074

NIWA. (2022a). *Overview of New Zealand's Climate*.

NIWA. (2022b). *Ventilation and Air Quality in 18 School Classrooms - Rapid Study* (Issue February). https://temahau-live-storagestack-pv-assetstorages3bucket-4pgakoc5n3r5.s3.amazonaws.com/s3fs-public/2022-03/FINAL_MoE_NIWA_Classroom ventilation study.pdf?VersionId=ifx0iLzPmSfs.DO_ASKu7eFNjTyq8dsl

Regional Educational Laboratory Program. (2018). *Optimal classroom temperature to support student learning*.

Rencken, G. K., Rutherford, E. K., Ghanta, N., Kongoletos, J., & Glicksman, L. (2021). Patterns of SARS-CoV-2 aerosol spread in typical classrooms. *Building and Environment*, *204*(July), 108167. https://doi.org/10.1016/j.buildenv.2021.108167

Saeed, D. M., Elkhatib, W. F., & Selim, A. M. (2021). Architecturally safe and healthy classrooms: eco-medical concept to achieve sustainability in light of COVID-19 global pandemic. *Journal of Asian Architecture and Building Engineering*, *00*(00), 1–16. https://doi.org/10.1080/13467581.2021.1972811

Stabile, L., Dell'Isola, M., Russi, A., Massimo, A., & Buonanno, G. (2017). The effect of natural ventilation strategy on indoor air quality in schools. *Science of the Total Environment*, *595*, 894–902. https://doi.org/10.1016/j.scitotenv.2017.03.048

The Chartered Institution of Building Services Engineers. (2015). *CIBSE Journal*. *April*.

United States Environmental Protection Agency. (2021). *Indoor Air Quality*.

Vassella, C. C., Koch, J., Henzi, A., Jordan, A., Waeber, R., Iannaccone, R., & Charrière, R. (2021). From spontaneous to strategic natural window ventilation: Improving indoor air quality in Swiss schools. *International Journal of Hygiene and Environmental Health*, *234*(April). https://doi.org/10.1016/j.ijheh.2021.113746

Villers, J., Henriques, A., Calarco, S., Rognlien, M., Mounet, N., Devine, J., Azzopardi, G., Elson, P., Andreini, M., Tarocco, N., Vassella, C., & Keiser, O. (2021a). SARS-CoV-2 aerosol transmission in schools: the effectiveness of different interventions. *MedRxiv*, 2021.08.17.21262169. https://www.medrxiv.org/content/10.1101/2021.08.17.21262169v2%0Ahttps://www.medrxiv.org/content/10.1101/2021.08.17.21262169v2.abstract

Villers, J., Henriques, A., Calarco, S., Rognlien, M., Mounet, N., Devine, J., Azzopardi, G., Elson, P., Andreini, M., Tarocco, N., Vassella, C., & Keiser, O. (2021b). SARS-CoV-2 aerosol transmission in schools: the effectiveness of different interventions. *MedRxiv*, 2021.08.17.21262169.

World Health Organization. (2021). Covid-19. *World Health Organisation*, *March*, 1–28.

Yao, R., Liu, J., & Li, B. (2010). Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms. *Applied Energy*, *87*(3), 1015–1022. https://doi.org/10.1016/j.apenergy.2009.09.028

Zivelonghi, A., & Lai, M. (2021). The role of classroom volume, occupancy, voice reduction and ffp2 masks in transmission risk of SARS-CoV2 in schools. *MedRxiv*, 2021.03.23.21253503.

6.0 List of Tables

7.0 List of Figures

8.0 Appendices

Author/s	Year	Title	Context	Typology	Type of Study	Measured	Ranking
Abuhegazy, M., Talaat, K., Anderoglu, O., Poroseva, S. V., & Talaat, K.	2020	Numerical investigation of aerosol transport in a classroom with relevance to COVID-19	New Mexico	School classroom	Simulation	Aerosol deposition	2
Aguilar, A. J., De La Hoz-Torres, M. L., Martínez-Aires, M. D., & Ruiz, D. P.	2021	Monitoring and assessment of indoor environmental conditions after the implementation of COVID-19-based ventilation strategies in an educational building in southern Spain.	Granada, Spain	University classroom	Experiment	temperature, relative humidity, CO2 concentration, acoustic environment, and air velocity	3
Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D.	2016	Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments.	USA	Office Building	Experiment	higher-order cognitive function	2
Alonso, A., Llanos, J., Escandón, R., & Sendra, J.	2021	Effects of the COVID-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a Mediterranean climate	Spain	School classroom	Experiment	Temperature, thermal comfort, CO2	3
Arjmandi, H., Amini, R., khani, F., & Fallahpour, M.	2022	Minimizing the respiratory pathogen transmission: Numerical study and multi-objective optimization of ventilation systems in a classroom.	Iran	School classroom	Simulation	Spread of particles, thermal comfort	2
Asanati, K., Voden, L., & Majeed, A.	2021	Healthier schools during the COVID-19 pandemic: ventilation, testing and vaccination.	UK	School classroom	Review		2
Ascione, F., De Masi, R. F., Mastellone, M., & Vanoli, G. P.	2021	Healthier schools during the COVID-19 pandemic: ventilation, testing and vaccination.	Italy	University classroom	Experiment and simulation	Energy Performance, temperature, airspeed, age of air	3
ASHRAE	2020	*Guidance for the Re-Opening of Schools*.		School classroom	Guidance		1
ASHRAE	2021	*Ashrae Epidemic Task Force. SCHOOLS & UNIVERSITIES*.		Schools and university classroom	Guidance		1
Azuma, K., Yanagi, U., Kagi, N., Kim, H., Ogata, M., & Hayashi, M.	2020	Environmental factors involved in SARS-CoV-2 transmission: effect and role of indoor environmental quality in the strategy for COVID-19 infection control.	Japan	General	Review		1
Baboli, Z., Neisi, N., Babaei, A. A., Ahmadi, M., Sorooshian, A.,	2021	On the airborne transmission of SARS-CoV-2 and relationship with indoor conditions at a hospital.	Iran	Hospital	Experiment	Airborne sars-cov-2 viral particles	2

Birgani, Y. T., & Goudarzi, G.							
Bartyzel, J., Zieba, D., Necki, J., & Zimnoch, M.	2020	Assessment of ventilation efficiency in school classrooms based on indoor-outdoor particulate matter and carbon dioxide measurements.	Poland	School classroom	Experiment	PM, CO2	3
Bhagat, R. K., Davies Wykes, M. S., Dalziel, S. B., & Linden, P. F.	2020	Effects of ventilation on the indoor spread of COVID-19.	UK	General	Review		2
Birmili, W., Selinka, H. C., Daniels, A., & Straf, W.	2022	*Ventilation concepts in schools to prevent transmission of highly infectious viruses (SARS-CoV-2) via aerosols in the room air.*	Germany	School classroom	Review		3
Biryukov, J., Boydston, J. A., Dunning, R. A., Yeager, J. J., Wood, S., Reese, A. L., Ferris, A., Miller, D., Weaver, W., Zeitouni, N. E., Phillips, A., Freeburger, D., Hooper, I., Ratnesar-Shumate, S., Yolitz, J., Krause, M., Williams, G., Dawson, D. G., Herzog, A., … Altamura, L. A.	2020	Increasing Temperature and Relative Humidity Accelerates Inactivation of SARS-CoV-2 on Surfaces.	USA	General	Experiment	Sars-cov-2 decay. Changing humidity and temperatur e.	2
Blocken, B., van Druenen, T., Ricci, A., Kang, L., van Hooff, T., Qin, P., Xia, L., Ruiz, C. A., Arts, J. H., Diepens, J. F. L., Maas, G. A., Gillmeier, S. G., Vos, S. B., & Brombacher, A. C.	2021	Ventilation and air cleaning to limit aerosol particle concentrations in a gym during the COVID-19 pandemic.	The Netherland s	Gymnasium	Experiment	ACH, PM	3
Buonanno, G., Stabile, L., & Morawska, L.	2020	Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment.	Italy	General	Simulation	Emitted viral load	2
Burgmann, S., & Janoske, U.	2021	Transmission and reduction of aerosols in classrooms using air purifier systems	Germany	School classroom	Experiment & Simulation	Transmissio n risk	5
Burridge, H. C., Bhagat, R. K., Stettler, M. E. J., Kumar, P., De Mel, I., Demis, P., Hart, A., Johnson-Llambias, Y., King, M. F., Klymenko, O., McMillan, A., Morawiecki, P., Pennington, T., Short, M., Sykes, D., Trinh, P. H., Wilson,	2021	The ventilation of buildings and other mitigating measures for COVID-19: A focus on wintertime.	UK	General	Review		4

S. K., Wong, C., Wragg, H., … Linden, P. F.							
Canha, N., Almeida, S. M., Freitas, M. C., Täubel, M., & Hänninen, O.	2013	Winter ventilation rates at primary schools: Comparison between Portugal and Finland.	Portugal, Finland	School classroom	Experiment	CO2	3
Cao, B., Zhu, Y., Ouyang, Q., Zhou, X., & Huang, L.	2011	Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing.	Beijing	University classroom	Experiment	PMV, temperatur e	3
Carriço de Lima Montenegro Duarte, J. G., Ramos Zemero, B., Dias Barreto de Souza, A. C., de Lima Tostes, M. E., & Holanda Bezerra, U.	2021	Building Information modeling approach to optimize energy efficiency in educational buildings.	Brazil	School and university classroom	Simulation	Daylight, thermal conditions, energy consumptio n, ventilation	2
Centers for Disease Control and Prevention	2021	COVID-19 Ventilation in Schools and Childcare Projects		School classroom	Guidance		1
Che, W., Ding, J., & Li, L.	2022	Airflow deflectors of external windowsto induce ventilation: Towards COVID-19 prevention and control.	China	School classroom	Experiment	Air diffusion performanc e index, infection risk	3
Chen, C. Y., Chen, P. H., Chen, J. K., & Su, T. C.	2021	Recommendations for ventilation of indoor spaces to reduce COVID-19 transmission.	Taiwan	General	Review		2
Chen, W., Kwak, D. Bin, Anderson, J., Kanna, K., Pei, C., Cao, Q., Ou, Q., Kim, S. C., Kuehn, T. H., & Pui, D. Y. H.	2021	Study on droplet dispersion influenced by ventilation and source configuration in classroom settings using low-cost sensor network.	USA	School classroom	Experiment	Particle concentrati on monitoring network	3
Chen, W., Kwak, D. Bin, Anderson, J., Kanna, K., Pei, C., Cao, Q., Ou, Q., Kim, S. C., Kuehn, T. H., & Pui, D. Y. H	2021	Realizing natural ventilation potential through window control: The impact of occupant behavior.	China	General	Simulation	Comfort degree hours, energy performanc e	3
Chillon, S. A., Millan, M., Aramendia, I., Fernandez-Gamiz, U., Zulueta, E., & Mendaza-Sagastizabal, X.	2021	Natural ventilation characterization in a classroom under different scenarios.	Spain	School classroom	Experiment	CO2, PM, Temperatur e, relative humidity	3
Christopherson, D. A., Yao, W. C., Lu, M., Vijayakumar, R., & Sedaghat, A. R.	2020	High-Efficiency Particulate Air Filters in the Era of COVID-19: Function and Efficacy.	USA	Office building	Review		3
Coley, D. A., Greeves, R., & Saxby, B. K.	2007	The effect of low ventilation rates on the cognitive function of a primary school class	UK	School classroom	Experiment	CO2, Cognitive performanc e	2

Conway-morris, A., Dphil, K. S., Bmbs, R. B., Mphil, M. M., Higginson, E., Forrest, S., Pereira-, J., Cormie, C., Ma, T. O., Brooks, S., Frca, I. H., Mbchb, K., Turner, A., White, P., Frcp, R. A. F., Dougan, G., Sc, D., Gkrania-klotsas, E., Gouliouris, T., & Baker, S.	2021	The removal of airborne SARS-CoV-2 and other microbial bioaerosols by air filtration on COVID-19 surge units	UK	Hospital	Experiment	Sars-cov-2 aerosols	2
Curtius, J., Granzin, M., & Schrod, J.	2021	Testing mobile air purifiers in a school classroom: Reducing the airborne transmission risk for SARS-CoV-2.	Germany	School classroom	Experiment	Aerosol concentrati on, aerosol size distribution	5
Day, J. K., & Gunderson, D. E.	2015	Understanding high performance buildings: The link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction	USA	General	Experiment	Environmen tal satisfaction, knowledge of building system	2
De Dear, R. J., & Brager, G. S.	2002	Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55.	USA	General	Review		2
Deme Belafi, Z., Naspi, F., Arnesano, M., Reith, A., & Revel, G. M.	2018	Investigation on window opening and closing behavior in schools through measurements and surveys: A case study in Budapest.	Hungary	School classroom	Experiment	Window opening behaviour and contextual factor	2
Deng, S., Zou, B., & Lau, J.	2021	The adverse associations of classrooms' indoor air quality and thermal comfort conditions on students' illness related absenteeism between heating and non-heating seasons—a pilot study.	USA	School classroom	Experiment	Illness related absenteeism , indoor air quality, thermal comfort	2
Díaz-Calderón, S. F., Castillo, J. A., & Huelsz, G.	2021	Indoor air quality evaluation in naturally cross-ventilated buildings for education using age of air	Mexico	School and university classroom	Experiment	ACH, age of air, renovation parameter	3
Díaz-López, C., Serrano-Jiménez, A., Lizana, J., López-García, E., Molina-Huelva, M., & Barrios-Padura, Á.	2022	Passive action strategies in schools: A scientific mapping towards eco-efficiency in educational buildings		School and university classroom	Review		1
Ding, E., Zhang, D., & Bluyssen, P. M.	2021	Ventilation strategies of school classrooms against cross-infection of COVID-19: A review.		School classroom	Review		3
Ding, E., Zhang, D., & Bluyssen, P. M.	2022	Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review.		School classroom	Review		2

Domingo, J. L., Marquès, M., & Rovira, J.	2020	Influence of airborne transmission of SARS-CoV-2 on COVID-19 pandemic. A review.		General	Review		2
Duill, F. F., Schulz, F., Jain, A., Krieger, L., van Wachem, B., & Beyrau, F.	2021	The impact of large mobile air purifiers on aerosol concentration in classrooms and the reduction of airborne transmission of Sars-Cov-2.	Germany	School classroom	Experiment	Number of particles, particle size distribution, CO2	5
Dutton, S., & Shao, L.	2010	Window opening behaviour in a naturally ventilated school.	UK	School classroom	Experiment	Window opening, CO2, temperatur e, exterior environmen tal conditions, occupancy levels, energy usage	3
Erhart, T., Guerlich, D., Schulze, T., & Eicker, U.	2015	Experimental validation of basic natural ventilation air flow calculations for different flow path and window configurations	Germany	Office Building	Experiment	ACH, CO2, windspeed	2
Fan, M., Fu, Z., Wang, J., Wang, Z., Suo, H., Kong, X., & Li, H.	2022	A review of different ventilation modes on thermal comfort, air quality and virus spread control.		General	Review		2
Farthing, T. S., & Lanzas, C.	2021	Assessing the efficacy of interventions to control indoor SARS-Cov-2 transmission: An agent-based modeling approach.	USA	General	Simulation	Indoor respiratory pathogen transmission	3
Feng, Y., Marchal, T., Sperry, T., & Yi, H.	2020	Influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission: A numerical study.	USA	General	Simulation	Aerosol transmission , wind, humidity	1
Fisk, W. J.	2017	The ventilation problem in schools: literature review	USA	School classroom	Review		2
Franceschini, P. B., & Neves, L. O.	2022	A critical review on occupant behaviour modelling for building performance simulation of naturally ventilated school buildings and potential changes due to the COVID-19 pandemic	Brazil	School classroom	Review		2
Franco, A., & Leccese, F.	2020	Measurement of CO2 concentration for occupancy estimation in educational buildings with energy efficiency purposes	Italy	School classroom	Experiment	CO2, occupancy	3
García-arquimbáu, A. L. D. E. R., & Arranz, B. A.	2020	Comprehensive evaluation of daylighting, air quality and themral comfort as a renovation impact in a Madrid classroom	Madrid	School classroom	Experiment	IAQ, thermal comfort, visual comfort	2
Gehrke, S. G., Förderer, C., Weiskirchen, R., & Stremmel, W.	2021	Cold traps as reliable devices for quantitative determination of SARS-CoV-2 load in aerosols	Germany	General	Experiment	Trapped sars-cov-2 particles in cold traps	2

Gettings, J., Czarnik, M., Morris, E., Haller, E., Thompson-Paul, A. M., Rasberry, C., Lanzieri, T. M., Smith-Grant, J., Aholou, T. M., Thomas, E., Drenzek, C., & MacKellar, D.	2021	Mask Use and Ventilation Improvements to Reduce COVID-19 Incidence in Elementary Schools — Georgia, November 16–December 11, 2020	USA	School classroom	Experiment	COVID-19 mitigation measures, COVID-19 transmission	3
Gil-Baez, M., Barrios-Padura, Á., Molina-Huelva, M., & Chacartegui, R.	2017	Natural ventilation systems in 21st-century for near zero energy school buildings.	Spain	School classroom	Experiment	CO2, occupancy, temperatur e, humidity	2
Gładyszewska-Fiedoruk, K.	2011	Analysis of stack ventilation system effectiveness in an average kindergarten in north-eastern Poland.	Poland	School classroom	Experiment	ACH, CO2, Temperatur e, humidity	2
Greenhalgh, T., Katzourakis, A., Wyatt, T. D., & Griffin, S.	2021	Rapid evidence review to inform safe return to campus in the context of coronavirus disease 2019 (COVID-19).	UK	University classroom	Review		2
Haddad, S., Synnefa, A., Ángel Padilla Marcos, M., Paolini, R., Delrue, S., Prasad, D., & Santamouris, M.	2021	On the potential of demand-contsrolled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms.	Australian	School classroom	Experiment	Infiltration, ventilation, CO2, thermal comfort	3
Hayashi, M., Yanagi, U., Azuma, K., Kagi, N., Ogata, M., Morimoto, S., Hayama, H., Mori, T., Kikuta, K., Tanabe, S., Kurabuchi, T., Yamada, H., Kobayashi, K., Kim, H., & Kaihara, N.	2020	Measures against COVID-19 concerning Summer Indoor Environment in Japan.	Japan	General	Experiment	Sars-cov-2 air diffusion and decay, humidity, temperatur e	2
He, R., Liu, W., Elson, J., Vogt, R., Maranville, C., & Hong, J.	2021	Airborne transmission of COVID-19 and mitigation using box fan air cleaners in a poorly ventilated classroom.		School classroom	Simulation	Sars-cov-2 aerosols	3
Hellwig, R. T., Antretter, F., Holm, A., & Sedlbauer, K.	2008	The use of windows as controls for indoor environmental conditions in schools.	Germany	School classroom	Experiment	Temperatur e, CO2, window opening	3
Henriques, A., Mounet, N., Aleixo, L., Elson, P., Devine, J., Azzopardi, G., Andreini, M., Rognlien, M., Tarocco, N., & Tang, J.	2022	Modelling airborne transmission of SARS-CoV-2 using CARA: Risk assessment for enclosed spaces.	Switzerland	General	Simulation	Infection probability	3
Heracleous, C., & Michael, A.	2019	Experimental assessment of the impact of natural ventilation on indoor air quality and thermal comfort conditions	Cyprus	School classroom	Experiment	IAQ, Thermal comfort,	3

		of educational buildings in the Eastern Mediterranean region during the heating period.				relative humidity, CO2, temperatur e	
Holgate, S., Grigg, J., Arshad, H., Carslaw, N., Cullinan, P., Dimitroulopoulou, S., Greenough, A., Holland, M., Jones, B., Linden, P., Sharpe, T., Short, A., Turner, B., Ucci, M., Vardoulakis, S., Stacey, H., & Hunter, L.	2021	Health Effects of Indoor Air Quality on Children and Young People.	UK	General	Review		1
Hou, D., Katal, A., Wang, L. (Leon), Katal1, A., & Wang, L. (Leon).	2021	Bayesian Calibration of Using CO2 Sensors to Assess Ventilation Conditions and Associated COVID-19 Airborne Aerosol Transmission Risk in Schools.	Canada	School classroom	Experiment	Occupancy, ventilation status, window status, CO2, infection probability	3
Jiang, J., Wang, D., Liu, Y., Di, Y., & Liu, J.	2020	A field study of adaptive thermal comfort in primary and secondary school classrooms during winter season in Northwest China	China	School classroom	Experiment	Thermal comfort	3
Jones E, Young A, Clevenger K, Salimifard P, Wu E, Luna ML, Lahvis M, Lang J, Bliss M, Azimi P, Cedeno-Laurent J, A. J.	2020	Healthy schools: risk reduction strategies for reopening schools.	USA	School classroom	Guidance		1
Kapoor, N. R., Kumar, A., Meena, C. S., Kumar, A., Alam, T., Balam, N. B., & Ghosh, A.	2021	A Systematic Review on Indoor Environmental Quality in Naturally Ventilated School Classrooms: A Way Forward.	India	School classroom	Review		2
Kirkman, S., Zhai, J., & Miller, S. L.	2020	Respiratory Droplets : Recommendations for Air Cleaner Selection for Campus Spaces.	USA	University classroom	Review		1
Kohanski, M. A., Lo, L. J., & Waring, M. S.	2020	Review of indoor aerosol generation, transport, and control in the context of COVID-19.	USA	General	Review		2
Kriegel, M., Hartmann, A., Buchholz, U., Seifried, J., Baumgarte, S., & Gastmeier, P.	2022	Sars-cov-2 aerosol transmission indoors: A closer look at viral load, infectivity, the effectiveness of preventive measures and a simple approach for practical recommendations.	Germany	General	Experiment	CO2, CO2 dose, person related volume flow rate, even volume flow rate, infection probability	3

Krishnaratne, S., Littlecott, H., Sell, K., Burns, J., Rabe, J. E., Stratil, J. M., Litwin, T., Kreutz, C., Coenen, M., Geffert, K., Boger, A. H., Movsisyan, A., Kratzer, S., Klinger, C., Wabnitz, K., Strahwald, B., Verboom, B., Rehfuess, E., Biallas, R. L., … Pfadenhauer, L. M.	2022	Measures implemented in the school setting to contain the COVID-19 pandemic: a rapid review		School classroom	Review		2
Kükrer, E., & Eskin, N.	2021	Effect of design and operational strategies on thermal comfort and productivity in a multipurpose school building.	Turkey	School classroom	Experiment and simulation	Temperature, relative humidity, mean air velocity, activity level, productivity	3
Larsen, T. S., & Heiselberg, P.	2008	Single-sided natural ventilation driven by wind pressure and temperature difference.	Denmark	General	Experiment	Tracer gas, velocity profiles	2
Lasser, J., Sorger, J., Richter, L., Thurner, S., Schmid, D., & Klimek, P.	2022	Assessing the impact of SARS-CoV-2 prevention measures in Austrian schools using agent-based simulations and cluster tracing data	Austria	School classroom	Simulation	Transmission rate	3
Lau, S. S. Y., Zhang, J., & Tao, Y.	2019	A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus	Singapore	University classroom	Experiment	Thermal comfort, ventilation type	3
Lee, J. H., Rounds, M., McGain, F., Schofield, R., Skidmore, G., Wadlow, I., Kevin, K., Stevens, A., Marshall, C., Irving, L., Kainer, M., Buising, K., & Monty, J.	2022	Effectiveness of portable air filtration on reducing indoor aerosol transmission: preclinical observational trials.	Australia	General	Experiment	Aerosol clearance rate	4
Lee, J., Park, S. H., Sung, G. B., An, I. H., Lee, K. R., Hong, S. P., Yook, S. J., & Koo, H. B.	2021	Effect of air cleaner on reducing concentration of indoor-generated viruses with or without natural ventilation.	Korea	School classroom	Experiment	Age of air	5
Lelieveld, J., Helleis, F., Borrmann, S., Cheng, Y., Drewnick, F., Haug, G., Klimach, T., Sciare, J., Su, H., & Pöschl, U.,	2020	Model calculations of aerosol transmission and infection risk of COVID-19 in indoor environments	Germany	School classroom	Simulation	Infection risk	5
Li, Y., Qian, H., Hang, J., Chen, X., Cheng, P., Ling, H.,	2021	Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant	China	Hospitality	Experiment and simulation	Ventilation rate, airflow dynamics	2

Wang, S., Liang, P., Li, J., Xiao, S., Wei, J., Liu, L., Cowling, B. J., & Kang, M.							
Lipinski, T., Ahmad, D., Serey, N., & Jouhara, H.	2020	Review of ventilation strategies to reduce the risk of disease transmission in high occupancy buildings.	UK	General	Review		4
Liu, H., Ma, X., Zhang, Z., Cheng, X., Chen, Y., & Kojima, S.	2021	Study on the relationship between thermal comfort and learning efficiency of different classroom-types in transitional seasons in the hot summer and cold winter zone of China.	China	School classroom	Experiment	Thermal comfort, learning performanc e, temperatur e, humidity, airflow	3
Lovec, V., Premrov, M., & Leskovar, V. Ž.	2021	Practical impact of the covid-19 pandemic on indoor air quality and thermal comfort in kindergartens. A case study of Slovenia.	Slovenia	School classroom	Experiment	CO2, temperatur e, humidity	3
Luongo, J. C., Fennelly, K. P., Keen, J. A., Zhai, Z. J., Jones, B. W., & Miller, S. L.	2016	Role of mechanical ventilation in the airborne transmission of infectious agents in buildings	USA	General	Review		1
Ma'bdeh, S. N., Al-Zghoul, A., Alradaideh, T., Bataineh, A., & Ahmad, S.	2020	Simulation study for natural ventilation retrofitting techniques in educational classrooms – A case study.	Jordan	School classroom	Simulation	Ventilation rate, indoor operative temperatur e, relative humidity, CO2	4
Meiss, A., Jimeno-Merino, H., Poza-Casado, I., Llorente-álvarez, A., & Padilla-Marcos, M. Á.	2021	Indoor air quality in naturally ventilated classrooms. Lessons learned from a case study in a COVID-19 scenario.	Spain	School classroom	Experiment	Temperatur e, CO2, PM, TVOC, Occupancy, RH, Ventilation	3
Melgar, S. G., Cordero, A. S., Rodríguez, M. V., & Márquez, J. M. A.	2021	Influence on indoor comfort due to the application of Covid-19 natural ventilation protocols for schools at subtropical climate during winter season.	Spain	School classroom	Experiment	CO2, temperatur e, energy demand	3
Melikov, A., Pitchurov, G., Naydenov, K., & Langkilde, G.	2005	Field study on occupant comfort and the office thermal environment in rooms with displacement ventilation	Denmark	Office building	Experiment	Temperatur e and uniformity, thermal comfort	3
Miller, S. L., Nazaroff, W. W., Jimenez, J. L., Boerstra, A., Buonanno, G., Dancer, S. J., Kurnitski, J., Marr, L. C., Morawska, L., & Noakes, C.	2021	Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event	USA	General	Experiment	Risk of infection, ventilation rate, duration of event, surface deposition	1

Miranda, M. T., Romero, P., Valero-Amaro, V., Arranz, J. I., & Montero, I.	2022	Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with a Mediterranean climate	Spain	School classroom	Experiment	CO2, temperatur e, thermal comfort	2
Monge-Barrio, A., Bes-Rastrollo, M., Dorregaray-Oyaregui, S., González-Martínez, P., Martin-Calvo, N., López-Hernández, D., Arriazu-Ramos, A., & Sánchez-Ostiz, A.	2022	Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID	Spain	School classroom	Experiment	CO2, temperatur e, ventilation	3
Morawska, L., Tang, J. W., Bahnfleth, W., Bluyssen, P. M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F., Haworth, C., Hogeling, J., Isaxon, C., Jimenez, J. L., Kurnitski, J., Li, Y., Loomans, M., Marks, G., Marr, L. C., … Yao, M.	2020	How can airborne transmission of COVID-19 indoors be minimised?		General	Review		3
Motamedi, H., Shirzadi, M., Tominaga, Y., & Mirzaei, P. A.	2022	CFD modeling of airborne pathogen transmission of COVID-19 in confined spaces under different ventilation strategies	UK	General	Simulation	Airborne transmission risk sars-cov-2	3
Mousavi, E. S., Godri Pollitt, K. J., Sherman, J., & Martinello, R. A.	2020	Performance analysis of portable HEPA filters and temporary plastic anterooms on the spread of surrogate coronavirus	USA	Hospital	Experiment	Aerosol removal rate	4
Narayanan, S. R., & Yang, S.	2021	Airborne transmission of virus-laden aerosols inside a music classroom: Effects of portable purifiers and aerosol injection rates	USA	School classroom	Simulation	Ventilation rate, aerosol removal rate	2
Navaratnam, S., Nguyen, K., Selvaranjan, K., Zhang, G., Mendis, P., & Aye, L.	2022	Designing Post COVID-19 Buildings: Approaches for Achieving Healthy Buildings.	Australia	General	Review		4
Nordic Ventilation Group.	2021	Criteria for room air cleaners for particulate matter Recommendation from the Nordic Ventilation Group.	Norway	General	Guidance		1
Nourmohammadi, M., Mirzaei, R., Taban, E., & Yari, S.	2020	Effect of Ventilation System on Spread and Control of Infections (COVID-19) in Indoor Environments: Based on Current Studies.	Iran	General	Review		2
Omrani, S., Matour, S., Bamdad, K., & Izadyar, N.	2021	Ceiling fans as ventilation assisting devices in buildings: A critical review.	Australia	General	Review		2
Pagel, C., & Squires, A.	2021	Schools: Still a gaping hole in the English COVID strategy.	UK	School classroom	Article		1
Park, J., Jeong, B., Chae, Y. T., & Jeong, J. W.	2021	Machine learning algorithms for predicting occupants' behaviour in the manual control of windows for cross-ventilation in homes.	South Korea	Residential	Experiment	Behaviour prediction, exterior conditions, interior conditions	3
Park, S., Choi, Y., Song, D., & Kim, E. K.	2021	Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building.	South Korea	School classroom	Experiment	Tracer gas decay	4
Peng, Z., Deng, W., & Tenorio, R.	2020	An integrated low-energy ventilation system to improve indoor environment performance of school buildings in the cold climate zone of China	China	School classroom	Experiment	PM, CO2, temperature	3
Polyzois, P., & Thompson, S.	2021	Practical Mitigation Strategies for Countering the Spread of Aerosolized COVID-19 Virus (SARS-CoV-2) Using Ventilation and HEPA Air Purifiers: A Literature Review.	Canada	General	Review		4
Ren, C., Cao, S. J., & Haghighat, F.	2022	A practical approach for preventing dispersion of infection disease in naturally ventilated room.	China	School classroom	Experiment	Airflow distribution	4

						performance index	
Rencken, G. K., Rutherford, E. K., Ghanta, N., Kongoletos, J., & Glicksman, L.	2021	Patterns of SARS-CoV-2 aerosol spread in typical classrooms.	USA	School classroom	Experiment	Tracer gas flow and dispersion	3
Robles-Romero, J. M., Conde-Guillén, G., Safont-Montes, J. C., García-Padilla, F. M., & Romero-Martín, M.	2021	Behaviour of aerosols and their role in the transmission of SARS-CoV-2; a scoping review.	Spain	General	Review		2
Rodríguez, M., Palop, M. L., Seseña, S., & Rodríguez, A.	2021	Are the Portable Air Cleaners (PAC) really effective to terminate airborne SARS-CoV-2?	Spain	General	Experiment	Sars-cov-2 capture	2
Saeed, D. M., Elkhatib, W. F., & Selim, A. M.	2021	Architecturally safe and healthy classrooms: eco-medical concept to achieve sustainability in light of COVID-19 global pandemic.	Egypt	School classroom	Experiment and simulation	Sars-cov-2 dispersion	2
SAGE EMG.	2020	Potential application of Air Cleaning devices and personal decontamination to manage transmission of COVID-19.	UK	General	Guidance		1
Saif, J., Wright, A., Khattak, S., & Elfadli, K.	2021	Keeping cool in the desert: Using wind catchers for improved thermal comfort and indoor air quality at half the energy.	Kuwait	School classroom	Experiment	IAQ, thermal comfort, energy use	4
Saini, J., Dutta, M., & Marques, G.	2020	Indoor air quality prediction systems for smart environments: A systematic review.		General	Review		1
Schechter-Perkins, E. M., Van Den Berg, P., & Branch-Elliman, W.	2022	The Science behind Safe School Re-opening: Leveraging the Pillars of Infection Control to Support Safe Elementary and Secondary Education during the COVID-19 Pandemic.	USA	School classroom	Review		2
Scheuch, G.	2020	Breathing Is Enough: For the Spread of Influenza Virus and SARS-CoV-2 by Breathing only	Germany	General	Review		2
Schibuola, L., Scarpa, M., & Tambani, C.	2016	Natural Ventilation Level Assessment in a School Building by CO2 Concentration Measures	Italy	School classroom	Experiment	CO2, ACH	3
Schibuola, L., & Tambani, C.	2021a	High energy efficiency ventilation to limit COVID-19 contagion in school environments.	Italy	School classroom	Experiment	CO2, ACH	3
Schibuola, L., & Tambani, C.	2021b	Performance comparison of heat recovery systems to reduce viral contagion in indoor environments.	Italy	General	Experiment	Energy use, temperature, ventilation rate	3
Settimo, G., & Avino, P.	2021	The dichotomy between indoor air quality and energy efficiency in light of the onset of the covid-19 pandemic.	Italy	General	Review		2
Shen, J., Kong, M., Dong, B., Birnkrant, M. J., & Zhang, J.	2021	A systematic approach to estimating the effectiveness of multi-scale IAQ strategies for reducing the risk of airborne infection of SARS-CoV-2	USA	General	Simulation	Transmission risk	3
Shen, Y., Li, C., Dong, H., Wang, Z., Martinez, L., Sun, Z., Handel, A., Chen, Z., Chen, E., Ebell, M. H., Wang, F., Yi, B., Wang, H., Wang, X., Wang, A., Chen, B., Qi, Y., Liang, L., Li, Y., … Xu, G.	2020	Community Outbreak Investigation of SARS-CoV-2 Transmission among Bus Riders in Eastern China	China	Transportation	Experiment	Transmission risk	2
Somsen, G. A., van Rijn, C., Kooij, S., Bem, R. A., & Bonn, D.	2020	Small droplet aerosols in poorly ventilated spaces and SARS-CoV-2 transmission	The Netherlands	General	Review		2
Son, S., & Jang, C. M.	2021	Air ventilation performance of school classrooms with respect to the installation positions of return duct.	Korea	School classroom	Experiment	Temperature, age of air, air flow	3
Spena, A., Palombi, L., Corcione, M., Carestia, M., & Spena, V. A.	2020	On the optimal indoor air conditions for Sars-Cov-2 inactivation. An enthalpy-based approach.	Italy	General	Experiment	Inactivation of sars-cov-2, temperature humidity	2
Stabile, L., Pacitto, A., Mikszewski, A., Morawska, L., & Buonanno, G.	2021	Ventilation procedures to minimize the airborne transmission of viruses in classrooms.		School classrooms	Experiment	CO2, transmission risk	3

Stabile, Luca, Dell'Isola, M., Russi, A., Massimo, A., & Buonanno, G.	2017	The effect of natural ventilation strategy on indoor air quality in schools.	Italy	School classroom	Experiment	CO2, PM	3
Stadnytskyi, V., Bax, C. E., Bax, A., & Anfinrud, P.	2020	The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission.	USA		Experiment	Sars-Cov-2 decay	2
Tawackolian, K., Lichtner, E., & Kriegel, M.	2020	Draught perception in intermittent ventilation at neutral room temperature.	Germany	General	Experiment	Draught perception, ventilation	3
Trompetter, W. J., Boulic, M., Ancelet, T., Garcia-Ramirez, J. C., Davy, P. K., Wang, Y., & Phipps, R.	2018	The effect of ventilation on air particulate matter in school classrooms.	New Zealand	Classroom	Experiment	Ventilation rate, PM	4
Vassella, C. C., Koch, J., Henzi, A., Jordan, A., Waeber, R., Iannaccone, R., & Charrière, R.	2021	From spontaneous to strategic natural window ventilation: Improving indoor air quality in Swiss schools	Switzerland	School classroom	Experiment	Ventilation rate	3
Villanueva, F., Notario, A., Cabañas, B., Martín, P., Salgado, S., & Gabriel, M. F.	2021	Assessment of CO2 and aerosol (PM2.5, PM10, UFP) concentrations during the reopening of schools in the COVID-19 pandemic: The case of a metropolitan area in Central-Southern Spain.	Spain	School classroom	Experiment	CO2, PM	3
Villers, J., Henriques, A., Calarco, S., Rognlien, M., Mounet, N., Devine, J., Azzopardi, G., Elson, P., Andreini, M., Tarocco, N., Vassella, C., & Keiser, O.	2021	SARS-CoV-2 aerosol transmission in schools: the effectiveness of different interventions.	Switzerland	School classroom	Simulation	Mean cumulative dose, mean viral concentration	5
Wang, Yang, Zhao, F. Y., Kuckelkorn, J., Liu, D., Liu, J., & Zhang, J. L.	2014	Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building.	Germany	School classroom	Experiment	Temperature, temperature mapping, CO2	2
Wang, Yang, Zhao, F. Y., Kuckelkorn, J., Spliethoff, H., & Rank, E.	2014	School building energy performance and classroom air environment implemented with the heat recovery heat pump and displacement ventilation system	Germany	School classroom	Experiment	Thermal comfort, CO2	2
Wang, Yu, Boulic, M., Phipps, R., Plagmann, M., & Cunningham, C.	2020	Experimental performance of a solar air collector with a perforated back plate in New Zealand.	New Zealand	University classroom	Experiment	Windspeed, temperature, airflow, thermal efficiency	2
Weyers, R., Jang-Jaccard, J., Moses, A., Wang, Y., Boulic, M., Chitty, C., Phipps, R., & Cunningham, C.	2018	Low-cost Indoor Air Quality (IAQ) Platform for Healthier Classrooms in New Zealand: Engineering Issues.	New Zealand	School classroom	Experiment	SKOMOBO performance	2
William, J.	2004	Concentrations and Student Attendance	USA	School classroom	Experiment	CO2, attendance	1
Yao, R., Liu, J., & Li, B.	2010	Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms	China	University classroom	Experiment	Thermal comfort, ventilation	3
Zafarnejad, R., & Griffin, P. M.	2021	Assessing school-based policy actions for COVID-19: An agent-based analysis of incremental infection risk	USA	School classroom	Simulation	Transmission risk	3
Zemitis, J., Bogdanovics, R., & Bogdanovica, S.	2021	The Study of Co2Concentration in A Classroom during the COVID-19 Safety Measures.	Latvia	School classroom	Experiment	CO2	3
Zhang, D., Ding, E., & Bluyssen, P. M.	2022	Guidance to assess ventilation performance of a classroom based on CO2 monitoring.	The Netherlands	School classroom	Guidance		2
Zhang, L., Tian, L., Shen, Q., Liu, F., Li, H., Dong, Z., Cheng, J., Liu, H., & Wan, J.	2021	Study on the influence and optimization of the Venturi effect on the natural ventilation of buildings in the Xichang area.	China	General	Simulation	Temperature, volume flow rate	2
Zhang, R., Li, Y., Zhang, A. L., Wang, Y., & Molina, M. J.	2020	Identifying airborne transmission as the dominant route for the spread of COVID-19.	USA		Experiment	Mitigation measures, transmission risk	2
Zhiqiang, B. Y., Zhai, J., Ashrae, F., Bahl, R., Trace, K., Gupta, B., Li, H. E.	2021	Mitigating COVID-19 In Public Spaces.		School classroom	Experiment	PM, ventilation rates	1
Zivelonghi, A., & Lai, M.	2021a	Optimizing ventilation cycles to control airborne transmission risk of SARS-CoV2 in school classrooms	Italy	School classroom	Simulation	Ventilation, transmission risk	3

Zivelonghi, A., & Lai, M.	2021b	The role of classroom volume, occupancy, voice reduction and ffp2 masks in transmission risk of SARS-CoV2 in schools.	Italy	School classroom	Simulation	Ventilation, transmission risk	2