State of Indoor Air in Australia 2025

Thrive

Australian Research Council
Training Centre for Advanced Building Systems
Against Airborne Infection Transmission (THRIVE)

Australian Academy of Science

Burnet

CASANZ Clean Air Society of Australia & New Zealand

Centre for Safe Air

HEAL

Foreword

The foundation of the United Nations Environment Program (UNEP) in 1972 was the catalyst for monitoring the state of the environment to inform policy making with scientific evidence and to coordinate responses to global environmental challenges.

State of the Environment (SoE) reporting has been increasingly adopted by UN member states since the 1980s. Australia has been producing SoE reports roughly every five years since 1995. Most Australian states and territories are also producing their own SoE reports periodically.

There are three key limitations to the SoE reports produced for Australia to date:

i. SoE reports assess ambient air (based on 211 fixed monitoring stations across the nation) and discuss pressures and management of ambient air. There has been scant focus on indoor air[1].

ii. Health and wellbeing were not included until the 2021 report, which highlighted that one of the key challenges to our health and wellbeing was considered to be climate change – its compounding effect on pollutants and the intensity and frequency of extreme weather events.

iii. The 2021 SoE report highlighted that environmental management was not well coordinated. In addition, there is little evidence of a co-ordinated multi-portfolio approach that could capture multiple dividends to improve health, building quality, carbon reduction, environmental management and community and economic resilience.

There has not been, until this publication, a national report focusing on the state of air in indoor environments, i.e. the quantification of airborne pollutants in Australian buildings.

This report starts to fill the knowledge gap by collating scientific evidence of indoor air quality measurements in Australian buildings. It will support the development of appropriate policy and market responses to prevent emissions and reduce exposure to these pollutants and the associated health, wellbeing and economic costs of such exposure.

[1] Indoor Air Quality accounted for 1.6% of the Air Quality chapter in Australia's 2021 SoE report.

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Thrive

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Established in 2023, the aim of THRIVE is to engineer building systems whose elements work together to reduce airborne infection transmission by improving indoor air quality while maintaining comfort and efficiency.

https://thriveiaq.com

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This report was proudly graphic designed by Global IQ Group and printed on 100% recycled paper using eco-friendly inks – reflecting our shared commitment to sustainability and creating a better future.

Executive Summary

Australia has been producing State of the Environment (SoE) reports for more than two decades, yet it has not, until this report, undertaken to quantify the state of indoor air. The scientific evidence of the importance of indoor air quality for occupant health is unequivocable, as is the evidence quantifying the health, social and economic costs of poor indoor air quality. Translating this evidence into policy and practice is challenging in the absence of data about the current status of air inside Australian buildings of all types.

A systematic literature search strategy identified 106 peer reviewed publications that have reported on measurements of some indoor air pollutants within residential, non-residential and public buildings in Australia since 2000. Over three quarters of these studies were conducted in Queensland (41%) and Western Australia (37%), and most (77%) were conducted since the introduction of energy efficiency requirements in the building code in 2003.

These publications collectively measured pollutants in about 2000 buildings. The geographic and temporal distribution of these publications are shown in Figures 1 and 2 respectively. NABERS Indoor Environment Quality (IEQ) ratings were also analysed, bringing the total number of buildings involved in IAQ studies to approximately 2,500 – less than 0.03% of Australia's building stock.

Residential dwellings account for 68% of the buildings, followed by offices (22%) and public assembly buildings, including schools (9%). Healthcare, residential care and factories each represent about 2% of the total buildings studied.

Chapter 1 provides the context for the report, including a summary of existing regulations relating to indoor air. Each of the following chapters, focused on a specific building class, provides an overview of the relevant studies, a summary of key pollutant measurement ranges, and key findings.

While each study individually was subject to each scientific journal's respective peer review process, as a collective it is not possible to generalise the findings to all buildings within each class or to assume that these 'snap-shots in time' indicate the current state of indoor air. Different building types (e.g. housing, offices, factories, public buildings), in different urban and climate contexts, have different occupancy modes, pollutant risks, exposure limits, health and economic consequences, and policy response options. The impact that indoor air has on individual and population health and wellbeing depends on the pollutants that may be present in the air, the respective concentration levels of those pollutants, and the exposure of occupants to those pollutants.

The data presented in this report is helpful in

- providing insights into the range of indoor air quality (IAQ) conditions in different building classes over time;
- highlighting some of the key contributors to, and impacts of, poor air quality;
- quantifying the importance of source control, ventilation and filtration as strategies for improving IAQ;
- presenting multi-disciplinary approaches in study design and implementation; and
- providing solutions or strategies that could be applied to buildings of the same class, or between buildings in different classifications.

The shortcomings of the studies as a collective include

- the short measurement timeframes (from a few hours up to, in a few instances, one year).
- the small number of rooms or zones that were included in each building study.
- a generalised focus on mean pollutant concentration values, with minimal discussion on peak concentrations.
- a generalised absence of analysis of the duration of concentrations at different levels. This is important because health risks, in simple terms, are a combination of pollutant concentration levels multiplied by duration of exposure at different pollutant concentrations.
- a generalised omission of important building data such as occupant density.

This report acts as a baseline report for indoor air quality and as a catalyst for multi-jurisdictional and transdisciplinary discussion and debate that leads to the development and implementation of a national strategy for indoor air quality. It is hoped that this report will be augmented periodically with more data as it becomes available, enabling improvements in indoor air quality to be tracked over time, and the impact of interventions to be evaluated.

Figure 1 Geographic distribution of IAQ studies (excluding NABERS IEQ ratings)

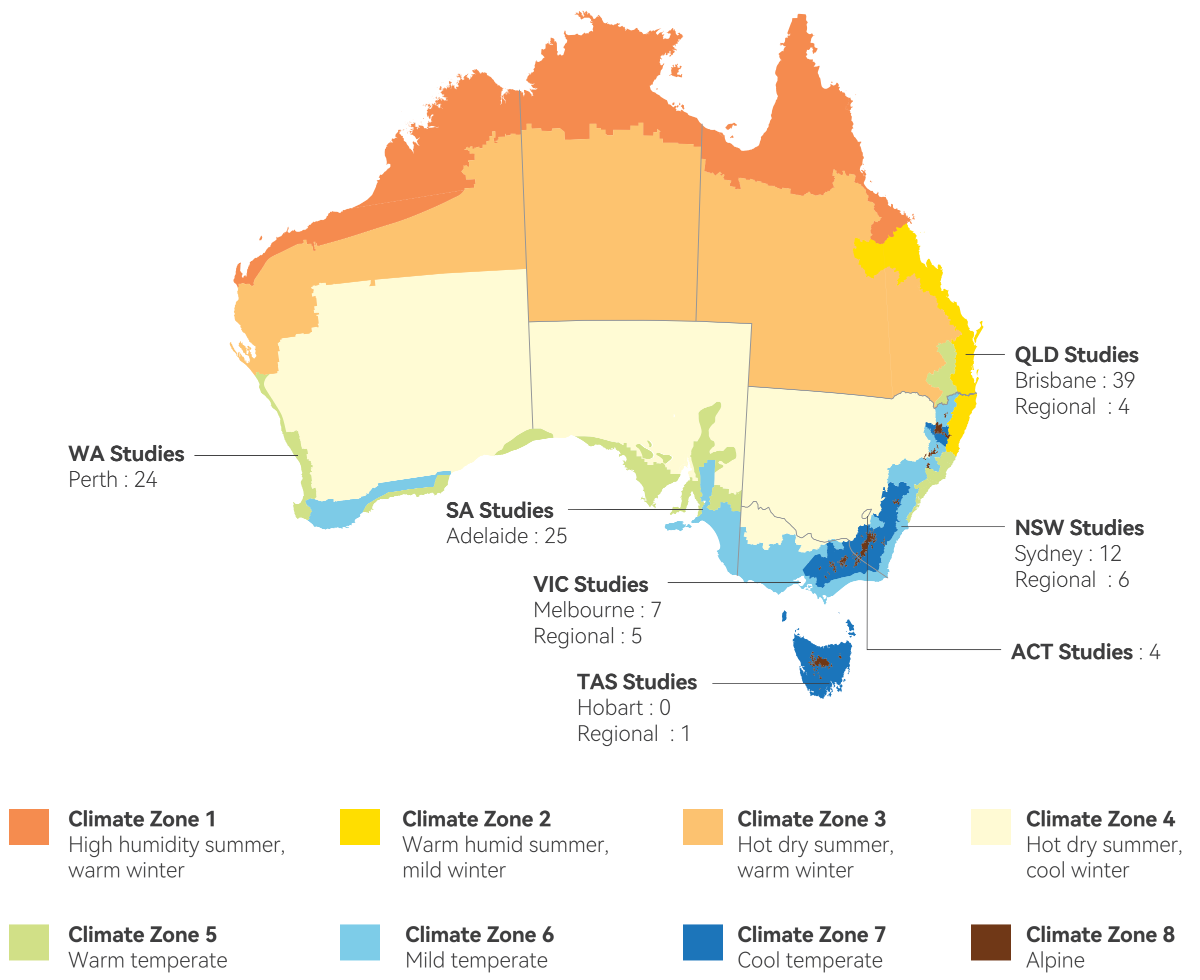
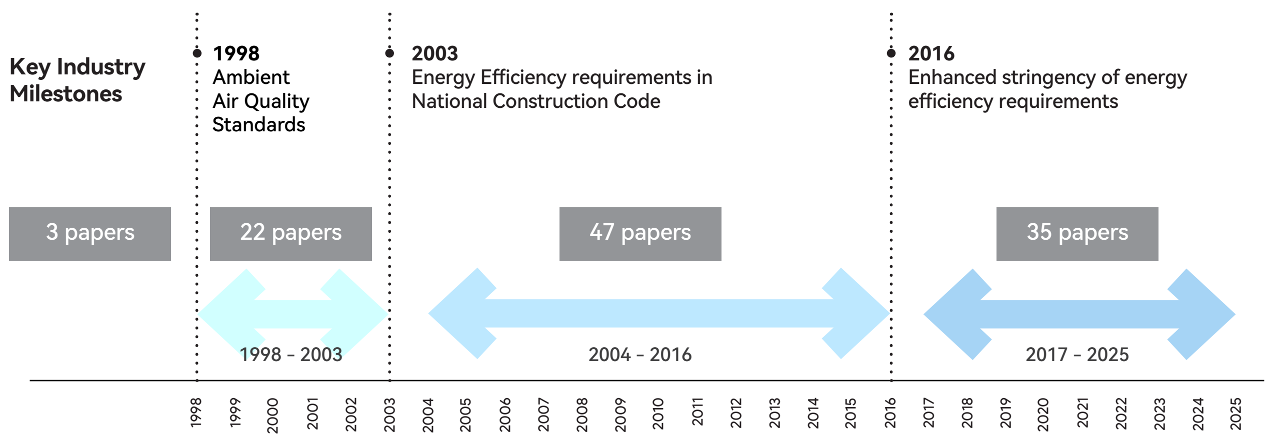


Figure 2 Temporal distribution of IAQ studies



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Glossary

AAQS	Ambient Air Quality Standard
ABCB	Australian Building Codes Board
ACH	Air Changes per Hour
Airborne Contaminant	A fume, mist, gas, vapour or dust that can be harmful to health when breathed in
AIHW	Australian Institute of Health and Welfare
AIOH	Australian Institute of Occupational Hygienists
BDL	Below Detection Limit
BTEX	Four common VOCs (benzene, toluene, ethylbenzene and xylene) frequently found together; often measured as a group in environmental samples of air
CH_2O	Formaldehyde
CO	Carbon monoxide
CO_2	Carbon dioxide
DPM	Diesel Particulate Matter
IAQ	Indoor Air Quality
IEQ	Indoor Enivronment Quality
I/O	Indoor/Outdoor
LOD	Limit of Detection
NABERS	National Australian Built Environment Rating System
NCC	National Construction Code
NEPM	National Environmental Protection (Ambient Air Quality) Measure
NO_2	Nitrogen dioxide
NPI	National Pollutant Inventory
O_3	Ozone
PAHs	Polycyclic Aromatic Hydrocarbons
PBDE	Polybrominated Diphenyl Ethers (a class of flame retardants)
PCBs	Polychlorinated Biphenyls
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter <2.5 micrometres in diameter
PM_{10}	Particulate Matter <10 micrometres in diameter
PN	Particle Number
PNC	Particle Number Concentration
PNSD	Particle Number Size Distribution
POP	Persistent Organic Compounds
SoE	State of Environment
SO_2	Sulfur dioxide
STEL	Short Term Exposure Limit
TSP	Total Suspended Particulates
TVOC	Total Volatile Organic Compounds
UFP	Ultra Fine Particles
UVAPS	Ultraviolet Aerodynamic Particle Sizer
VAH	Volatile Aromatic Hydrocarbons
VOCs	Volatile Organic Compounds

1.0 Context

1.1 Buildings, air quality and health

The link between indoor air quality and health is not in dispute in Australia.

"The built environment is a determinant of health due to its ability to affect health through activity levels, access to nutritious food and clean water, the houses we live in, where we work, contact with nature and the spaces we have for social interactions. It also affects the air we breathe and the water we drink and shelters us from the weather."[2]

The incorporation of indoor air quality into strategies to improve national health is, however, missing. Australia's National Preventive Health Strategy 2021 – 2030 identifies the built environment as one of the environmental causes of ill health. In that report's detail, urban planning is listed as one of the focal points within the built environment, but it neglects to mention buildings specifically. Similarly, the National Action Plan for the Health of Children and Young People, and the National Asthma Strategy, don't include indoor air quality in buildings as part of the respective strategies.

Air pollution is a key societal risk, affecting human health, wellbeing, comfort, performance and productivity – and hence impacting Australia's economy. There are recent attempts to highlight the need for a multi-portfolio coordinated approach, in particular, a forthcoming report on indoor air by the Australian Academy of Science (to be published in 2025). In addition to providing a broad overview of the scientific evidence on indoor air pollution and the impacts of exposure to these pollutants, that report will examine policy pathways to improve indoor air quality in Australia.

Indoor air can be defined as:

"the air within a building occupied for at least one hour by people in varying states of health. This can include the office, classroom, transport facility, shopping centre, hospital and home.

Indoor air quality can be defined as the totality of attributes of indoor air that affect a person's health and wellbeing".[3]

The impact that indoor air has on individual and population health and wellbeing depends on the pollutants that may be present in the air, the respective concentration levels of those pollutants, and the exposure of occupants to those pollutants. Exposure includes the activity level of occupants, their proximity to pollutants, and the amount of time spent in specific indoor environments. The health risks of the combined effect (concentration x time) are impacted by susceptibility factors such as age or pre-existing health conditions as well as the nature of specific pollutants (e.g. what body systems are impacted).

Short-term and long-term exposures can present significant chronic and acute health conditions, and different building typologies present different pollutant risks and concentration levels.

[2] AIHW. 2 July 2024. Built Environment and Health

[3] NHMRC, as quoted on DCCEEW webpage on Indoor Air. https://www.dcceew.gov.au/environment/protection/air-quality/indoor-air

The Australian Institute of Health and Welfare indicates at a population level we spend approximately 90% of our time indoors, including about 70% in residential environments.

Data from the Australian Bureau of Statistics (ABS) can help us to better understand differences in the types of activities undertaken in various indoor environments that then impact on exposure to airborne contaminants in those environments.

Tables 1-2 respectively summarise the 'types of time' characterised by the ABS and the percentage of time Australians spend on each type. Note that working from home changed with the COVID-19 pandemic and restrictions, and has remained quite high. 30% of people in April 2022 worked from home on all or most days of the week, and there have been recent moves to introduce a right to work from home for at least 2 days per week into Victorian legislation.

Table 1 Types of time as characterised by the ABS[4]

Type of Time	Descriptions
Necessary	Activities performed for personal survival: sleeping, eating, personal hygiene
Contracted	Paid work and regular education (explicit contracts which control periods of time in which the activities are performed)
Committed	Personal committed time to household, social or community interactions (e.g. housework, household management, home and vehicle maintenance, child /adult care, shopping, volunteering)
Free	The amount of time left

Table 2 Where Australians spend their time (ABS Time Use Surveys 2006 and 2021)

Type of Time	% of the day (population average of a whole year 2006)[4]		% of the day (population average of a whole year 2020-21)[5]		Location of activity[6] / Building Class
	Men	Women	Men	Women	
Necessary	45.0	46.2	43.8	44.2	Home (Class 1,2)
Contracted	21.1	11.9	17.9	12.9	Home (Class 1,2) Workplace (Class 3 – 9) Education building (Class 9b)
Committed	12.0	21.7	11.3	17.5	Home (Class 1,2) Office buildings (Class 5) Shops (Class 6) Public assembly buildings (Class 9b)
Free	21.4	19.7	22.9	20.8	Home (Class 1, 2) Public assembly buildings (Class 9b) Shops (Class 6) Outdoors

4 ABS Time Use Survey 2006

5 ABS Time Use Survey conducted 2020-2021 financial year, during COVID-19 pandemic.

6 Derived from the activities undertaken by type of time

1.2 Regulation of indoor air quality in Australia

There is a common view that there are no specific legislated standards for IAQ in Australia, however there are two national bodies that provide 'model' laws or codes that relate to indoor air quality. Each state and territory decides to what extent these model codes are adopted, and each jurisdiction is responsible for the regulation, compliance monitoring and enforcement of these codes within their respective jurisdictions. These national bodies and their codes relate to building design and construction, and to workplace health and safety.

1.2.1 National Construction Code

The Australian Building Codes Board (ABCB) is a standards writing body. It produces and maintains the National Construction Code (NCC) – a performance-based code that sets out the technical design and construction provisions for new buildings. These provisions establish the minimum performance requirements for safety, health, amenity, accessibility and sustainability in buildings. Compliance generally needs to be verified at the design and construction stages of buildings, and acceptable verification methods are included in the code.

The NCC has three mandatory performance requirements relating to indoor air:

- For occupied spaces to be ventilated with outside air to maintain adequate air quality (F6P3 NCC Volume One and H4P5(1) NCC Volume Two)
- For mechanical air-handling systems to control circulation of objectionable odours and accumulation of harmful contamination by micro-organisms, pathogens and toxins (F6P4 NCC Volume One and H4P5(2) NCC Volume Two)
- For contaminated air to be disposed of so as not to unduly create a nuisance to people in the building or other property (F6P5 NCC Volume One and H4P5(3) NCC Volume 2)

The ABCB's Indoor Air Quality Verification Methods Handbook "provides guidance to practitioners seeking to understand the IAQ requirements of the NCC" by providing "support to understand the IAQ Verification Methods"[7]. These verification methods "help define the point where adequate air quality is achieved". The two verification methods relevant to this report are F6V1 Verification of suitable indoor air quality (for commercial buildings) and H4V4 Verification of indoor air quality (for class 1 residential buildings).

The verification methods in the NCC specify maximum exposure levels for eight contaminants: carbon dioxide, carbon monoxide, nitrogen dioxide, ozone, total volatile organic compounds, formaldehyde, and particulate matter 2.5 and 10.

It is assumed that '*adequate air quality*' can be met through dilution (i.e. addition of outdoor air through natural or mechanical ventilation) and that outdoor air in Australia is usually clean and suitable for building ventilation purposes,

Residential buildings (Class 1) and most commercial buildings (Classes 2 – 9c, except for Classes 8 and 9a) are deemed to provide adequate air quality if, under typical conditions in use:

- there is sufficient ventilation with outdoor air to ensure maximum contaminant levels documented in the Handbook are not exceeded, and
- the proposed ventilation solution controls the accumulation of harmful contamination by micro-organisms, pathogens and toxins.

The handbook does not deal with *tobacco smoke*.

Biological contaminants (e.g. house dust mites, moulds and fungi, allergens, bacterial and viral pollutants) are not covered by the verification methods for two reasons:

(i) Accurate modelling, sampling, testing and measurement of many biological species is not universally agreed; and

(ii) Acceptable limits for many biological contaminants have not been established.

Industrial contaminants are assumed to be covered by Workplace Exposure Standards.

[7] Indoor Air Quality Verification Methods Handbook, 2023, Page 1.

1.2.2 Safe Work Australia

This agency, formerly the Occupational Health and Safety Commission, provides model codes relating to workplace exposure standards for airborne contaminants:

"... a contaminant in the form of a fume, mist, gas, vapour or dust, and includes microorganisms. An airborne contaminant of this type is a potentially harmful substance that is either not naturally in the air or is present in an unnaturally high concentration and to which workers may be exposed in their working environment."

Workplace Exposure Standards (WES) are a list of airborne contaminants and exposure standards that must be met to enable businesses to meet their obligations under the relevant jurisdiction's workplace health and safety legislation (which is based on model Workplace Health and Safety (WHS) Regulations). The current WES are legally mandated standards.

Australia is in the process of transitioning to Workplace Exposure Limits (WEL) – to come into force from December 2026. A review of the WES and the transition to WEL, was based on contemporary evidence and on providing the best protection for workers and others in the workplace. Under the soon-to-be introduced WEL, businesses will be required to undertake five key steps to ensure safe indoor air, as outlined in Figure 3.

These activities are premised on what is 'reasonably practicable' - the elements of which are shown in Figure 4.

Figure 3 Workplace Exposure Limits requirements by business

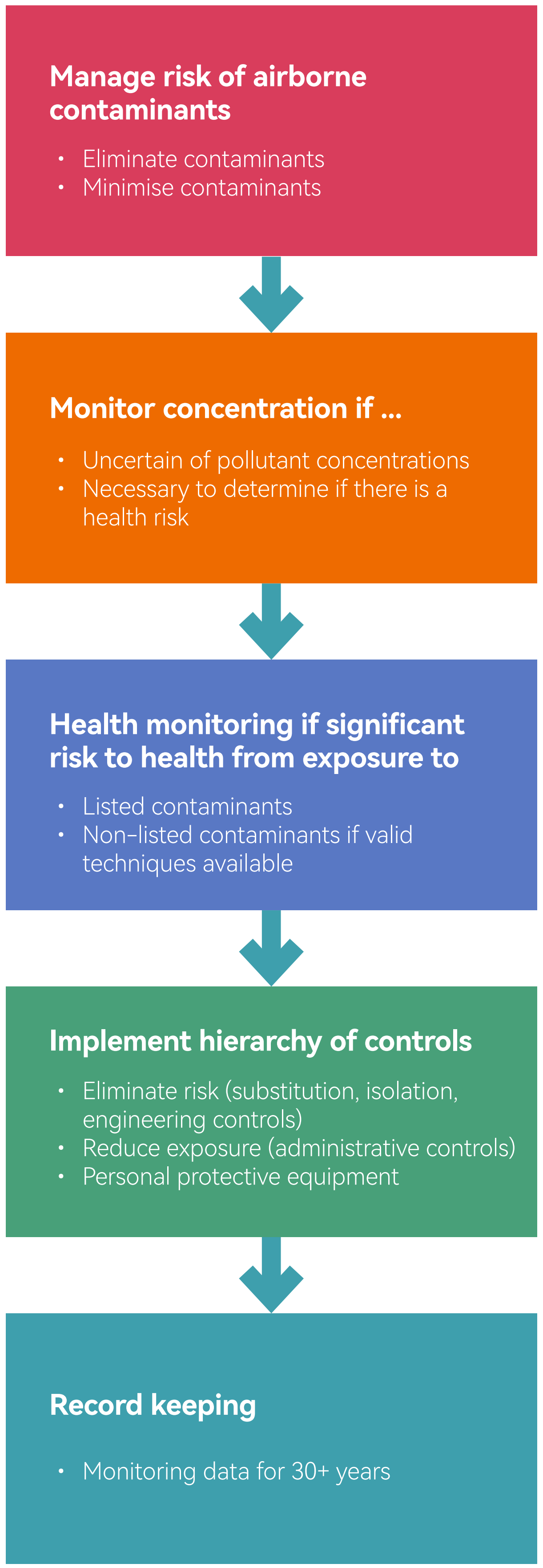
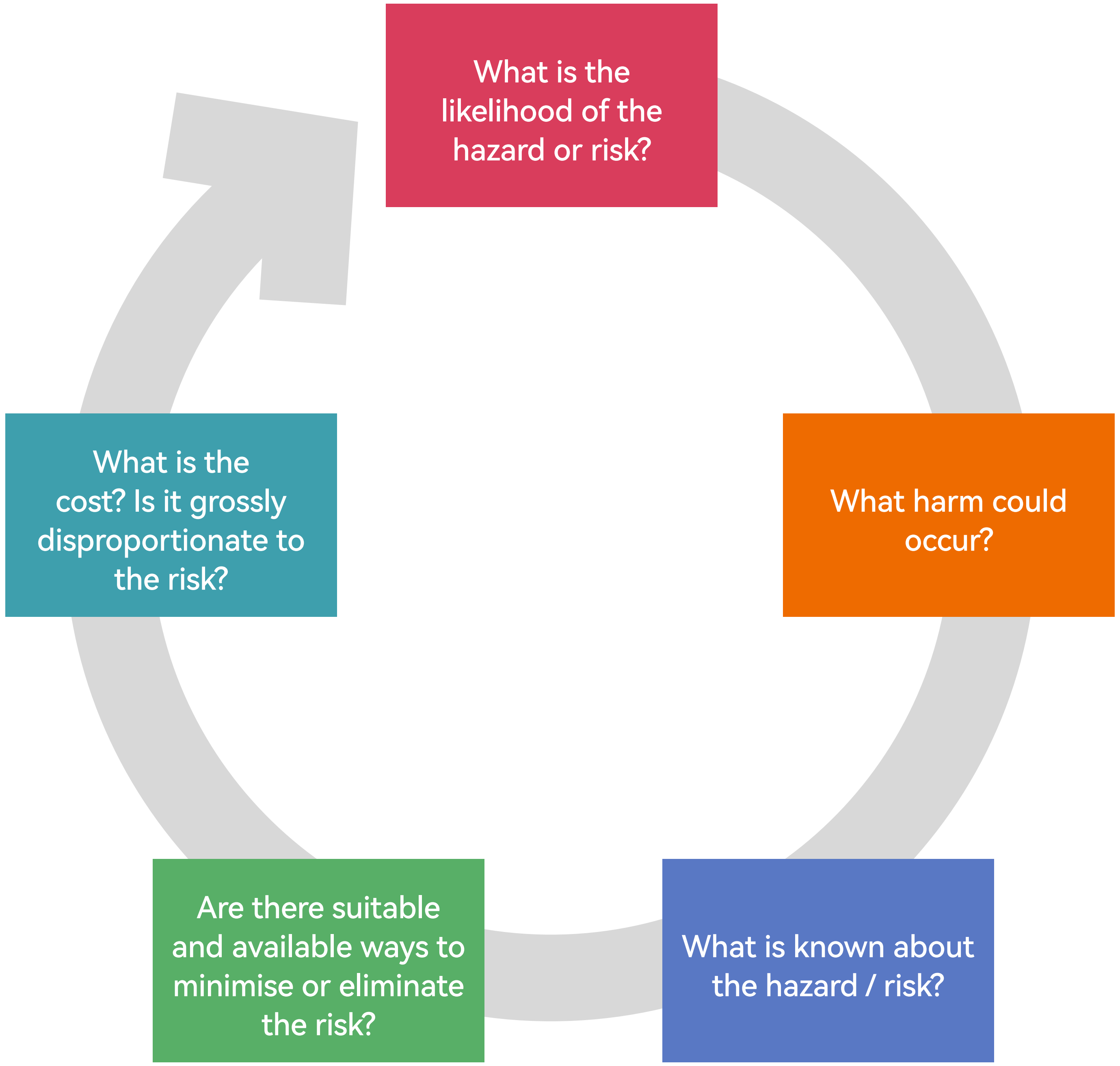


Figure 4 Questions to determine 'reasonably practicable' [8]



[8] https://www.safeworkaustralia.gov.au/safety-topic/managing-health-and-safety/identify-assess-and-control-hazards/managing-risks

1.3 State of Indoor Air – Purpose and Objectives

The purpose of this report is to fill the knowledge gap of previous State of Environment (SoE) reports and provide the scientific evidence to support the development of appropriate policy and market responses to reduce exposure to these pollutants and the associated health, wellbeing and economic costs of such exposure.

The two objectives of this report are to:

- collate and review existing published evidence of the concentrations of ten pollutants measured in Australian buildings; and
- evaluate what is known and unknown about indoor air quality and what this may mean for moving forward.

1.4 Priority Indoor Air Contaminants

It is not possible for this inaugural report to collate evidence of all indoor air pollutants in Australian buildings. Nine priority pollutants were initially selected based on expert advice on three pollutants recommended for mandatory enforcement in public buildings (2024) [1], the six pollutants addressed by the 2021 World Health Organisation (WHO) guidelines [2], and the eight contaminants included in the ABCB IAQ handbook (2023) [3]. Ultrafine particles (UFPs) were added to this list because their importance has been recognised by the WHO with the following recommendation: "Efforts should be stepped up to utilize the emerging science and technology to advance approaches to the assessment of exposure to UFP for application in epidemiological studies and management."[2]. It is recognised that, due to their small size and inertia, UFPs reach the deep part of the respiratory tract (alveoli), from where they penetrate to the blood system, which in turn produces, among other impacts, systemic effects [4]. Furthermore, their potential impact on the brain is increasingly recognised through a route other than the respiratory tract, which is direct penetration to the brain via the olfactory system [5].

Table 3 Targeted indoor air pollutants and exposure limits

Pollutant	Symbol	Measurement	Exposure Limits
Carbon dioxide	CO_2	Parts per million (ppm)	~ 850 ppm (ambient + 450) [Ref [3]] (averaged over 8 hours)
Carbon monoxide	CO	Parts per million (ppm)	3.5 ppm (24 hr) [Ref [2]]
Respirable Particles	PM_{10}	Micrograms per cubic meter	45 $\mu g/m^3$ (24 hr) [Ref [2]]
	$PM_{2.5}$	Micrograms per cubic meter	15 $\mu g/m^3$ (24 hr) [Ref [2]]
	UFP	Particle Number Concentration (PNC)	No existing limit [Ref [2]]
Nitrogen dioxide	NO_2	Micrograms per cubic meter	25 $\mu g/m^3$ (24 hr) [Ref [2]]
Ozone	O_3	Micrograms per cubic meter	100 $\mu g/m^3$ (8 hr daily max) [Ref [2]]
Formaldehyde	CH_2O	Milligrams per cubic meter	0.1 mg/m^3 (30 min) [Ref [3]]
Total Volatile Organic Compounds	TVOC	Micrograms per cubic meter	500 $\mu g/m^3$ (1 hr) [Ref [3]]
Sulfur Dioxide	SO_2	Micrograms per cubic meter	40 $\mu g/m^3$ (24 hr) [Ref [2]]

1.5 Data sources

The ten pollutants shown in Table 3 formed the basis of a structured literature search strategy in four scientific publication data bases (Scopus, PubMed, Scopus, Embase) for peer reviewed journal articles published since 2000. Articles had to report onsite measurements conducted within buildings in Australia. Full text of some older studies could not be sourced, so were excluded from analysis.

Some identified studies measuring the above pollutants also measured pollutants such as specific VOCs, mould, fungi, organic compounds (e.g. PAHs) and manmade organic compounds (e.g. PCBs) because of their presence in gaseous form or in particulate matter. Reporting on these papers focuses on the ten pollutants listed above; findings about these additional contaminants are not robustly analysed in this report.

Future editions of this report may expand the list of contaminants.

1.6 Layout of the report

This report is presented in chapters relating to specific building classes, based on the building classifications of Australia's National Construction Code. This enables indoor air quality to be examined and addressed for different occupancy modes, pollutant risks, exposure limits, health and economic consequences, and policy responses.

Data about the number of buildings and floor area per classification was derived from the Commercial Building Baseline Study 2022[6], which states an error rate of ± 30% at a national and state level. The total number of buildings and the floor area are both important for understanding the scale and challenges of monitoring indoor spaces and managing indoor air quality.

Each chapter contains an analysis of quantified data/reports of air pollutant measurements in specific building classes in Australia, beginning with an outline of the scope of the chapter (i.e. a definition of the building class and the estimated number of buildings related to that class). It then presents the current state of indoor air as reported in identified scientific papers, followed by:

- The geographic distribution of the studies;
- The temporal distribution of the studies compared to key air quality and building regulations as shown in Table 4;
- The measurement instruments and protocols utilised;
- The pollutant levels measured; and
- Key findings.

Each chapter concludes with key insights and considerations to provoke discussion and action on ways forward to improve the state of IAQ in each building typology.

Table 4 Key dates in air quality and building standards

Year	Air Quality standards	Building standards
1988		Building Code of Australia established
1995	Introduction of Workplace Exposure Standards (WES)	
1998	Ambient Air Quality Standards (AAQS) established for CO, lead, NO_2, O_3, PM_{10}.	
2003	Provided a framework for monitoring and reporting these pollutants	Energy efficiency provisions introduced for houses
2005	AAQS: introduction of advisory reporting for $PM_{2.5}$	Energy efficiency provisions extended to all residential buildings
2006		Energy efficiency provisions extended to all building classes
2010		Increase in energy efficiency requirements for all buildings
2016	AAQS: Variations to the standards for particulates	Council of Australian Governments (COAG) Energy Council signals review and potential strengthening of provisions for all buildings (this leading to the NCC2022)
2019		Trajectory for Low Energy Buildings agreed by all energy ministers. Aims to achieve zero energy and carbon-ready buildings (all classes)
2020	Update on WES	
2021	AAQS variations to standards for O_3, NO_2 and SO_2	
2022	Update on WES	Whole of Home energy budget; aim to reduce energy use and improve occupant comfort.
2026	Change from Workplace Exposure Standards to Workplace Exposure Limits	
2028		Focus on residential: (near) net zero energy and emissions; Full electrification or support electrification with pathway for gas

Utilising focused discussion, expert consensus and other collaborative methods, future iterations of this report may include:

- Analysis of data from other sources (e.g. government agencies)
- Status scorecards and an analysis of impacts and trends;
- An analysis of the drivers and pressures that impact on IAQ; and
- An evaluation of existing and possible management responses, such as regulatory, legislative, research and other opportunities, that may fill gaps in policy and practice.

2.0 Class 1 and 2 Buildings - Residential

Residential
Class 1 & 2

2.1 Scope

Class 1 and Class 2 buildings are dwellings or homes in different forms, including:

- Class 1a – single dwelling (detached) or group of attached dwellings (e.g. townhouse, row house etc). This includes tiny homes, mobile homes and caravans intended as permanent or long-term dwellings.
- Class 1b – boarding house, guest house or hostel less than 300m^2 and occupied by less than 12 people. Could also refer to four or more single dwellings on one allotment used for short-term holiday accommodation
- Class 2 – apartment buildings, multi-unit residential buildings, single storey attached dwellings with a common space below.

There were approximately 11.29 million residential dwellings in Australia in December 2024[9], housing 26.6 million people.

Residential Buildings

Building Count 2024	11.29 m
People	26.6 m

[9] Australian Bureau of Statistics, Total Value of Dwellings, December Quarter 2024. https://www.abs.gov.au/statistics/economy/price-indexes-and-inflation/total-value-dwellings/latest-release

2.2 Current State

2.2.1 Overview and purpose of identified studies

Forty-three studies of residential buildings were identified, spanning about 25 years (1998 – 2024)[10]. The studies encompassed both new and existing housing (at the time of the studies) with a range of building materials (e.g. double brick, brick veneer, timber / weatherboard). Most studies were undertaken in detached houses (Class 1a), with very few semi-detached homes and flats/units monitored. Approximately 1700 dwellings were included in the identified studies (assuming each study was for a different set of dwellings, unless indicated otherwise). This means that about 0.15% of Australia's total dwellings have been subject to some form of IAQ testing and reporting through scientific articles.

A summary table of these studies can be found in Table 19 (in Chapter 12). It shows, for each paper, the year of data collection and publication, the location of the study, the number of buildings studied, the general purpose of each study, the pollutants measured and measurement timeframes. Most studies included multiple dwellings (1 – 200 dwellings), however not necessarily multiple locations within each dwelling. The most commonly measured pollutants were particulate matter ($PM_{2.5}$, PM_{10}, UFP and PNC), VOCs and NO_2. While all studies measured one or more indoor pollutants, the main purpose of the studies varied, including characterising indoor pollutants (e.g. sources, links with activities, deposition rates), examination of indoor/outdoor relationships (e.g. seasonal variations, prescribed burns, closeness to major roads), relationships between pollutants (e.g. IAQ and mould growth), the effectiveness of ventilation strategies (e.g. airflow velocity or HEPA filters), and health risks (e.g. asthma) and personal exposure.

[10] Note that publication year is typically not the same as study year.

2.2.2 Geographic And Temporal Distribution Of Studied Dwellings

Figure 5 shows the geographic distribution of the houses studied. Of note is the very high percentage of studies conducted in capital cities (and hence very few in regional areas), and the absence of any studies in SA and NT. This geographic distribution also demonstrates the concentration of studies in 3 climate zones only (Zones 2, 5 and 6) and the lack of studies in the remaining climate zones (e.g. Zones 1, 3, 4, 7 and 8).

Figure 6 shows how those papers have been published over time, with the bulk of the studies being undertaken since the introduction of energy efficiency standards for residential buildings.

Figure 5 Geographic distribution of residential IAQ studies

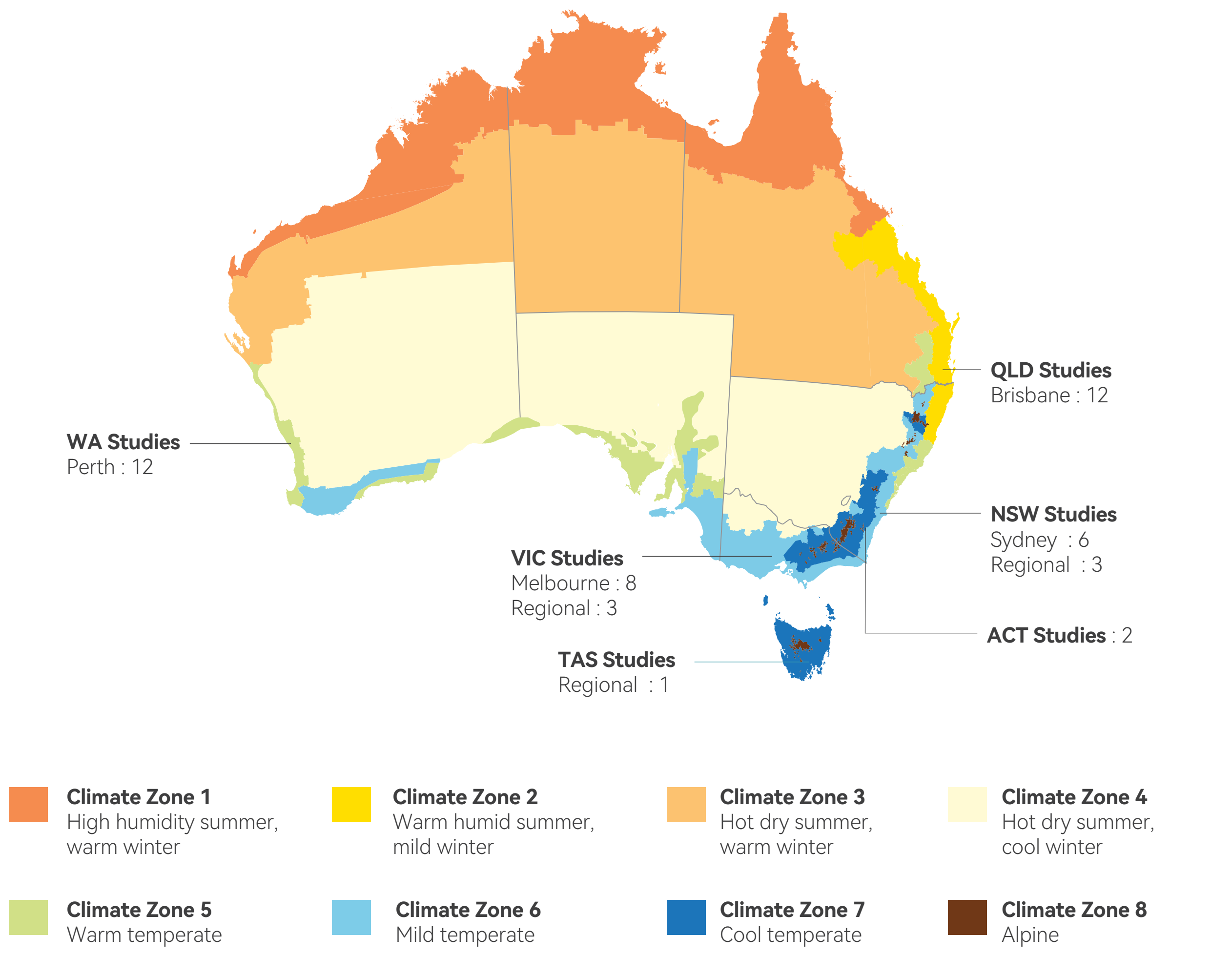
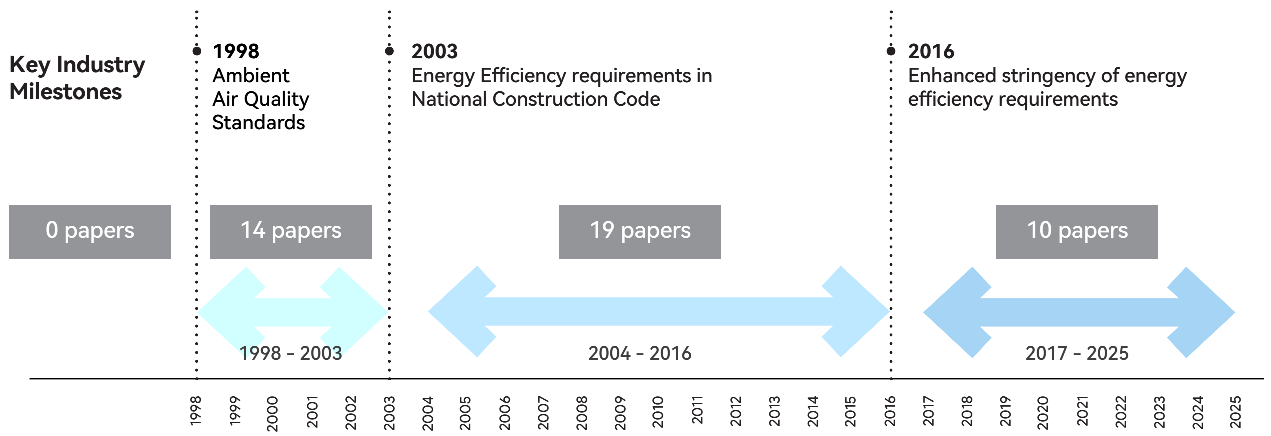


Figure 6 Temporal distribution of residential IAQ studies



2.2.3 Measurement instruments

Some studies provided no information on the measurement instruments used, while others described measurement instruments in very generic terms (e.g. 'non-dispersive infrared sensor' or 'light scattering sensors' or 'low volume sampler').

Of those studies that reported measurement instrument details, the most frequently used instruments were those by USA company TSI, with different models utilised as instrument capabilities evolved over time:

- Desk top battery- operated monitors for particulate matter
  - TSI DustTrak 8520 (from early 1990s; real-time aerosol mass readings)
  - TSI DustTrak II 8530 (from 2008; real-time aerosol mass readings with gravimetric sampling)
  - TSI DRX 8533 (from 2008; mass concentrations of different PM fractions simultaneously, with gravimetric sampling). The DRX also has plug-in probes for VOCs and air velocity
  - TSI P-Trak 8525 (from ~ 2006; condensation (UFP <0.1μm) particle counter)
- Indoor air quality monitoring
  - TSI Q-Trak (from 2021; measures CO_2, CO, temperature and humidity)

Other air sampling instruments included:

- MicroVol (low volume sampler)
- SAMBA IEQ device (a bespoke multi-sensor monitoring system encompassing air and radiant temperatures, air speed, humidity, acoustics, lighting, CO_2, CO, TVOC, CH_2O and PM_{10})
- SMOG 20 (a CSIRO-developed Smoke Observation Gadget provided as a low-cost air-monitoring kit for school and citizen science use).

NO_2 was measured by passive filter badges.

CH_2O was measured using a GRAYWOLF FM-801 Formaldehyde Multi Mode Monitor – short-term sampled measurements or continuous monitoring via a colorimetric sensor cartridge.

Another GRAYWOLF product was used in two studies to measure VOCs. The GRAYWOLF AdvancedSense Pro supports up to 6 sensors per probe (up to 4 probes), including TVOCs, CO_2, CO, O_3, NO_2, SO_2, CH_2O etc. Most studies involving VOC measurements used sorbent tubes.

2.2.4 Contaminant measurements and key findings

Each of the studies presented a range of measurements for the pollutants monitored, and most presented the results as mean concentrations (across all measurements in the respective study sites). The mean concentrations were variously recorded as the mean of all measurements or for specific time periods (e.g. 1 hour, 8 hours, 24 hours).

The measurements reported in this cohort of studies cannot be considered representative of the current status of IAQ in residential buildings because:

- The sample size for each study, and the collective of all studies, is much too small;
- The measurement ranges were specific to each study's cohort and the time of the study;
- The 'mean' aggregated results are not relevant for current IAQ status nor exposure to the pollutants.

Table 5 gives an indication of the range of concentrations (minimum and maximum) reported in the identified studies. It should be read in conjunction with Table 6 which iterates some of the key findings from individual studies. These 'key findings' should be read and interpreted as being valid for the specific study they relate to, and the historic, physical and climate context of the homes that were studied.

Table 5 Range of concentration measurements reported vs exposure limits

Pollutant	Measurement range	Exposure Limits
CO_2 (ppm)	397 to 1328 ppm [data from multiple studies]	~ 850 ppm (ambient + 450) [Ref [3]]
CO (ppm)	0.02 – 1.53 ppm [data from multiple studies]	3.5 ppm (24 hr) [Ref [2]]
PM_{10} (μg/m³)	5.00 to 144 μg/m³ [data from multiple studies]	45 μg/m³ (24 hr) [Ref [2]]
$PM_{2.5}$ (μg/m³)	3 to 89 μg/m³ [data from multiple studies] Range 4.7 – 18.4, mean 3.9 (mechanically ventilated homes); 4.4 – 15.3, Range 4.4 – 15.3; mean 10.8 (naturally ventilated homes) [Ref [7]]	15 μg/m³ (24 hr) [Ref [2]]
UFP (particles/cm³)	~ 700 to 35,941 particles/cm³ [Ref [8]] PNC 24h range: 6.1 – 22.1 (x 1000, p/cm⁻³); 24h mean 10.9; indoor activities 18.2 ± 3.9; nonactivities 12.4±2.7 [Ref [9]] PNC range: 0.7 – 18.7 (x 1000, p/cm⁻³); mean 7.4±5.4 [Ref [10]] PNC range 0.98 – 35.9 (x 1000, p/cm⁻³); mean 11.3 [Ref [8]] Submicrometre range 4.85 – 21.3; mean 12.7 (mechanically ventilated homes); Range 5.29 – 40.0; mean 21.7 (naturally ventilated homes [Ref [7]]	No existing limit [Ref [2]]
NO_2 (ppb)	BDL to 119.8 [data from multiple studies] 1–97 ppb (range of weekly average); Geometric weekly mean 9.1 (Living area); 8.0 ppb (bedrooms); 9.3ppb (outdoors) [Ref [11]]	25 μg/m³ (24 hr) [Ref [2]]
O_3 (ppb)	0.11 to 3.59 (hourly); 13.6 to – 26.7 (daily) [data from multiple studies] 0.1 – 46 (week) [Ref [12]]	100 μg/m³ (8 hr daily max) [Ref [2]]
CH_2O (μg/m³)	BDL to 375 [data from multiple studies]	0.1 mg/m³ (30 min) [Ref [3]]
TVOC (μg/m³)	220 – 5000 [data from multiple studies] 97.6 – 1888.4 ppb; mean 406.6 ± 272.0 [Ref [13]]	500 μg/m³ (1 hr) [Ref [3]]
BTEX / VOCs (μg/m³)	BTEX: BDL to 145 benzene: BDL to 39 toluene: 0.8 – 82 ethylbenzene: BDL to 14 mp-xylene: 0.3 to 24 o-xylene: 0.1 to 17 styrene: BDL to 12 naphthalene: BDL to 34	

Table 6 Selected key findings for each pollutant in residential buildings

Pollutant	Key Findings
CO_2 (as a proxy for ventilation effectiveness)	Occupants still exposed to CO_2 of 1000 ppm when trickle ventilators used with exhaust system [Ref 11] Ambient cold air contributes to higher CO_2 decrease, but created small pockets of CO_2 concentration that could increase risk of virus transmission [Ref 14]
CO and particulate matter	Gas stoves and wood heaters were key contributors to elevated concentrations [Ref 15] Newer energy efficient homes had low concentration compared to older homes with poorer natural ventilation [Ref 15] Higher concentration levels in summer/autumn were attributed to bushfire smoke (infiltration) and increase in off-gassing from materials [Ref 12]
NO_2	Roadway emissions are a dominant source of outdoor NO_2 infiltration, especially for near road dwellings [Ref 13] Concentration levels significantly influenced by ventilation rates and indoor sources such as gas appliances [Ref 16] NO_2 significantly higher in homes using unflued gas heating or cooking appliances [Ref 11] Indoor pollutant levels (especially gas cooking) and transportation levels should be integrated into personal exposure models [Ref 18] Peak concentrations significantly higher in homes with gas cookers compared to non-gas homes. Average concentrations do not adequately identify exposure to short-term peaks of NO_2 that may be caused by gas cookers. Lack of peak exposure data may explain some inconsistent findings in epidemiological studies [Ref 19]
PM in general	Major sources in homes are cooking and environmental tobacco smoke [Ref 9] Indoor PM concentrations significantly associated with increase in heart rate and blood pressure [Ref 20] Houses with smoking activities are likely to be exposed to PM concentrations above ambient health standards [Ref 21] Smoke from wood heaters (in home and neighbouring homes) are main sources of indoor PM in winter [Ref 21] PM can be reduced by 42.6% by an Active green wall [Ref 22]
PM_{10}	PM_{10} levels different between homes with / without smokers. PM_{10} levels highly correlated with nicotine levels [Ref 12]
$PM_{2.5}$	Concentrations depended on different activities, cooking different foods and house characteristics; poor correlation between particle number and particle concentration [Ref 23,24,9] Prescribed burns and wildfires can contribute to high indoor levels. Indoor concentrations dependent on duration of fire event and ventilation of houses [Ref 25] Staying indoors without additional filtrations provides limited protection against smoke infiltration. HEPA air cleaners can significantly improve IAQ (30-74%) during prescribed burns [Ref 26] Indoor exposures to $PM_{2.5}$ and PM_1 are strongly associated with vascular risk markers [Ref 20]
UFP	Under normal ventilation conditions, and in the absence of indoor sources, indoor concentrations of UFP (and larger particles) tend to closely follow outdoor concentrations [Ref 8] PNC highly variable from day to day and from house to house [Ref 9] Residential $PM_{2.5}$ and UFP exposure is associated with blood pressure and some BP functional components: e.g. higher UFP concentrations were associated with higher diastolic blood pressure and lower pulse wave velocity (for women) and lower augmented pressure (for men) [Ref 10]
CH_2O	Formaldehyde emissions decay slowly. Source control is the most effective strategy to manage concentrations [Ref 27]
TVOC	TVOCs decayed over an 8 month period (post construction) (in a 'healthy' house). Measurement of TVOCs may underestimate the risks associated with individual compounds [Ref 28]
VOCs (including volatile aromatic hydrocarbons (VAH))	Contaminants primarily originate indoors [Ref 29] Indoor exposure may increase risk of cardiovascular disease [Ref 13] For every 10 unit increase in the concentration of toluene and benzene, the risk of having asthma increased by almost two and three times, respectively [Ref 28] Attention should be paid to building materials, indoor furnishing, building construction and indoor activities [Ref 13] Older homes have lower levels, suggesting a natural decay over time [Ref 30] Active green walls can reduce TVOCs (by 28%) [Ref 22] Internal garages are identified as a major source of VAH, with internal garages having concentrations 1.5 to 2 times that of bedrooms or living rooms [Ref 30] Elevated toluene levels found in dwellings close to major roads [Ref 16]
Semi VOCs	PCBs predominantly from indoor sources; PAHs influenced by outdoor sources [Ref 31]

2.3 Key Insights for Residential Buildings

The information provided in this chapter has provided glimpses into the past – vignettes of the IAQ in an extremely small sample of Australian dwellings over 25 years. It does not give us an understanding of the current state of indoor air in Australian residential buildings.

We do not know, for example, if IAQ – across all ten pollutants of interest in this study – is 'good' or 'bad' or 'adequate'; whether it is improving or getting worse; how widespread poor IAQ may be; or whether IAQ is worse in regional areas than in cities, or worse in apartments compared with detached houses.

All of these previous studies, however, do provide us with a picture of the IAQ issues that have been found in homes in the past 25 years, and, as such, provide some potential avenues for moving forward. The following subsections provide some thoughts on barriers and issues to be addressed, or policy ideas to investigate. These discussion points relate specifically to Class 1 and 2 buildings.

2.3.1 Key considerations for pollutant measurements

- For any pollutant measurement, what should be the focus: average concentrations, peak concentrations or the range of concentrations? Is there a problem of using long-term monitoring to investigate health effects as a result of short-term peak exposures?
- Should pollutant measurements be considered for each individual dwelling or for cohorts of dwellings (i.e. individual level or population level)?
- What are the benefits and risks for measuring groups of pollutants (e.g. TVOCs) as opposed to individual pollutants within groups? Is it more relevant or beneficial to measure BTEX?
- Which pollutants should be the main focus for the next 25 years? Why? How? Where?

2.3.2 Key considerations for improving health

It is estimated that 7 million Australian homes use gas internally, through 18 million gas appliances (heating, cooking, hot water)[11]. Asthma Australia[12] reports that 48% of Australians use a gas cooktop, and cooking with gas is estimated to be responsible for up to 12% of childhood asthma burden in Australia.

- Do medical professionals routinely ask patients with asthma or respiratory illnesses questions about gas appliances in their home? Why / why not? Is identification of the source (i.e. understanding and reducing exposure) considered part of medical care?
- How can the health impacts of combustion appliances be more clearly communicated to Australians, especially those with respiratory illnesses? What role can their medical teams play in limiting patient exposure to combustion-related pollutants?
- Should personal exposure devices be recommended for high-risk individuals? How could this be implemented?

2.3.3 Key considerations for Building Codes

- Is it desirable / feasible to mandate CO (and NO_2) sensors in all homes with gas appliances or wood-fired heaters / stoves?[13]
- Is it desirable / feasible to extend regulations for flueless gas heaters / open flued gas heaters (as implemented in Victoria) to all other jurisdictions? Why / why not?
- What role could / should building codes play in reducing infiltration risk by pollutants from other homes (e.g. wood fire smoke), transport emissions and environmental emissions (e.g. prescribed burns / wildfires)? What are the pros / cons of managing exposure in this way?
- Have the building codes addressed the issue of pollutants coming into the home via attached / internal garages?
- Can health improvements be included in 'least cost analysis' of modelling for electrification of the housing stock (for new builds, envisaged in 2028[14])? Why / why not?
- Is increasing the airtightness of homes, combined with mechanical ventilation with heat exchangers, the answer to both energy efficiency and indoor air quality?

2.3.4 Key considerations for other policy directions

- Should wood heaters be phased out? Why / why not? What are the barriers to buy back schemes? Similarly for household gas appliances.
- How can / should health impacts be considered in the Trajectory for Low Energy Buildings (low energy and net zero emissions buildings sector by 2050)?
- How do residential buildings interplay with the National Preventive Health Strategy?
- How can health, affordability, accessibility and resilience be combined to deliver multiple benefits across different policy portfolios? What evidence is required to enable ill health avoidance / good health to be accounted for in productivity policies and programs / health budgets?

[11] Frontier Economics. "Gas Vision 2050: Delivering A Clean Energy Future".

[12] Homes, Health and Asthma in Australia. 12/1/2023. Asthma Australia.

[13] CO sensors are required in the UK in residential rooms with fixed combustion appliances (Smoke and Carbon Monoxide Alarm (Amendment) Regulations 2022)

[14] The 2028 National Construction Code, in supporting the Trajectory for Low Energy Buildings, will model new residential buildings using a 'least cost option' for net zero energy and emissions. Full electrification is one of the scenarios to be modelled, as is 'support for electrification with a pathway for gas'.

3.0 Class 3 and 4 Buildings - Other Dwellings

Other Dwellings
Class 3 & 4

3.1 Scope

Class 3 buildings provide long term or transient accommodation for a number of unrelated people, such as boarding houses, hotels, motels, hostels, backpackers' accommodation, and dormitory style accommodation. It also includes workers' quarters on agricultural properties, and care-type facilities such as accommodation buildings for children, the elderly, or people with a disability, which are not Class 9 buildings.

Class 4 relates to a part of a non-residential building that is used as a sole dwelling or residence (e.g. caretaker's or security person's residence).

Other Dwellings

Building Count 2021: 88,529

Floor Area

Building Floor Area (m^2): 51,075,923

3.2 Current State

3.2.1 Overview and purpose of identified studies

Only two studies were identified that examined Class 3 or 4 buildings: one conducted in a correctional facility, and the other in the dormitory section of eight fire stations[15]. A summary of these studies is shown in Table 20. Note that there are no published scientific articles related to hotels / motels / holiday accommodation, in boarding schools or similar dormitory style accommodation, nor in other types of workers' accommodation.

The study in the correctional facility was focused on measuring the impact of smoking bans, whilst the fire station study focused on understanding the impact of fire station activities on IAQ – in this instance, on the air quality of the dormitory facilities located within the fire stations. The exact year of the fire station study is unknown but is estimated to be around 2015/16.

[15] This chapter only reports on the IAQ measured in the accommodation section of the fire stations. Results relating to the other parts of the fire stations are reported in the chapter on Class 6 buildings

3.2.2 Geographic and temporal distribution of studies

Figure 7 Geographic distribution of Class 3-4 IAQ studies

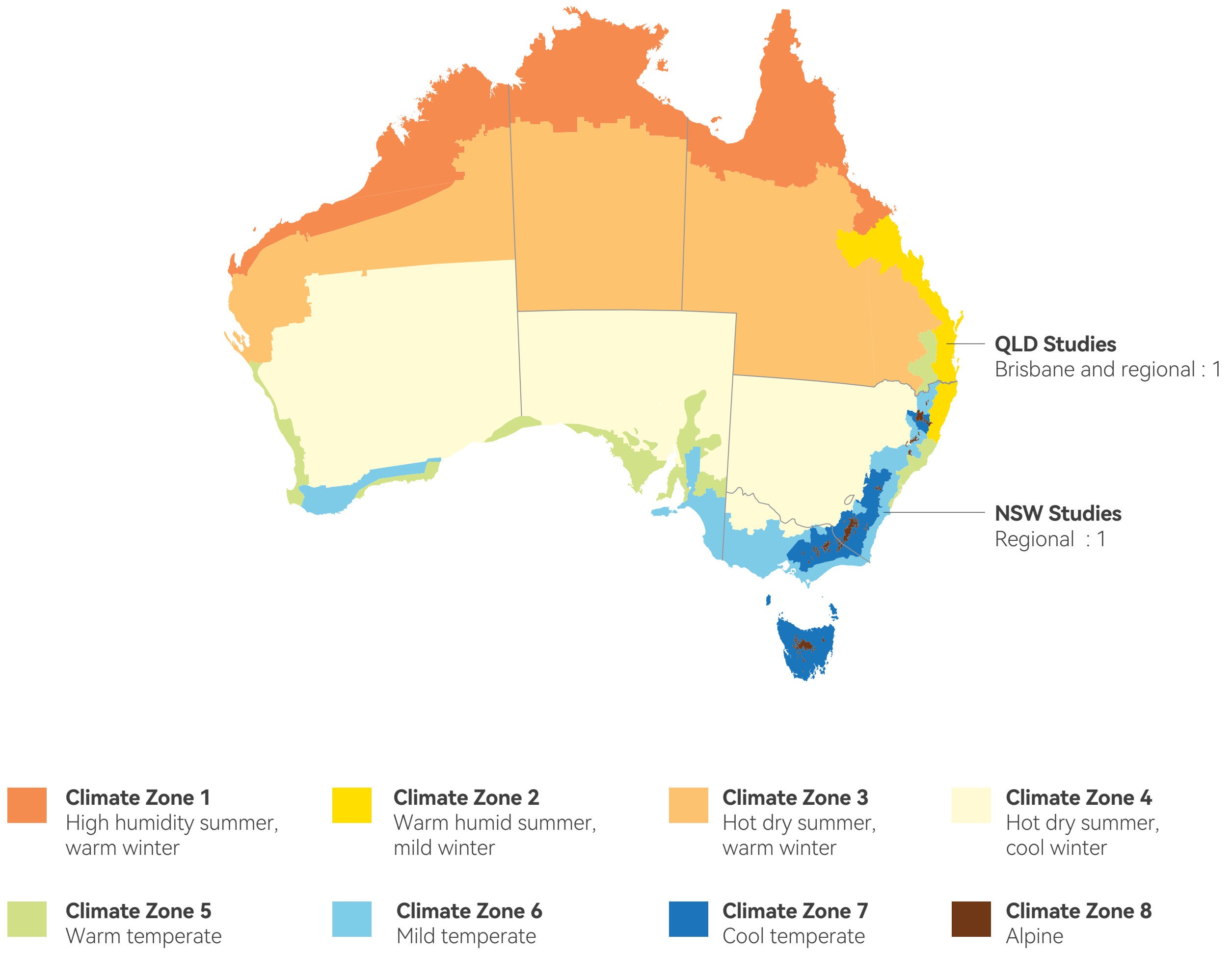
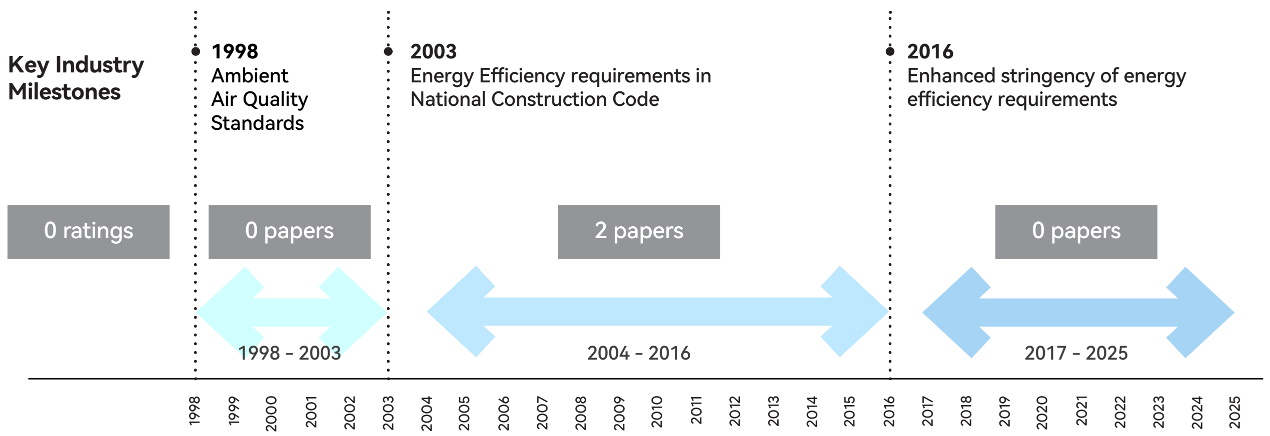


Figure 8 Temporal distribution of Class 3-4 IAQ studies



3.2.3 Measurement instruments

The correctional facility study (2013-14) utilised multiple TSI instruments:

- Q-Trak 8554 for indoor and outdoor CO_2, CO, temperature and relative humidity
- Model 3787 for particulate matter. This instrument is a water-based condensation particle counter with a high sample flow rate to detect airborne particles down to 5 nm. Note that this model has since been discontinued and replaced with 3rd generation Model 3789.
- DustTrak for $PM_{2.5}$

These devices were supplemented by wearable monitors by some personnel (Aerasense NanoTracer). VOCs were measured using stainless steel desorption tubes filled with Tenax.

In the fire stations, particulate matter was measured using SKC cassettes with quartz filters connected to SKC PCXR*Universal Sample Pumps. Polycyclic aromatic hydrocarbons were measured using AirChek 2000 programmable direct flow compensated air sampling pumps and glass tubes containing Tenax.

3.2.4 Contaminant measurements and key findings

Contaminant measurements for the two different types of residential situations are shown in Table 7. As both of these situations represent both residential and workplace environments simultaneously, the exposure limits are shown for comparative purposes.

Key findings from each of the studies are presented in the following paragraphs. These findings then inform the questions raised in section 3.3 for moving forward.

3.2.4.1 Smoking bans in correctional facility

The results from the correctional facilities indicate likely clandestine smoking by inmates post the smoking ban, indicated by increased particle number, $PM_{2.5}$ concentrations and TVOCs in some areas of the facility. This increased the personal exposure of staff located in close proximity to inmate cells, or working directly with inmates (e.g. providing medical care). The study highlights the importance of considering the goal of the policy. If limiting personal exposure to pollutants from smoking is the goal, the findings suggest

Table 7 Summary of pollutant measurements in Class 3 buildings vs exposure limits

Pollutant	Measurement range	Exposure Limits
	Correctional Facility [Ref 30]	
$PM_{2.5}$	6 – 17 µg/m³ pre-ban 7 – 71 µg/m³ post-ban	15 µg/m³ (24 hr) [Ref 2]
UFPs	PNC pre-ban 24h range 4.88 – 5.13 x 1000, p/cm^{-3} PNC post-ban 24h range 18.2 – 24.0 x 1000, p/cm^{-3} PNC pre-ban 24h mean 5.1 x 1000, p/cm^{-3} PNC post-ban 24h mean 21.1 x 1000, p/cm^{-3}	No existing limit [Ref 2]
TVOCs	154 – 240 µg/m³	500 µg/m³ (1 hr) [Ref 3]
	Dormitories in Fire Stations [Ref 31]	
Diesel Particulate Matter	<Limit of Detection (LOD) – 0.002 mg/m³	0.01 mg/m³ (for coal mine environments; accepted by AIOH in the absence of an Australian exposure standard)
$PM_{2.5}$	10 hr average <3 µg/m³	15 µg/m³ (24 hr) [Ref 2]
Semi VOCs (PAH (Total))	0.1 – 0.9 mg/m³	

that smoking bans may be unreliable and that engineering approaches (e.g. smoke detectors, increased outside air ventilation, and improved filtration systems) might be more reliable in reducing staff exposure. If smoking cessation is a goal, a multifaceted approach may be required that includes counselling (strategies to assist individuals to give up smoking), combined with enforcement and adoption of engineering controls. The study also highlights challenges associated with facilities that combine residential functions and work obligations.

3.2.4.2 Diesel particulates in fire station dormitories

$PM_{2.5}$ measurements (10 hr averages) were well below the WHO limit. (Note that 10-hour averages were used for this study because it represents the workers' shift time).

Diesel particulate matter measurements were also below the STEL set for coal mine environments (the default limit accepted by occupational hygienists in the absence of limits set for non-mining work places). The study reports that PAH concentrations (semi VOCs) in dormitories were also below values set by the US EPA (there were no concentration limits for collective PAHs in Australia at the time of the study, although the limit of 0.01 is in the WEL).

Elemental carbon levels were highly correlated with start of shift processes, while overall concentration levels were also affected by vehicles (e.g. older vehicles not compliant with current vehicle emission standards), proximity to major roads and industrial areas (other sources of pollutants), and fire station design and operation (e.g. engine bay design with one entry or drive through).

While the pollutant levels measured in the dormitories were low, the most feasible option for reducing firefighter exposures to diesel engine exhaust in the dormitories is to minimise the potential for air movement between the engine bay and other areas of the fire station through building design (e.g. door seals).

3.3 Key Insights for Class 3 Residential Buildings

The findings from these two papers are arguably still relevant to other buildings in this class, as well as to non-residential buildings in other classes. The following paragraphs present barriers and issues that need to be addressed and policy ideas that could be investigated.

3.3.1 Key considerations for pollutant measurements / analysis in Class 3 buildings

- What is the purpose of measuring any of the pollutants of interest? To quantify personal exposure or to quantify pollutant 'averages' in the indoor environment?
- What pollutants should be the main focus for this class of building (short term accommodation)?
- What pollutants should be measured to protect the health of workers in this class of building? Is there an argument for wearable devices?
- What concentration limits (of specific pollutants) should be applied to this class of building which has a high overlap of accommodation and workplace functions? Are there some pollutants that should be included / added to exposure limits for some types of buildings?

3.3.2 Key considerations for improving health

- Is smoking a pollution source of concern in the hotel / motel / shared accommodation sector?
- To what extent can the activities of individuals (e.g. smoking) be regulated / constrained if they impact on the air quality of others (e.g. smoking on balconies / outside motel rooms etc)?

3.3.3 Key considerations for Building Codes and building operation

- What is an appropriate 'balance' between source elimination (e.g. smoking bans) and source control (e.g. ventilation, filtration etc) in short term accommodation buildings utilised by many different persons for varying amounts of time?
- How are the interplays between 'workplace' and 'sleep space' considered in the building codes? In WorkSafe Australia exposure guidelines / limits?
- How can living spaces be protected from diesel emissions? E.g. separation of garages from living areas? Requirement for reverse parking at motels?

4.0 Class 5 Buildings - Offices

Offices
Class 5

4.1 Scope

Office buildings are used for professional or commercial activities such as administrative, professional and clerical functions and other information-based activities (e.g. accountancy, advertising, architecture, banking, engineering, government agencies, marketing, medical practices, property and real estate).

4.2 Current State

4.2.1 Overview and purpose of identified studies

Fourteen journal publications, involving about 110 office buildings in total, were identified, representing 0.08% of Class 5 buildings in Australia.

Table 21 summarises the key data from these studies. The three main pollutants studied were CO_2, $PM_{2.5}$ and UFP/PNC. CO, PM_{10}, NO_2 and TVOCs were measured in 2 studies, and CH_2O and SO_2 in one study each. One study focused on ultrafine emissions from office printers. Some studies were focused on specific pollutants related to the location of specific buildings (e.g. elevated $PM_{2.5}$ in Brisbane offices located near high-traffic corridors; or PM effects from extreme bushfire events in Canberra). Two studies included airborne fungi in the pollutants measured.

The buildings in the published studies included high-rise buildings and mid-rise buildings, from pre-1900s (heritage listed), 1960s – 2000s ('conventional' offices), portable buildings and modern buildings (post 2000, including certified 'green' buildings).

Offices

Building Count 2021 **127,295**

Building Floor Area (m^2) **157,191,084**

Commercial buildings not elsewhere counted

Building Count 2021 **12,478**

Building Floor Area (m^2) **11,330 337**

As expected for this building class, the majority of buildings were mechanically ventilated, although some studies compared IAQ in buildings with different ventilation systems (natural, mechanical or mixed). The main objectives of the studies included HVAC performance during extreme events (e.g. bushfire smoke infiltration); pollutant concentrations; exposure risks from building proximity to traffic; and modelling to optimise indoor environment quality. There were no studies in regional contexts (outside of capital cities). All buildings were located in or near the central business district (CBD) of a capital city.

4.2.2 Geographic and temporal distribution of studies

Figure 9 Geographic distribution of Class 5 IAQ studies

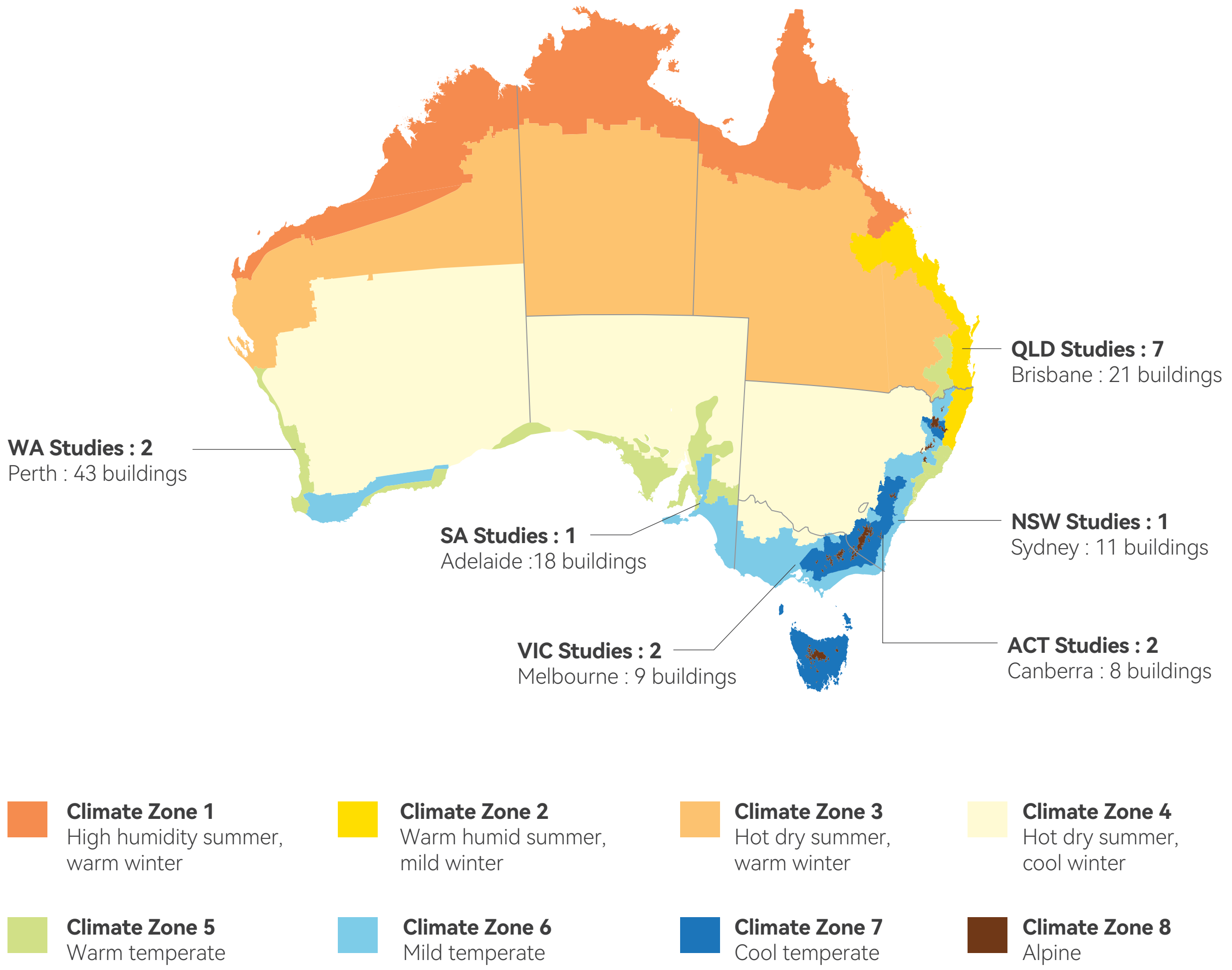
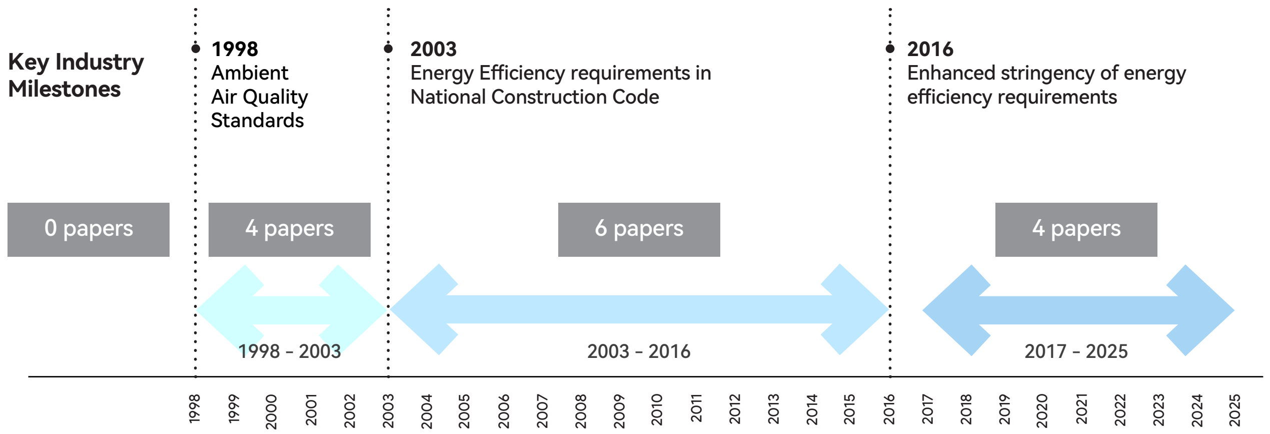


Figure 10 Temporal distribution of Class 5 IAQ studies



Two of the papers published in 2000 report on measurements undertaken in office buildings prior to 1998, when Ambient Air Quality Standards were introduced. These papers investigated CH_2O and PNC. The other two papers published prior to 2003 investigated NO_2, TVOCs and CH_2O. Eight of the studies were conducted in the 2004–2016 period, when energy efficiency standards were introduced to commercial buildings, then tightened. These studies focused either on ventilation performance, or on indoor air pollution sources and levels. The two most recent studies, undertaken in 2019, compared IAQ in different building typologies and the impact of bushfires (Table 21).

4.2.3 Measurement instruments

The studies employed different methodologies and instruments for their specific IAQ objectives, with significant variations in instrument selection, sampling locations and timeframes. Continuous sampling was common but conducted over periods ranging from 2 days to a whole year. Sampling location varied (e.g. breathing zone of seated office workers, HVAC intake or randomised locations) as did the number of sample locations per building.

Similar to the instruments used in the residential building studies, commonly used instruments were from the TSI family: Q-Trak (for multiple pollutants); TSI Model 3022 and 3025A (condensation particle counters); TSI 8525 P-Trak (ultrafine particle counter); and DustTrak and DustTrak II (for aerosol monitoring). One study used a different product – Sensedge SE-100 – instead of TSI instruments. Passive badges were used for NO_2, and Flame Ionization Detector (FID) for VOCs.

4.2.4 Contaminant measurements and key findings

The concentrations measured in the 55 buildings involved in these studies cannot be considered representative of the indoor air quality of commercial office buildings in Australia. Table 8 shows the measurement ranges reported in this study and the target thresholds related to each contaminant.

As a collective, the studies point to policy gaps, such as outdated or insufficient ventilation standards or protocols, unpreparedness for unexpected events, and the lack of guidelines for some pollutants (e.g. some VOCs and fungi), while suggesting possible insights for building design, monitoring and assessments, and occupant health protection.

The contaminant profiles in office buildings in these studies were impacted by three main contexts:

- The location of the building (e.g. near major roads)
- Ventilation design (mechanical, natural or mixed) and HVAC design and operation (e.g. filter types, location of air intake, air exchanges per hour)
- Extreme events impacting ambient air quality (e.g. infiltration of outdoor air impacted by bushfires impacts on the safety of 'shelter in place' strategies in such circumstances)

In particular, peak concentrations of CO and PM (10, 2.5 and UFP) were closely linked to outdoor concentrations. For example, Quang et al [37] measured peak particulate concentrations up to 41% higher during rush-hours and up to 57% during nucleation events. An exception to this, in relation to UFPs, related to emissions from office printers, with 27% of the 62 printers investigated in 2006 classed as high submicrometer particle emitters [38].

Table 8 Summary of pollutant measurements in office buildings vs exposure limits

Pollutant	Measurement range	Exposure Limits
CO_2 (ppm)	<400 to 1086	~ 850 ppm (ambient + 450) [Ref [3]]
CO (ppm)	BDL to 3.25	3.5 ppm (24 hr) [Ref [2]]
PM_{10} (µg/m³)	10 to 35 (mean range from multiple studies)	45 µg/m³ (24 hr) [Ref [2]]
$PM_{2.5}$ (µg/m³)	4.5 to 60 (mean range from multiple studies) (outdoor peaks up to 600 during bushfires) Pre-HVAC redesign: median 7 µg/m³; Post HVAC redesign: range 3-5 µg/m³ [Ref [35]]	15 µg/m³ (24 hr) [Ref [2]]
UFP (particles/cm³)	Range 2.6 – 4.8 (x 1000, p/cm^{-3}); Mean 3.72 [Ref [36]] Range 3.4 – 4.56 (x 1000, p/cm^{-3}); Mean 3.87±0.61 (during work hours) [Ref [37]] Pre-HVAC redesign: median PNC 7.4 x 103 particle/cm³; post HVAC redesign: median PNC 2.7 x 103 particle.cm³; range 2.3 – 3.4 x 103 particle/cm³ [Ref [35]] Highest PNC 38.2 (x 1000, p/cm–3) [Ref [38]]	No existing limit [Ref [2]]
NO_2 (µg/m³)	10.0 to 470.3	25 µg/m³ (24 hr) [Ref [2]]
CH_2O (µg/m³)	14.2 (1 study) Conventional office buildings: Range 10-78 ppb; mean 22ppb; Portable office buildings: Range 420 0 2110 ppb; mean 1138 ppb; 11% reduction in concentrations when 20 plants (variety of species) added [Ref [39]]	0.1 mg/m³ (30 min) [Ref [2]]
TVOC (µg/m³)	BDL (1 study)	500 µg/m³ (1 hr) [Ref [3]]

Collectively the studies indicate a critical need to address infiltration (the unwanted, unplanned entry of ambient air into the building) and ventilation (the type and design of the HVAC system, the location of air intake, the use of high efficiency filters, and the air exchange rate).

A strategy for successfully addressing these challenges was demonstrated in reference [35]. This study clearly demonstrated the impact of a comprehensive approach to improving indoor air, encompassing measuring outdoor pollution levels, relocating air intake and redesigning the HVAC system.

Results included significant reductions in outdoor particle number and $PM_{2.5}$ concentrations and particle number penetration rates, and a significant increase in overall HVAC system filtration efficiency.

Some findings from studies relating to formaldehyde and VOCs include:

- Different spaces / buildings on a university campus had different VOC indoor/outdoor ratios.[40]
  - A green building had the highest I/O ratios of formaldehyde, toluene and xylenes;
  - Renovated offices had highest I/O ratios of benzene;
  - Restrooms and campus services had highest I/O ratios of d-limonene and ethanol.
- Building materials and fragranced consumer products can be main indoor sources.[40]
- Plants are not an efficient means of removing formaldehyde and large numbers are required to achieve any detectable reduction in concentrations.[39]

4.3 NABERS IEQ Ratings for Office Buildings

4.3.1 Overview

In addition to the identified scientific papers, a national indoor environment data base was analysed. NABERS is Australia's national building energy rating scheme. In accordance with Australia's Commercial Building Disclosure (CBD) Program established in 2009, all office buildings with a net lettable area equal to or greater than 1000 m² are required to have a NABERS Energy Rating and to disclose that rating at point of sale or lease. NABERS also released, in 2009, an Indoor Environment Quality (IEQ) rating scheme which is voluntary.

NABERS IEQ Ratings can be conducted for a base building, whole building, or tenancy within a building. The overall IEQ rating includes an IAQ component in all three rating types. Refer to Table 9 for a summary of IAQ pollutants and the weighting of IAQ within an overall IEQ assessment, and Table 10 for the relative weightings of the different pollutants within the IAQ assessment.

The Rules for NABERS IEQ assessments [41] determine the minimum number of occupied floors of an office building that must be sampled, the minimum number of samples required per assessed floor, the sampling locations and times, measurement equipment and placement, and plant room sampling requirements.

All air pollutant measurements are typically on-site spot measurements taken by real-time monitoring equipment during 'normal' working hours for each site. At least 2 samples are required in each sampling location (morning and afternoon, minimum 5-minute average) on the selected sampling day. Formaldehyde and TVOCs can be assessed via a laboratory method rather than real time equipment (i.e. one sample per floor assessed collected over a 4-6 hour period). Ratings are only valid for 12 months.

All assessments must be conducted by NABERS Indoor Environment Accredited Assessors, although some on-site measurements may be sub-contracted to appropriately qualified indoor environment professionals.

Table 9 Pollutants included in IAQ assessment of different NABERS IEQ ratings

Pollutant	Base Building	Whole Building	Tenancy
IAQ weighting in overall IEQ certification	40%	30%	40%
Carbon dioxide (CO_2)	Yes (5 minutes at each sampling location near supply air diffuser, and at outdoor air intake in each plant room)	Yes (5 minute sampling at each sampling location in occupied space, and at outdoor intake in each plant room)	Yes (5 minute sampling at each sampling location in occupied space, and at outdoor intake in each plant room)
Carbon monoxide (CO)	Yes (at outside air intake in each plant room)	Yes (at outside air intake in each plant room)	No
PM_{10}	Yes (5 minute sampling near supply air diffuser at each sampling location)	Yes (5 minute sampling in each sampling location in occupied space)	Yes (5 minute sampling in each sampling location in occupied space)
TVOCs	No	Yes (5 minute sampling in each sampling location in occupied space or 1 sample per floor, collected over 4-6 hours)	Yes (5 minute sampling in each sampling location in occupied space or 1 sample per floor, collected over 4-6 hours)
Formaldehyde (CH_2O)	No	Yes (5 minute sampling in each sampling location in occupied space or 1 sample per floor, collected over 4-6 hours)	Yes (5 minute sampling in each sampling location in occupied space or 1 sample per floor, collected over 4-6 hours)

Table 10 Weightings of subcomponents within the IAQ component of the IEQ ratings

Component	Base Building	Whole Building	Tenancy
Occupant Satisfaction Survey (OSS) of air quality		50%	50%
CO_2 (Ventilation effectiveness)	55%	20%	20%
PM_{10}	30%	10%	10%
CH_2O		10%	10%
TVOCs		5%	10%
CO	15%	5%	

4.3.2 Geographic and temporal distribution

1673 IEQ ratings were conducted across Australia in the period 11/9/2009 to 10/3/2025 (Figure 12). In contrast to the scientific studies, NABERS assessments have occurred in all states and territories, although the vast majority are in capital cities (where one would expect to find the highest density of commercial office buildings) (Figure 11).

Figure 11 Geographic distribution of NABERS IEQ ratings

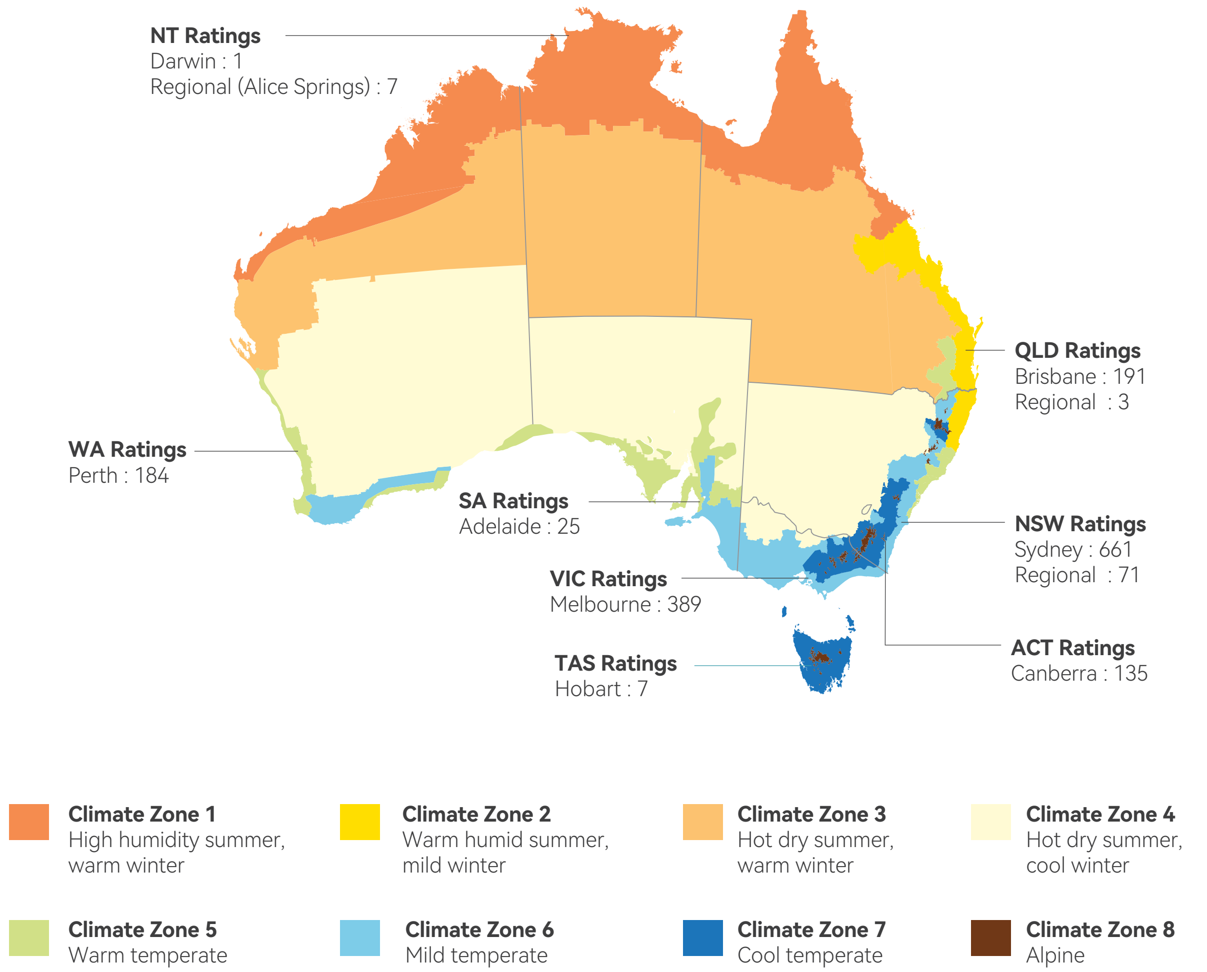
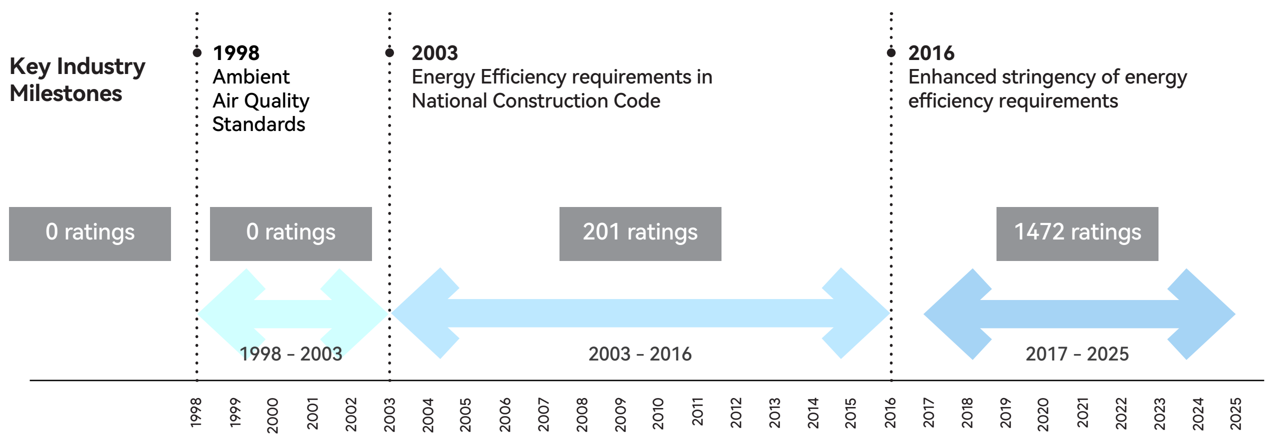


Figure 12 Temporal distribution of NABERS IEQ ratings



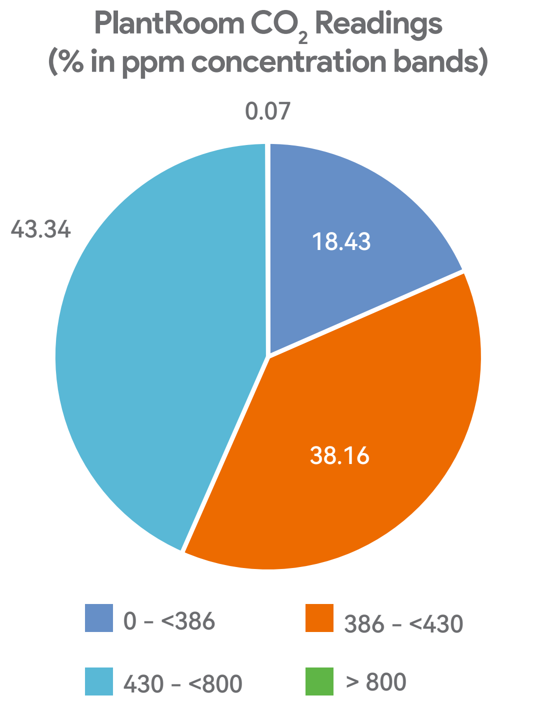
4.3.3 Rated buildings

450 commercial office buildings, all mechanically ventilated, account for the total number of rating certificates issued since inception of the NABERS IEQ rating scheme (2009). This is approximately 0.3% of Australia's commercial office buildings. Building profiles ranged from single storey up to 57 storeys, with occupied floor areas ranging from 491m² to 121,000m². 54% of these buildings had repeat certifications (2–12 each), while 25% had been rated once. The overwhelming majority of the ratings (97.5%) were for a base building, with 1.7% for tenancies, and 0.7% for whole of building. This has implications for what pollutants were measured, and where, as previously shown in Table 9.

4.3.4 Contaminant measurements and key findings

CO_2 ppm concentrations measured in plant rooms (within 3m of outdoor air intake) are shown in Figure 13. The concentration band 386 – <430 indicates possible ambient CO_2 concentrations in the period 2009 – 2025. While 38% of readings were within this range, the data shows 18.5% of readings were under feasible ambient CO_2 concentrations, possibly indicating faulty readings, non-calibrated instrumentation or the possibility of air purification strategies (e.g. filters or scrubbers) applied to the outdoor air intake. Conversely, 43% of readings from the plant room were above ambient concentrations, possibly indicating faulty readings, non-calibrated instrumentation, or additional sources of CO_2 inside the plant room. Less than 0.1% of measurements exceeded 800 ppm.

Figure 13 Percentage of plant room CO_2 readings in different concentration bands



CO_2 concentrations (measured close to 1m vertically and horizontally from supply air diffusers) in office spaces are shown in Figure 14. Over 94% of readings were between the lowest likely ambient concentration and 800ppm. This would seem to indicate that the majority of buildings rated had very good CO_2 levels, however it is worth remembering the two main limitations of the data:

- CO_2 is measured, in base buildings, at supply air diffusers, not in other locations across a floor plate; and
- the measurements are 'point in time' samples (i.e. 5 minute samples on a particular morning and afternoon) and are not averages based on occupied time.

Even with this constraint, 252 of the ratings had CO_2 concentrations above 1000ppm, with the highest recorded concentration of 4785 ppm.

NABERS target range for CO_2 concentrations in offices is ambient CO_2 + 400 (with an assumption that the ambient is around 400 ppm). For base buildings, the purpose of measuring CO_2 concentrations near air diffusers is to reflect the air quality delivered by the HVAC system, not the CO_2 concentration levels experienced by occupants.

Figure 14 Percentage of supply air CO_2 concentrations in different concentration bands

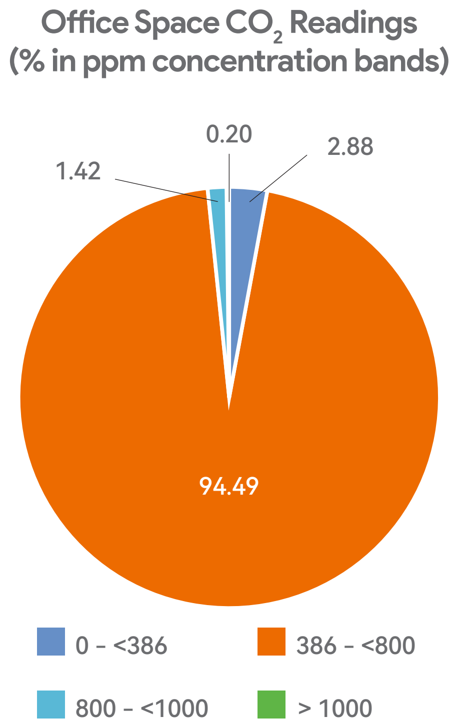
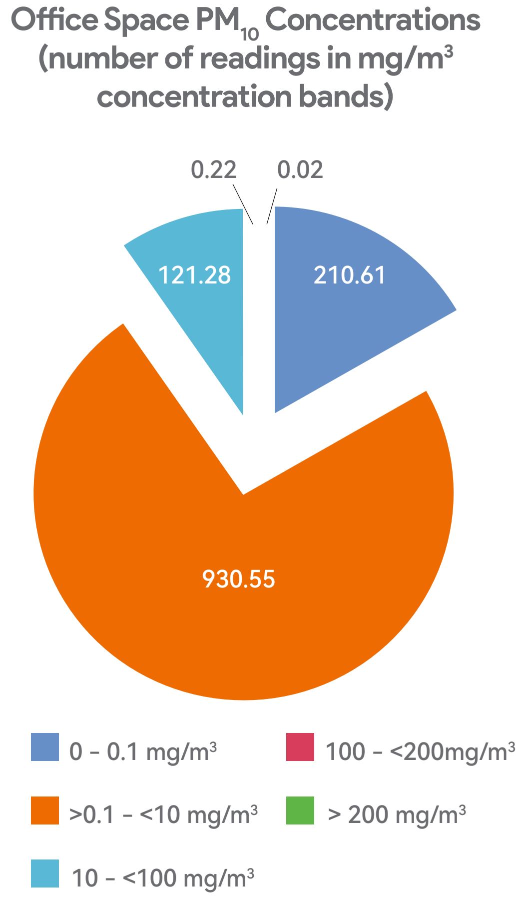


Figure 15 PM_{10} concentrations near supply air in office buildings



4.4 Key Insights for Office Buildings

The scientific studies highlight that office buildings were impacted predominantly by four contexts: location, infiltration, ventilation design and operation, and extreme events that impact ambient air quality.

The NABERS data highlighted the importance of understanding the purpose of monitoring, and the location and duration of monitoring. Collectively these key findings raise questions for a range of stakeholders, as discussed below.

4.4.1 Key considerations for pollutant measurements

- Should CO_2 be monitored in all occupied areas of office buildings? And should monitoring occur at supply air vents or in the breathing zone of occupants? Is the purpose of CO_2 monitoring to determine ventilation effectiveness or the impact of exposure on occupant health / productivity? Refer to [1].
- Do offices need to monitor both PM_{10} and $PM_{2.5}$? Which is more important / prevalent in office buildings? Which has a greater impact on occupant health?
- For better clarity and communication, can / should the units used for pollutant concentrations by scientists and occupational hygienists be harmonised (e.g. $\mu g/m^3$ or mg/m^3; ppb or $\mu g/m^3$)?
- When / where is CO monitoring required?
- Is CH_2O a problem in offices? Why / why not? Is it adequately managed by source control?
- What are the limits of TVOC measurements? Should specific VOCs be targeted instead? If so, which ones? BTEX?

4.4.2 Key considerations for facilities managers / building owners / Property Council of Australia

- What changes to building management systems are required to consider using CO_2 measurements as a means of communicating risk of spread of airborne pathogens as opposed to ventilation effectiveness for thermal comfort / energy efficiency?
- Are additional ventilation strategies applied to offices used for medical professional services (e.g. general practitioner healthcare services) where bioaerosol loads can reasonably be expected to be higher? What other types of 'office tenancies' might present a higher than 'typical' pollutant load?
- How can the air quality of workers in mid-tier commercial buildings be better regulated?
- Is the Australian Paint Approval Scheme which stipulates VOC limits for products likely to lead to lower VOC concentrations in refurbished offices?
  Over what timeframe? How can / will 'success' be verified?

[16] https://www.cbre.com.au/insights/articles/understanding-sustainability-ratings-and-its-impact-on-the-property-lifecycle

4.4.3 Key considerations for building certification schemes

- CBRE[16] states that over ¾ of Australian office stock is NABERS rated, with 54% of office buildings in 2024 rated as 5 star and above, and 43% of office buildings constructed prior to 2000 being upgraded to at least 5 stars. This is arguably substantially driven by the Commercial Building Disclosure program that requires tenancies above 1000m² to disclose a NABERS rating. Does a NABERS energy rating guarantee good indoor air quality? What drives / could drive more buildings to undertake a NABERS IEQ rating (or WELL rating or similar)? Why are air quality ratings considered less important than energy ratings? Should air quality be incorporated into the energy rating?
- It is arguable that most of the NABERS IEQ ratings have involved top tier commercial office space (Premium and Class 1 buildings) as defined by the Property Council of Australia[17]. How can IAQ of mid-tier buildings be measured /improved?
- Is there a correlation between energy ratings and indoor air quality ratings and thermal comfort ratings? What can be learned from the different NABERS data sets?
- Given the demonstrated uptake of voluntary indoor air quality assessments through NABERS IEQ, could this scheme be a mechanism for implementing voluntary air quality assessments in public buildings (Class 9b)?
- Is it feasible / desirable to modify NABERS IEQ guidelines and processes to include measures relating to occupant exposure?

4.4.4 Key considerations for Regulators

- The National Pollutant Inventory (NPI) requires facilities to report VOC emissions if they exceed certain thresholds. Are the current thresholds (and listed pollutants) relevant to the commercial building sector? Is the NPI meant to be a comprehensive list of harmful pollutants in the workplace and the limits of exposure to protect the health of workers (even office workers) or is it restricted to 'industrial pollutants'?
- Limits to VOC levels in coatings came into effect on January 1, 2024. Are these limits known and understood by office building owners, managers and occupants? How are these limits enforced?
- To what extent do Workplace Exposure Standards (WES), and the Workplace Exposure Limits (WELS) from December 2026, apply to office buildings? Are the pollutants and exposure limits commensurate with the context of office buildings? How are pollutants monitored, communicated and managed now? How could things be changed to improve IAQ in office buildings?
- What role does the National Construction Code play in mandating / regulating indoor air quality in office buildings (and other building classes)?

4.4.5 Key considerations for all stakeholders

- How can the health of workers in mid-tier office buildings be better protected?
- How can unions, the medical profession, scientists and building owners / managers work collaboratively to build the business case and value proposition for improving air quality in office buildings (and other building classes)?

[17] Guide to Office Building Quality: Third Edition (2019). Property Council of Australia

5.0 Class 6 - Retail and Class 7 - Storage and Wholesale

Retail
Class 6

Storage & Wholesale
Class 7

5.1 Scope

Class 6 buildings include shops, restaurants and cafes, and places for the sale of retail goods or the supply of services direct to the public. It includes parts of buildings that may have other classifications, such as a dining room or shop within a hotel, or a showroom / salesroom within a factory.

Class 7 buildings include car parks (7a) and warehouses, storage buildings or buildings for the display of goods or produce for wholesale (7b).

5.2 Current State

5.2.1 Overview and purpose of identified studies

Only two studies were found that encompass retail and wholesale building classes involving a total of 18 buildings (approximately 0.006% of the buildings in these two classes). There are no publications about IAQ in venues that could arguably have pollutants affecting IAQ, due to the nature of their goods or activities (e.g. hairdressers [42], nail salons [43], public laundries[44], furniture and clothing stores, food outlets [45], or stores demonstrating personal care and/or scented products [46,47]). It is worth noting that a study focused on measuring formaldehyde was apparently conducted in 38 retail stores in Perth (hardware, clothing, furniture, fabric, carpet and hair salons) around 2000-2001, yet the published paper for that study could not be found.

Retail & Wholesale Trade

Building Count 2021 175,504

Building Floor Area (m^2) 73,285,412

Warehouse

Building Count 2021 103,665

Building Floor Area (m^2) 135,047,037

The two identified studies were concerned with specific pollutants: tobacco smoke in coffee shops and restaurants in Perth in the early 2000s, and diesel particulates in fire stations in Queensland (2016). A summary of these two papers can be found in Table 22 in section 12.

5.2.2 Geographic and temporal distribution of studies

Figure 16 Geographic distribution of Class 6-7 IAQ studies

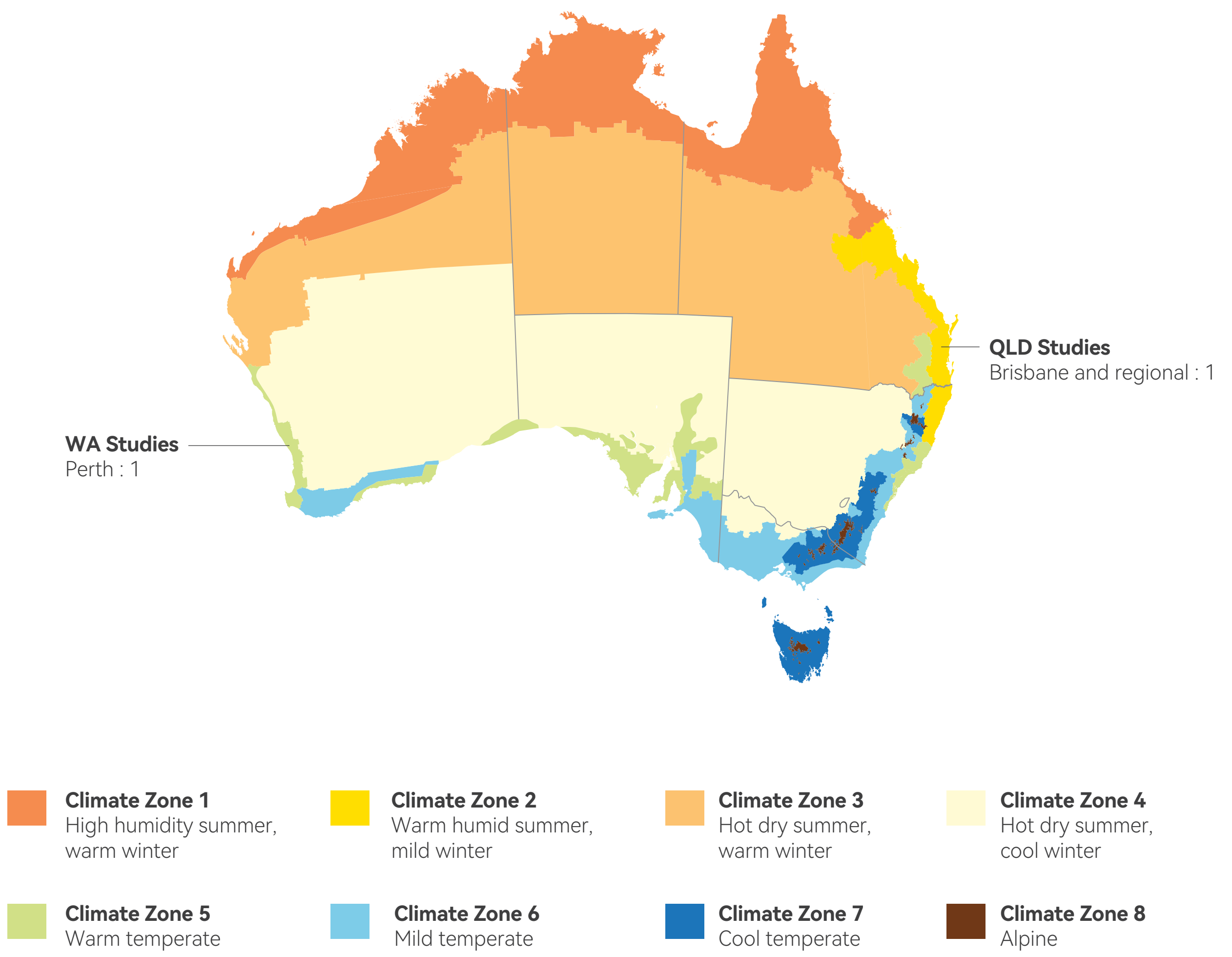
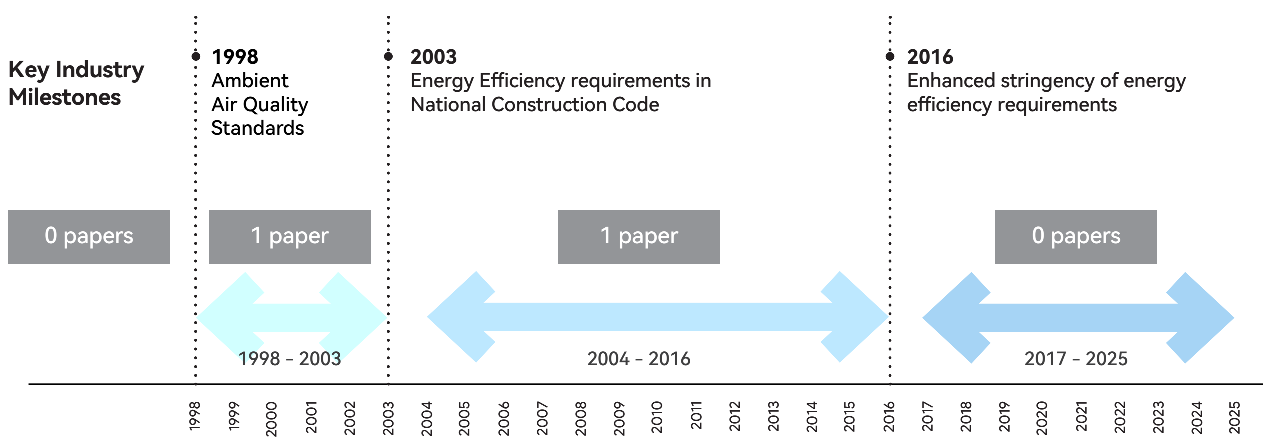


Figure 17 Temporal distribution of Class 6-7 IAQ studies



5.2.3 Measurement instruments

The first generation DustTrak by TSI was used in the tobacco smoke study for monitoring of $PM_{2.5}$ and PM_{10}. Other instruments used in that study were Telaire Systems Blaq Box 1350 for CO_2 and Amahsco Gas Exposure Monitor for CO. Note that the availability of second generation TSI instruments (e.g. DustTrak II and Q-Trak) since 2008 negates the need for multiple instruments such as those used in this study.

The diesel particulate study conducted air sampling using an SKC cassette with quartz filter and SKC PCXR8 Universal Sample Pump, with samples analysed using Sunset Laboratory's Thermal/Optical Carbon Analyzer (combination of high temperatures and laser radiation). Polycyclic aromatic hydrocarbons (PAHs) were sampled using an SKC AirChek 2000. This instrument's isothermal flow sensor enables electronic control of the flow rate, enabling sampling from 5ml/min – 3250 ml/min.

5.2.4 Contaminant measurements and key findings

The measurement data from the cafes and restaurants (Table 11) show a wide range of pollutant concentrations, with concentrations in some venues exceeding the WHO guidelines for CO, PM_{10} and $PM_{2.5}$. The CO_2 concentrations in some venues exceeded the guidelines set by the ABCB.

Elemental carbon measurements (a component of $PM_{2.5}$) in engine bays exceeded WHO guidelines. Eight PAH compounds (semi-VOCs) were detected in measurable quantities, with another eight not detected in measurable quantities. Naphthalene levels in two fire stations exceeded the calibration range of the instrumentation.

The key findings from each of the studies are presented below in Table 11.

Table 11 Summary of pollutant measurements in cafes and restaurants vs exposure limits

Pollutant	Range of average contaminant levels per venue	Average of all venue averages	Exposure Limits
	Cafes and restaurants [48]		
CO_2	500 to 1420 ppm	793 ppm	~ 850 ppm (ambient + 450) [Ref 3]
CO	2.0 to 12.0 ppm	3.8 ppm	3.5 ppm (24 hr) [Ref 2]
PM_{10}	25 to 481 $\mu g/m^{-3}$	150 $\mu g/m^{-3}$	45 $\mu g/m^3$ (24 hr) [Ref 2]
$PM_{2.5}$	Below detectable limit (1 venue) to 63.6 $\mu g/m^{-3}$	30.68 $\mu g/m^{-3}$	15 $\mu g/m^3$ (24 hr) [Ref 2]
Nicotine	Below detectable limit (7 venues) to 14.0 $\mu g/m^{-3}$	2.234 $\mu g/m^{-3}$	
	Fire Stations [31]		
$PM_{2.5}$	0.001 – 0.026 mg/m^3 in engine bays (10 hr)		15 $\mu g/m^3$ (24 hr) [Ref 2]
PAH	0.05 – 1.85 $\mu g/m^3$ in engine bays (10 hr) 0.1 – 0.6 $\mu g/m^3$ in duty offices (10 hr)		0.2 mg/m^3 (8 hr) Safe Work Australia

5.2.4.1 Cafes / restaurants

- CO levels were affected by location of venue relative to main road / traffic.
- PM_{10} levels are impacted by the activity level of the venue (i.e. customer numbers / density / number of smokers) – an indication that the respective ventilation was not adequate.
- Elevated PM_{10} and CO_2 was linked to HVAC systems 'faults' in a number of ways:
  - inadequate design / sizing to deal with increased levels of pollutants (by smoking and/or by number of patrons);
  - inappropriate settings (e.g. set up for thermal comfort not air quality);
  - type of ventilation system (e.g. recycled air rate vs fresh air rate);
  - inappropriate design (e.g. contaminated air directed past positions regularly occupied by staff);
  - incorrect scheduling (e.g automatic controls out of sync with patronage numbers / times);
  - poor documentation (system design, operation, maintenance);
  - poor staff training (lack of staff knowledge and understanding);
  - lack of maintenance to Australian Standards.

5.2.4.2 Impact of diesel particulates

- The exposure standard limit for diesel particulates, adopted for coal mine environments, is 0.1 mg/m³. This limit was supported by the Australian Institute of Occupational Hygienists (AIOH), in the absence of an Australian Workplace Exposure Standard. (Australia has now accepted this WEL). Exposure limits are based on 8-hour time-weighted averages (note that these fire stations had 10-hour day shifts and 14-hour night shifts).
- Eight PAH compounds were found in measurable quantities, with naphthalene being the predominant compound in all measurements. Total PAH concentrations exceeded outside concentrations in all stations.
- The elemental carbon and PAH concentrations recorded in the fire stations were below values set by the US EPA (there are no Australian concentration standards), even accounting for extended shift time, and none of the measured PAHs were, at the time of the study, classified as carcinogenic or possibly carcinogenic to humans
- Highest concentrations were in the engine bays and were highly correlated with start of shift processes (which involves checking and operating all appliance engines, generators and ancillary petrol-driven equipment). Overall concentration levels were also affected by vehicle age (e.g. older vehicles not compliant with current vehicle emission standards), proximity to major roads and industrial areas (other sources of pollutants), and fire station design and operation (e.g. engine bay design with single entry/exit or drive through).
- Fire stations with the highest engine bay concentrations also had the highest duty office concentrations, highlighting the need for door seals between these areas. Possible methods of reducing firefighter exposures to diesel engine exhaust include minimising the potential for air movement between the engine bay and other areas of the fire station through building design (e.g. door seals).
- Suggested solutions to reduce concentrations include improving ventilation in engine bays, improving vehicle emissions standards, reviewing start of shift procedures, and minimising air movement between the engine bay and other areas of fire stations.

5.3 Key Insights for Retail, Wholesale and Warehouse buildings

It is concerning that so few Class 6 and 7 buildings have been assessed for indoor air quality. The two identified studies highlight four key findings that are arguably applicable to other buildings in these classes, and to other classes of buildings:

(i) the location of the building relative to main roads and other pollutant sources (i.e. external sources of pollutants);

(ii) occupant type (e.g. worker / customer), and variable density and exposure times;

(iii) building and ventilation design and operations; and

(iv) business equipment (e.g. age, type, fuel source) and processes (e.g. shift time, start up / shut down procedures etc).

5.3.1 Key considerations for pollutant measurements

- Are the same pollutants to be monitored as for other building classes? Are there additional pollutants that should be monitored in Class 6 and 7 buildings?
- What monitoring is required to differentiate the exposure risks for workers compared to customers / visitors?

5.3.2 Key considerations for building and HVAC design and operation

- At what point in building and HVAC design are issues of occupancy (e.g. density, schedules, activities, worker / customer ratio, demographics) and impacts on air quality considered? How are these design considerations translated into construction / implementation / operation?
- Is it feasible for dynamic control of ventilation systems in retail / wholesale buildings?

5.3.3 Key considerations for building owners / operators

- Who is responsible for managing the air quality in retail and wholesale buildings?
- Does air quality need to be managed for workers or for customers?
- To what extent are occupational hygienists involved in air quality sampling / remediation in Class 6 and 7 buildings? Is it common?

5.3.4 Key considerations for policy

- Are there barriers to mandating $PM_{2.5}$ monitoring in all building classes? Should some additional pollutants (e.g. CH_2O, VOCs) be subject to mandatory monitoring in 'high risk' stores (e.g. similar to mandating smoke detectors)?

6.0 Class 8 Buildings - Factories

Factories
Class 8

6.1 Scope

Class 8 buildings are used for the production, assembling, altering, repairing, finishing, packing or cleaning of goods or produce. This includes laboratories (except when part of a healthcare building), food production or packing facilities, and businesses such as computer or automotive repairs.

6.2 Current State

6.2.1 Overview and purpose of identified studies

Five papers (4 studies) relating to Class 8 buildings were identified, as summarised in Table 23 in section 12: two in food production facilities (beer and bread), one agricultural building (swine confinement building) and two 'other' industrial building (multiple laboratories), representing <0.001%, 0.001% and 0.005% of the respective subdivisions of buildings within this class. Note that the two papers on IAQ in laboratories are from the same study.

The publications are in two distinct groups separated by approximately 20 years. Two of the identified studies focused on the viability of specific test procedures while the purpose of the remaining two was to evaluate pollutant levels / exposure. The measured pollutants in each study reflected the specific contaminants of concern for the respective facility type: CO_2 (as an industrial source in a brewery), PM (in bakery and animal confinement building) and multiple contaminants (particulate matter ranging from UFP to PM_{10}; VOCs) in laboratories.

Factories and other secondary production buildings

Building Count 2021: 146,728

Building Floor Area (m²): 72,119,567

Agricultural and aquacultural buildings

Building Count 2021: 72,648

Building Floor Area (m²): 35,257,098

Other industrial buildings

Building Count 2021: 36,948

Building Floor Area (m²): 20,945,274

6.2.2 Geographic and temporal distribution of studies

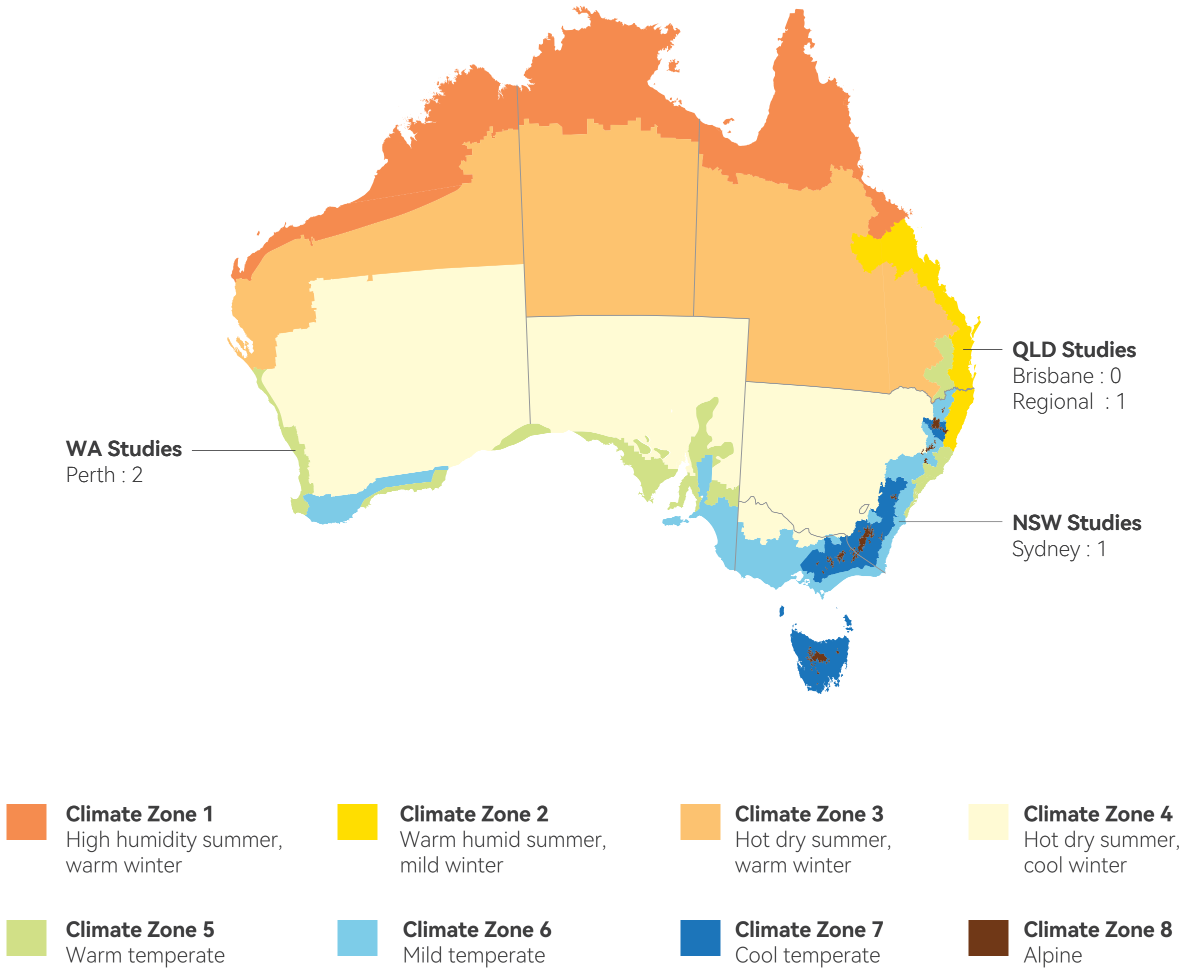


Figure 18 Geographic distribution of Class 8 IAQ studies

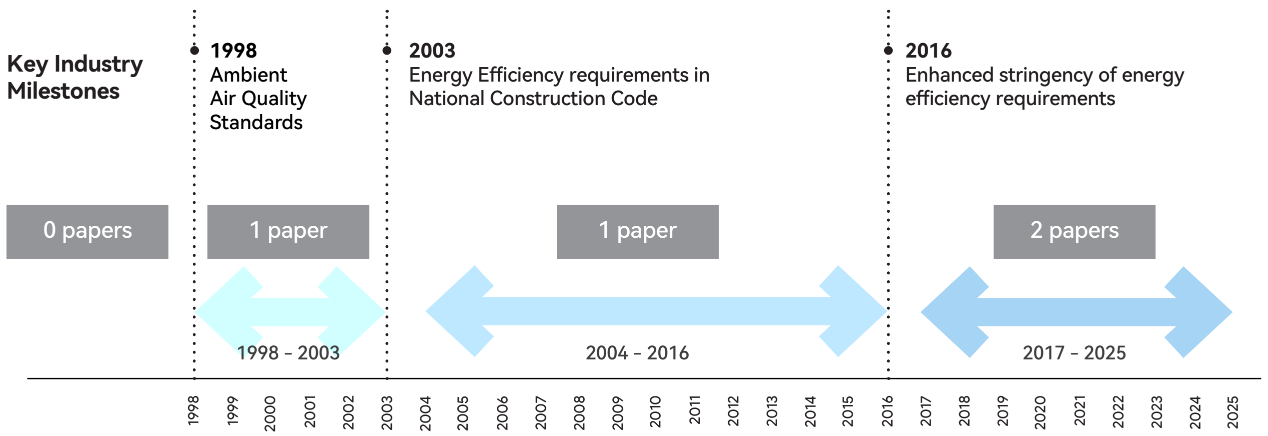


Figure 19 Temporal distribution of Class 8 IAQ studies

6.2.3 Measurement instruments and protocols

In the laboratories, TSI DustTrak (first generation) was used for recording mass concentrations of particulate matter, and P-Track used for measuring the number of ultrafine particles.

DustTrak II (second generation) monitors were used in the bakery study for mass concentrations and gravimetric sampling. Monitoring was undertaken in different production zones of the facility, to determine variations in worker exposure.

The agricultural building study (animal confinement building) trialled a novel aerosol counter – an ultraviolet aerodynamic particle sizer (UVAPS) for real-time monitoring of viable bioaerosols. This method was validated against measured concentration and particle size distribution measurements using a six-stage Anderson microbial impactor and AGI-30 impingers (instruments typically used for the bioaerosols).

The microbrewery study also used a novel measurement method. Such factories typically use a single hard-wired, fixed CO_2 sensor that triggers alarms at extremely high levels (e.g. 15,000 – 30,000 ppm). This study implemented an Internet-of-Things (IoT) sensor network to monitor CO_2 levels in different parts of the facility (production and office parts). Date was analysed by location and time, revealing implications for worker exposure.

6.2.4 Contaminant measurements and key findings

The contaminant concentrations recorded for each facility are shown in Table 12, followed by key findings from each of these facilities.

6.2.4.1 Craft brewery

- CO_2 is a by-product of fermentation, and small breweries don't have access to the same capture and re-use technologies as large breweries. This presents potential exposure risks that aren't managed through standards.
- A single CO_2 sensor (required by legislation) is inadequate for IAQ monitoring because it
  - only triggers an alarm at extremely high levels (15,000 – 30,000 ppm), giving no indication of long-term exposure at lower concentration levels; and
  - only measures emissions at a single point (e.g. the main source), failing to cater for varying concentration levels in different parts of the factory.
- Significant rise in CO_2 concentration was correlated with venting (30 min duration) of fermentation tanks, but dispersal of vented CO_2 was influenced by people movement, use of fans, and outdoor air flow (e.g. roller door open / closed).
- Some CO_2 emissions from refilling of CO_2 storage tanks (unintentional venting).
- High concentrations levels and exposure times present a hazardous workplace environment especially for workers in the unventilated office.
- Options for improved monitoring include a network of portable sensors and/or wearable CO_2 sensor nodes.
- Options for reduced exposure include consideration of ventilation in brewery design, personal protective equipment, and 'fresh air' breaks during significant time frames.

Table 12 Summary of pollutant measurements in factory and industrial buildings vs exposure limits

Pollutant	Measurement range	Exposure Limits
	Microbrewery [Ref 49]	
CO_2 (ppm)	18,420 ppm max (near fermentation tanks); 5,538 ppm max (near canning line); 13,100 ppm max (office) Max consecutive minutes CO_2 >1000 ppm: 425 (office); 78 (fermentation tanks); 53 (canning line). CO_2>10000 on two occasions in office for durations of 26min	~ 850 ppm (ambient + 450) [Ref 3]
	Bakery [Ref 50]	
PM in general	Mean 0.004 – 6.220 mg/m³ Concentrations were higher in the three factory work zones compared to the office. The highest concentrations were in the dough room, followed by the production room. Highest short term peak concentrations (>4 min) were 6.22 (dough room), 1.06 (production room) and 0.238 (prep room)	
PM_{10} (µg/m³)	Dough room (0.181 mg/m³) Production room (0.054 mg/m³) (NOTE: exceeds WHO standard of 0.050)	45 µg/m³ (24 hr) [Ref 2]
$PM_{2.5}$ (µg/m³)	Dough room (0.143 mg/m³) (NOTE: exceeds WHO standard of 0.025)	15 µg/m³ (24 hr) [Ref 2]
	Animal confinement building [Ref 51]	
PM (aerosols)	Approx. 95% of total and viable particles were respirable (< 7µm) Approx. 60% of total and 50% of viable particles were < 2.5 µm	
	Laboratories [Ref 52]	
TVOCs (µg/m³)	3.4 – 83.4; median 29.9 (chemistry labs) 6.3 – 85.1; median 22.3 (biology labs) 12.7 – 31.3; median 13.9 (engineering labs)	500 µg/m³ (1 hr) [Ref 3]
PM_{10} (µg/m³)	8.2 – 46.1; median 17.0 (chemistry labs) 13.1 – 47.3; median 19.5 (biology labs) 10.1 – 29.2; median 27.0 (engineering labs)	45 µg/m³ (24 hr) [Ref 2]
$PM_{2.5}$ (µg/m³)	4.2 – 25.1; median 9.0 (chemistry labs) 5.2 – 43.3; median 10.0 (biology labs) 4.1 – 14.2; median 8.1 (engineering labs)	15 µg/m³ (24 hr) [Ref 2]
UFP (n/cm³)	6,029.2 – 33,998.1; median 21,694.5 (chemistry labs) 5,485.1 – 21,740.2; median 5,637 (biology labs) 5,634.1 – 12,019.2; median 9,245 (engineering labs)	No existing limit [Ref 2]

6.2.4.2 Industrial bakery

- Four work zones were measured: the dough room (where ingredients are weighed, transferred and mixed); the prep room (highly automated pastry manipulation and rolling); production room (manual finishing of product and dusting); and office zone.
- The dough room had the highest concentrations.
- Short-term peak concentrations are important in that they may trigger respiratory symptoms but are associated with specific tasks (e.g. manually handling flour).
- Changes to work practices and the use of PPE can reduce exposure / risks.

6.2.4.3 Agricultural Confinement Building (ACB)

- Airborne pollutants in ACBs are a risk to workers, animals and the environment.
- Short term monitoring (minutes) does not produce representative data on aerosol levels with confinement buildings, as concentrations can vary greatly in very short periods of time (minutes).
- Majority of particles carried viable material, so total particle concentrations can be used to draw trends for bioaerosol concentrations, thus informing sampling strategies for bioaerosol investigations.

6.2.4.4 Laboratories

- Laboratory type affects pollutant concentrations:
  - Seven organic compounds detected, with highest measured concentrations for toluene (chemistry lab) and benzene (biology lab);
  - Median concentrations of TVOCs and number of UFPs where higher in chemistry lab than biology and engineering lab;
  - Engineering lab had higher PM_{10} levels.
- Air conditioning affects concentrations:
  - Labs without air conditioning had higher (though not significant) concentrations of PM_{10} and TVOCs.
- There are correlations between pollutants / environmental conditions:
  - PM_{10} was significantly correlated with UFP;
  - Indoor temperature was significantly correlated with TVOCs.
- Space occupancy / utilisation affects pollutant concentrations:
  - Concentrations (PM_{10}, $PM_{2.5}$, TVOCs and UFPs) were significantly higher during semester than during semester break (changes to lab usage).
- Exposure and health are linked:
  - Highest number of respiratory related complaints were for the chemistry lab;
  - Participants who reported asthma had higher exposure to PM_{10} and TVOCs;
  - Health symptoms included cough, wheeze, eczema, trouble breathing and itchy eyes;
  - Workers who reported respiratory symptoms had a longer employment history (in the labs).

6.3 Key Insights for Factory Buildings

The three key insights from the studies are that:

(i) pollutant sources in Class 8 buildings are predominantly internal;

(ii) different zones within a facility can have different pollutants, concentration levels and therefore exposure risk; and

(iii) short term and peak concentrations are important. Some key considerations relating to these key findings are presented below.

6.3.1 Key considerations for pollutant measurements

- Low-cost sensors, IOT capabilities and wearable sensors present opportunities for more comprehensive monitoring networks in all workplaces. How can the value proposition for such networks be developed / communicated, for example through cost-benefit analysis?

6.3.2 Key considerations for exposure limits

- What health effects are considered / important for setting exposure limits? What is the evidence to support short term limits to exposure at high concentrations vs long term / consistent exposure to lower concentrations vs concurrent / accumulative exposure to multiple pollutants?
- Do WES / WEL adequately address
  - different occupancy patterns (e.g. workers on daily shifts of 8 hrs compared to visitors / customers / students who may be exposed for a few hours)?
  - the protection of vulnerable occupants?
- How is 'reasonably practicable' interpreted by businesses of different sizes? What are the impacts on how small and medium size enterprises operate with regard to air quality? What are the resultant implications for workers?

6.3.3 Key considerations for building regulations

- What is the rationale for Class 8 buildings being specifically excluded from the ABCB's IAQ Verification Methods?
- Pollutant sources in Class 8 buildings (and other classes) can be variable and continuous. Is demand driven ventilation / dynamic control the answer? Is it feasible? Could / should it be regulated?

6.3.4 Key considerations for policy

- Does the 'as far as is reasonably practicable' caveat of Safe Work Australia mean different things to different businesses (e.g. a large national company vs a small / medium enterprise)? Does this result in differentiation between workers in terms of their health protection?

7.0 Hospitals and Healthcare Facilities

7.0 Class 9a Buildings - Hospitals and Healthcare Facilities

Hospitals & Healthcare
Class 9a

7.1 Scope

A sub-classification of public buildings that includes hospitals and clinics i.e. buildings in which occupants or patients undergo medical treatment and may need physical assistance to evacuate in the case of an emergency.

7.2 Current State

7.2.1 Overview and purpose of identified studies

Four studies were initially identified through the literature review process. An additional study was included even though it did not meet the strict inclusion criteria (e.g. contaminants were modelled rather than measured). It was included because of its analysis of multiple zone types within a real hospital, its use of actual air change rates (with CO_2 as a tracer), and the application of these parameters to modelling the spread of common airborne infection pathogens. Refer to Table 24 (section 12) for a summary of each study.

Four of the studies examined particulate concentrations and distribution while a fifth study focused on characterising particulates (indoor bioaerosols). Sampling periods were very short (days – weeks). The studies measured pollutants in one (2 studies), three (2 studies) or fifteen (1 study) 'units' or zones within hospital settings. Three of the studies focused specifically on understanding the impact of ventilation and/or filtration systems.

Studies specifically related to COVID 19 have not been included in this analysis.

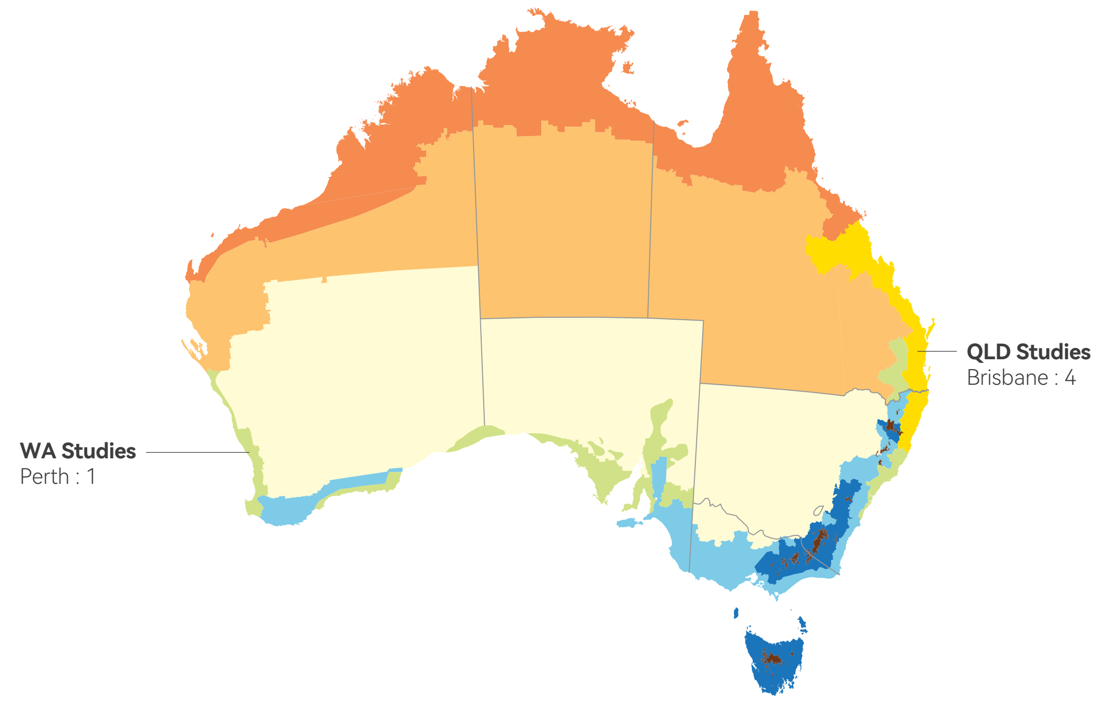
Hospitals and Healthcare Facilities

Building Count 2021 **22,752**

Building Floor Area **11,908,928** m²

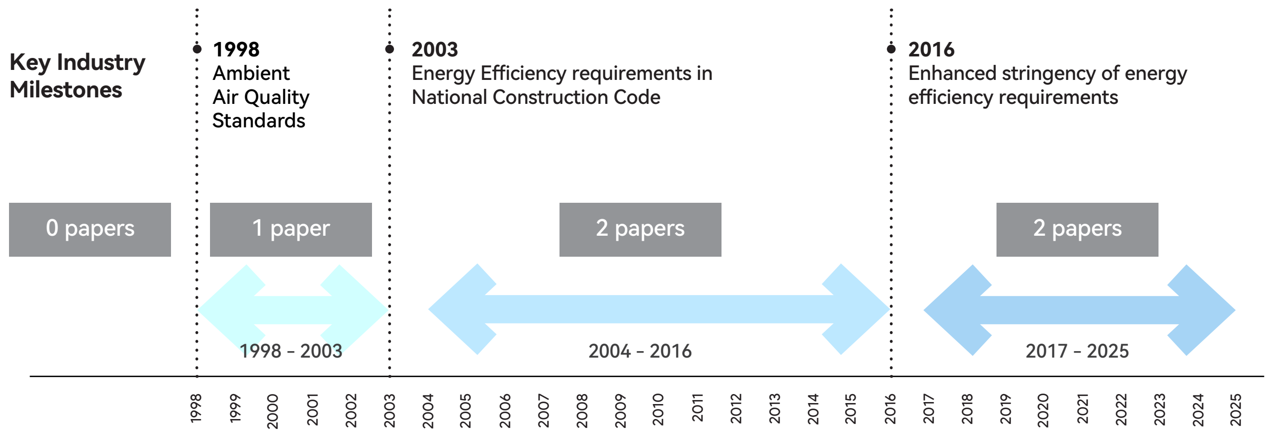
7.2.2 Geographic and temporal distribution of studies

Figure 20 Geographic distribution of Class 9a IAQ studies



Climate Zone 1 High humidity summer, warm winter
Climate Zone 2 Warm humid summer, mild winter
Climate Zone 3 Hot dry summer, warm winter
Climate Zone 4 Hot dry summer, cool winter
Climate Zone 5 Warm temperate
Climate Zone 6 Mild temperate
Climate Zone 7 Cool temperate
Climate Zone 8 Alpine

Figure 21 Temporal distribution of Class 9a IAQ studies



7.2.3 Measurement instruments and protocols

The 1998 Brisbane study, focused on particulate matter in multiple zones in two hospitals, used first generation TSI instruments (Model 3984 Scanning Mobility Particle Sizer and Model 3310 Aerodynamic Particle Sizer).

The 2014 Brisbane study utilised a range of second generation TSI instruments to measure particle number (Model 3312A UVAPS; AeroTrak 9306 handheld particle counter; Model 3787 condensation particle counter; Model 3007 condensation particle counter; P-Track) and particle mass (DustTrak-DRX for indoors; DustTrak II for outdoors). Bioaerosol measurements were undertaken using a Coriolis µ Air Sampler (in addition to the TSI UVAPS).

Note that the potential usefulness of UVAPS (Ultraviolet Aerodynamic Particle Sizer) for bioaerosol monitoring was studied in 2004 in an animal confinement building and reported in the previous chapter (6.3). A decade later it is an instrument of choice in hospital settings as it is one of few commercially available instruments that detects fluorescent particles in real time (indicating bioaerosols), thus enabling rapid detection and implementation of exposure reduction and control measures [53].

The most recent study (2023 in Adelaide) used a range of instruments for different purposes:

- TSI AeroTrak 9306 V2 (for particle number);
- TSI DustTrak DRX (for dust);
- TSI Q-Trak 757 (for CO_2, CO, temperature and humidity);
- Aeroqual series 500 (for NO_2) (this series has swappable sensor heads enabling measurement of 16 different pollutants);
- InDevR 2B Technologies 202 (for O_3 analysis); and SKC Airchek XR5000 (a direct flow sampling pump for VOCs, CH_2O).

7.2.4 Contaminant measurements and key findings

The contaminant concentrations for each of the studies are presented in Table 13 which is followed by a summary of the key findings.

7.2.4.1 ACH and risk of airborne infections [54]

- The Lung Function Lab and Emergency Department (ED) isolation room had high ACH rates and increasing these rates would not significantly alter already very low pathogen transmission risk.
- Outpatient consulting rooms met ACH guidelines for patient examination rooms and general wards but presented a higher risk of infection transmission than the Lung Function Lab and ED isolation room.
- Placement of return air vents in relation to doors can impact on ACH rate.
- Need for development of rigorous scientific basis for prescribing / customising ventilation rates for airborne infection control within a diverse range of hospital environments.

7.2.4.2 PM and bioaerosols in hospital environments

- In hospital units where medical procedures can result in the generation of potentially hazardous organic aerosols, filtration / ventilation systems are the most critical parameter in reducing indoor particulate concentration levels. [56]
- Paediatric intensive care unit (PICU) [55]:
  - Particulate number and mass were lower than in other indoor hospital environments.
  - The average PN concentrations were about 17 times higher than the supply air.
  - Particle concentrations were mainly from indoor sources (medical and cleaning).
  - Particles generated at beds can be transmitted to other beds and the nurses' station.

Table 13 Summary of pollutant measurements in healthcare buildings

Pollutant	Measurement range	
	Hospital in Brisbane [Ref 54]	
CO_2 (as tracer for air changes per hour (ACH))	Lung Function Laboratory 4.9 ACH ED isolation room 23.8 ACH Consulting room A (door closed) 2.0 ACH Consulting room A (door open) 3.7 ACH Consulting room B (door closed) 1.7 ACH Consulting room B (door open) 2.6 ACH	
	Paediatric intensive care unit (Brisbane) [Ref 55]	
PM_{10}	Overall average 24h concentrations 1.1 ± .5 $\mu g/m^{-3}$; range 0.6 – 2.2 24h average indoor concentrations were 11% of the outdoor average. Indoor particulate matter and particulate number were influenced by indoor sources, predominantly nebulisation therapy and cleaning activities.	
$PM_{2.5}$	Overall average 24h particle number 0.93 ± 0.94 x 10^3 p/cm^{-3} Very weak relationship between indoor and outdoor concentrations	
UFP	PMC range 0.005 – 16.0 (x 1000, p/cm^{-3}); mean 3.43 [Ref 56] PNC range 24h 0.1 – 2.8 (x 1000, p/cm^{-3}), Mean 24h 0.67 [Ref 55]	
	Adult and Children's hospitals (Brisbane) [Ref 53]	
PM in general	Average particle concentrations were higher in the adult hospital compared to the children's hospital (total particle concentration levels were approximately 3.6 times higher; average total fluorescent particles were about 2 times higher). The proportion of fluorescent particles, however, was higher in the children's hospital.	
	Royal Brisbane and Royal Children's hospitals (Brisbane) [Ref 56] **(sample results)**	
	Adult hospital average particle concentration [$particles.cm^{-3}$]	**Children's hospital average particle concentration [$particles.cm^{-3}$]**
Submicrometer particles 0.017 – 0.7µm	Intensive care unit 3.4 x 10^2 Isolation rooms 5.0 x 10^1 Patients ward 1.4 x 10^3 Casualty waiting area 7.5 x 10^3	Intensive care unit 5.6 x 10^2 Oncology 1.1 x 10^2 Respiratory unit 10.3 x 10^3 Infectious diseases unit 1.2 x 10^3
Larger particles 0.5 – 30 µm	Intensive care unit 7.4 x 10^{-1} Isolation rooms 1.8 x 10^{-1} Patients ward 1.4 x 10^0 Casualty waiting area 1.2 x 10^{-1}	Intensive care unit 4.1 x 10^{-1} Oncology 1.5 x 10^{-1} Respiratory unit 3.3 Infectious diseases unit 8.6 x 10^{-1}
	Surgery recovery suite (Adelaide) [Ref 57]	
	Pre-intervention (MERV 13 filters)	**Post-intervention (advanced filter system)**
Virus like particles (VLPs)	Room concentration 0.3 – 0.5 $\mu m/m^3$ Pre intervention (MERV 13 filter) 1060 x 10^3 and post intervention 74 x 10^3	
Supply air virus load	30 CFU/m^3	14 CFU/m^3
Bacteria like particles (BLPs)	Room concentration 0.5 – 5 $\mu m/m^3$ Pre intervention (MERV 13 filter) 282 x 10^3 and post intervention 61 x 10^3	
Supply air bacteria load	120 CFU/m^3	4 CFU/m^3
VOCs	1282 $\mu g/m^3$	1045 $\mu g/m^3$
CH_2O	7.6 $\mu g/m^3$	8.3 $\mu g/m^3$
O_3	< 1 ppb (below limit of detection)	< 1 ppb (below limit of detection)
SO_2	< 0.1 ppm (too low for reliable detection)	< 0.1 ppm (too low for reliable detection)
CO	< 1ppm (too low for reliable detection)	< 1ppm (too low for reliable detection)
CO_2	400 – 750 ppm	400 – 750 ppm

- The generation / source of particles [53] is related to
  - Medical processes (e.g. spirometry, nebulisation)
  - Cleaning (bedmaking, vacuum cleaning, washing hands in sink)
  - Maintenance (removal of suspended ceiling tiles; plant room activity)
  - Room furnishings (carpet)
  - Human activity levels (commencement of morning activities; general human movement and people density)

7.2.4.3 Air filters and airborne infection transmission

- Particles generated at any indoor location could be quickly transported to other locations, even when originating from isolated single-bed rooms [55]
- The intervention (the new filtration technology tested) [57] was inferred to result in a 5.33-fold risk reduction in virus transmission and a 2-fold reduction in risk of bacteria transmission, with no changes to fan size or power, and the potential to reduce outside air requirement and energy costs.
- ACH measurements combined with modelling provide a useful means of assessing the suitability of room ventilation for preventing airborne disease transmission [54]

7.3 Key Insights for Hospitals and Healthcare Buildings

Hospitals have a diverse range of environments, multiple internal sources of air pollutants, risk of airborne infection spread, and heterogeneous occupants with varying risk and exposure factors. While some of these risks are managed through existing hospital design guidelines, there is arguably room for further development and refinement of the design guidelines, as well as hospital operation and maintenance.

7.3.1 Key considerations for hospital design and operation

- Safe Work Australia espouses the three-tier approach to reducing risk to workers: eliminate risks, reduce exposure and use PPE. The three-tier approach to managing pollutants in the building industry is source control, dilution and filtration. What is the approach of the medical profession? Can the different approaches be better co-ordinated / synchronised? Can / should different professions be encouraged to prioritise the top tier of management (eliminate risk / source control)?
- Different departments / sections of hospitals present different exposure risks. Risks are also different for building occupants due to the length of time in specific areas. How are these risks managed in current hospital design / operation guidelines by the respective health departments? Is there room for improvement?

7.3.2 Key considerations for other building classes

- Do hospitals have strategies and solutions that could be transferred to other building classes (e.g. offices, retail stores, factories) where there are also diverse indoor environments, risk of airborne infection spread and heterogeneous occupants?
- To what extent do non-health related buildings consider the risks of airborne infection spread in their design and operation? Could / should such strategies be reasonably implemented (e.g. increasing ventilation rates during flu season)?
- Should the higher risks of poor IAQ posed to vulnerable people be considered in the design / operation of buildings where these people may work / shop / visit?

8.0 Class 9b Buildings - Public Assembly Buildings

Public Assembly Buildings
Class 9b

8.1 Scope

This sub-classification of public buildings includes assembly buildings in which people may gather for social, theatrical, political, religious or civil purposes. It includes schools, universities, libraries, childcare centres, pre-schools, sporting facilities, night clubs and public transport buildings.

8.2 Current State

8.2.1 Overview and purpose of identified studies

Very few papers have studied non-education public buildings. This review found one paper each for entertainment venues, sports facilities and transport buildings[18], and two papers relating to cultural buildings (Table 25). The entertainment venues were studied over 20 years ago (with a focus on tobacco smoke), while the other venues have been studied more recently. No papers were found relating to religious buildings, art galleries, museums, concert halls or theatres.

In contrast, thirty published studies measure indoor air quality in Australian educational facilities (Table 26), including kindergartens, childcare facilities, primary and secondary school classrooms, and university buildings[19]. Of these education facilities, the first identified study dates back to 2002, with the majority of the studies conducted since 2016. These studies involved about 100 schools, three universities, 49 early childhood centres (including kindergartens / childcare), and included both new and older (< 50 years) buildings.

Education buildings

Building Count 2021: **50,251**

Floor Area (m^2): **28,552,064**

Religious buildings

Building Count 2021: **19,260**

Floor Area (m^2): **13,042,429**

Entertainment and recreation buildings

Building Count 2021: **80,735**

Floor Area (m^2): **68,713,393**

Transport buildings

Building Count 2021: **34,157**

Floor Area (m^2): **97,556,683**

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[18] Poor air quality has been measured in Melbourne's Southern Cross Station, however that data is not available for scientific analysis. https://www.abc.net.au/news/2024-03-06/melbourne-southern-cross-station-air-pollution-data-revealed/103486852.

[19] Studies relating to university classrooms, lecture theatres and meeting spaces are recorded in this chapter. Studies about university office buildings and laboratories are included in the relevant chapters.

Occupant density in classrooms was not typically recorded[20]. The studies in general focused on buildings with different ventilation strategies, including natural or passive ventilation, mechanical HVAC systems, and demand-controlled ventilation (DCV).

The majority of these studies aimed to quantify and compare the indoor and outdoor levels of various air pollutants and analyse the impact of room characteristics and behavioural factors on indoor air pollutant levels. Study timeframes ranged from short-term assessments (48–72 hours) to year-long monitoring.

8.2.2 Geographic and temporal distribution of studies

Figure 22 Geographic distribution of Class 9b IAQ studies

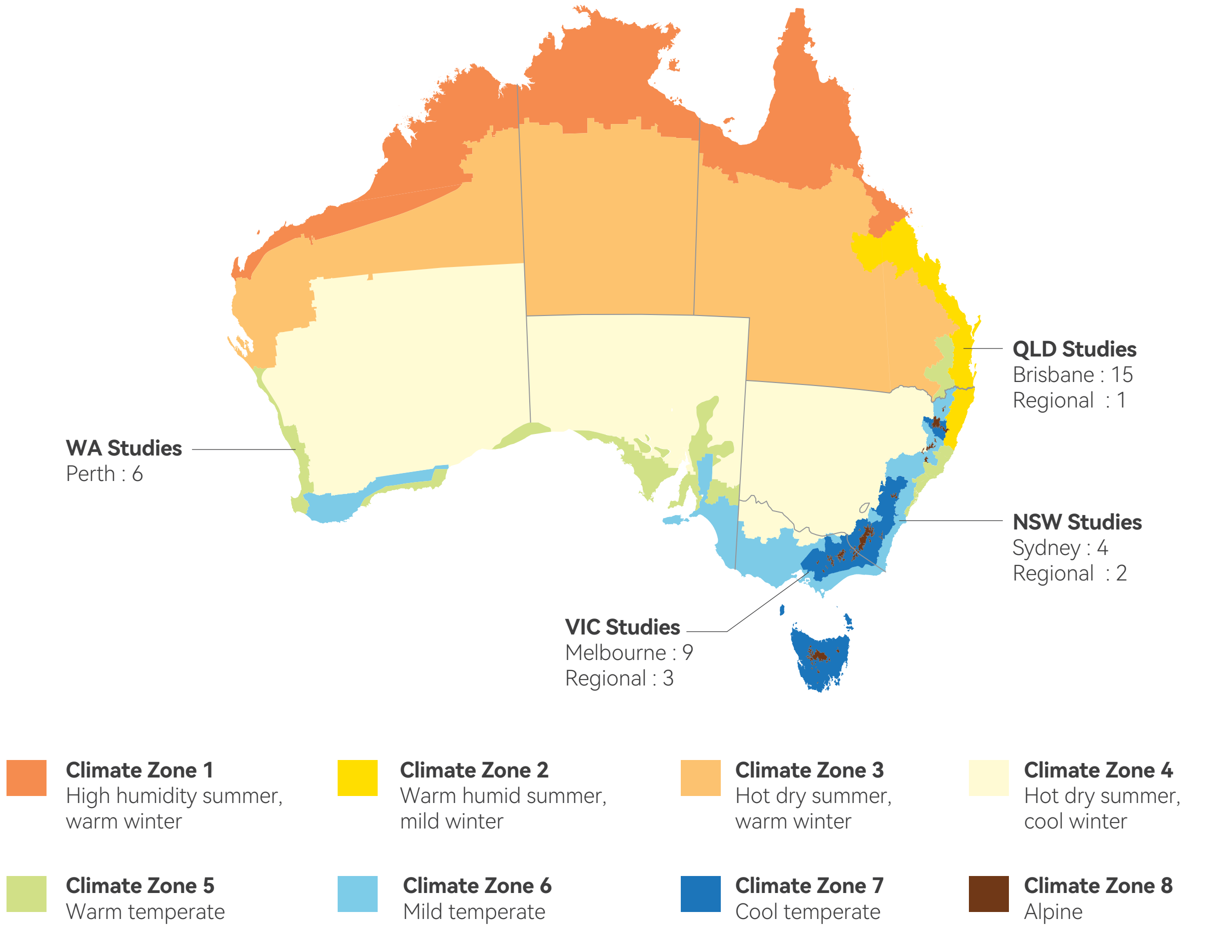
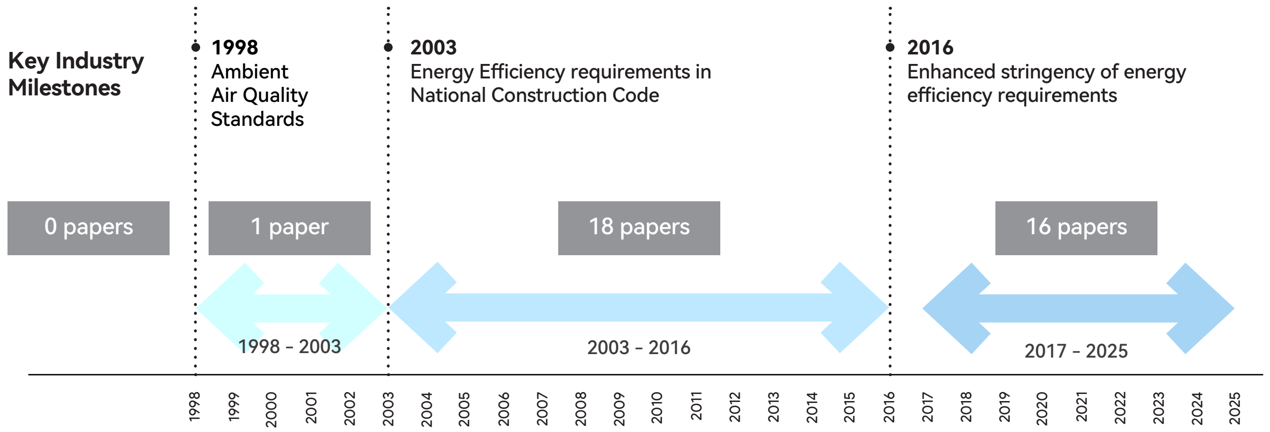


Figure 23 Temporal distribution of Class 9b IAQ studies



[20] Occupant density for classrooms is 4m²/child for early childhood and 2m²/student for schools (NCC Vol 1 Table D2D18). Student occupancy varies from state to state but is commonly 20-25 students per classroom in early childhood and upper secondary school, and 25-30 students in primary / middle / junior secondary school. Teacher/student ratios are higher in early childhood.

8.2.3 Measurement instruments and protocols

Non-education public buildings used instruments similar to those used in commercial (non-residential) buildings, such as:

- the previously mentioned range of TSI first and second generation instruments
- instruments by other scientific instrument manufacturers
  - Telaire Systems (Blaq Box 1350)
  - Siemens (QPA2002)
  - Amahasco Gas Exposure Monitor
- Custom built instruments by research organisations
  - Mobile Built Environment Laboratory (MABEL) – University of Geelong
  - Smoke Observation Gadget (SMOG) – CSIRO
- TSI instruments were generally absent from studies in education buildings, with other commercial brands more common, for example
  - Vaisala CMP243 for CO_2
  - Aerocet 531S and Aeroqual Series 500 for PM_{10} and $PM_{2.5}$
  - Philips Aerasense Nanotracers (for UFPs)
  - pSense Model AZ 0018 (for CO_2)
  - MyAir sensors (for CO_2, TVOC)

With the exception of the UFP studies in QLD schools, studies in schools in particular reported the use of instruments that were not generally found in commercial building studies, perhaps reflecting the ‘citizen science’ and education component of IAQ studies in schools. These instruments included:

- HOBO MX1102 and Testo 480 (for general environmental conditions)
- Study Fresh IAQ logger (custom built for purpose by University of Queensland)
- Air Quality Egg (AQE)
- HibouAir sensors

8.2.4 Contaminant measurements

The range of measurements reported in the studies are shown in Table 14 (for non-education public assembly buildings) and Table 15 (for education buildings). Key findings are discussed separately for non-education and education buildings (sections 8.2.5 and 8.2.6 respectively).

8.2.5 Key Findings - Non-education public assembly buildings

The following sections summarise key findings for each of the studies of non-education public buildings.

8.2.5.1 Public Library

- Centralised HVAC system provided cleaner air than outside (average 70% reduction in $PM_{2.5}$ compared with ambient concentrations); the addition of a portable HEPA cleaner in a smaller room within the library provided additional benefits (87% reduction).
- Portable HEPA filters have an important role to play in improving IAQ in small spaces during bushfire / smoke events, taking into account the restrictions of the filter grade and cleaning capacity.
- Portable HEPA filters are only one of a range of strategies that can provide safer IAQ (others include looking at door openings / infiltration – leakage etc).

8.2.5.2 University Library

- CO_2 sensor data enables better control over IAQ compared with occupancy time schedules / room area.
- Integrating CO_2 sensor data with CO_2 mass balance equation enables better damper modulation to control outdoor ventilation rates.
- Mass balance equation should be incorporated into the Australian ventilation standard AS 1668.2.

Table 14 Summary of pollutant measurements in non-education public assembly buildings vs exposure limits

Pollutant	Measurement range		Exposure Limits
Taverns, nightclubs, sporting clubs [Ref 48]			
CO	Range of average in 10 venues 1 – 7 ppm		3.5 ppm (24 hr) [Ref 2]
PM_{10}	Range of average in 10 venues 24 – 2284 ug/m³		45 µg/m³ (24 hr) [Ref 2]
$PM_{2.5}$	Range of average in 10 venues 17.1 – 427.6 ug/m³		15 µg/m³ (24 hr) [Ref 2]
Library [Ref 58]			
$PM_{2.5}$	9.8 – 36.2 ug/mg inside library (Ambient concentrations 12.2 – 85.9) 5.5 – 8.5 ug/m³ media room with HEPA operating (Ambient concentrations 12.0 – 49.1)	Portable filters restricted by filter grade and cleaning capacity	15 µg/m³ (24 hr) [Ref 2]
Train stations [Ref 59]			
PM_{10}	Ground level platform 20.1 ± 10.4; underground platform 54.9 ± 20.7 (range of mean)		45 µg/m³ (24 hr) [Ref 2]
$PM_{2.5}$	Ground level platform 16.7 ± 6.5; underground platform 40.6 ± 12.0 (range of mean)		15 µg/m³ (24 hr) [Ref 2]
Sports Hall [Ref 60]			
CO_2	60% readings < 800ppm; 40% 800 – 11ppm ACH when fans off 0.4; ACH when fans on 2.67		~ 850 ppm (ambient + 450) [Ref 3]

Table 15 Examples of pollutant measurements in education facilities vs exposure limits

Pollutant	Measurement range	Exposure Limits
CO_2 (ppm)	397 – 5000 ppm; Range of mean 430 – 2235 (from all school studies) 72% of occupied rooms <800 ppm; 18% of occupied rooms 800 – 1000 ppm; 10% of occupied rooms >1000 ppm [Ref 61]	~ 850 ppm (ambient + 450) [Ref 3]
CO (ppm)	Mean 2.1 ppm (3.3 ppm summer, 1.2 ppm winter) [Ref 62]	3.5 ppm (24 hr) [Ref 2]
PM_{10} (µg/m³)	Range 1 – 143.9 ug/m³; range of mean 7.23 – 47.17 ug/m³ [Ref 63]	45 µg/m³ (24 hr) [Ref 2]
$PM_{2.5}$ (µg/m³)	Range 2 – 74.6 µg/m³ [Ref 64] Range 6.3 – 39.9 µg.m³ [Ref 63]	15 µg/m³ (24 hr) [Ref 2]
UFP	Range 0.188 to 14.3 (x 1000, p/cm^{-3}); Mean 2.11 [Ref 65] Mean PNC 3.19±2.36 (x 1000, p/cm^{-3}) [Ref 66] Mean near high traffic) 8.50 (x 1000, p/cm^{-3}); Mean near light traffic 8.35 (x 1000, p/cm^{-3}) [Ref 67] During art activities PNC > 1.4 x 105 particles cm^{-3} [Ref 68]	No existing limit [Ref 2]
NO_2 (ppb)	3.5 – 135.2 ppb (95% geometric range) [Ref 69] Range of mean 17.5 – 31.6 ppb [Ref 69]	25 µg/m³ (24 hr) [Ref 2]
CH_2O (ppb)	Range 3.1 – 62.1 ppb; range of mean 24.7 – 32.6 ppb [Ref 69]	0.1 mg/m³ (30 min) [Ref 3]
TVOC (µg/m³)	Range 8 - 1070; geometric mean 125 µg/m³ [Ref 70]	500 µg/m³ (1 hr) [Ref 3]

8.2.5.3 Taverns / clubs

- CO levels affected by smoking and level of motor traffic.
- Contaminant levels directly associated with occupancy numbers and proportion of smokers.
- Ventilation systems (adequacy for changes in occupancy, maintenance, operation, scheduling) were implicated in high CO_2 and PM_{10} in taverns and night clubs (regardless of presence of smokers).

8.2.5.4 Sports hall

- This particular sports hall had low CO_2 levels even at high occupancy levels in a hot month. CO_2 sensors could be utilised to control vents and fans as needed instead of the current continuous ventilation strategy (which introduces hot outdoor air, impacting on thermal comfort).
- Moderate thermal stratification is common in buildings with large open spaces.

8.2.5.5 Train stations

- PM_{10} and $PM_{2.5}$ concentrations were higher on underground platforms (2.7 and 2.5 times respectively) than ground level platforms.
- Underground PM concentrations exceeded standards for PM_{10} (50 (µg/m³)) and $PM_{2.5}$ (25 (µg/m³)).
- PM in railway environments has heavy metals produced by friction, wear and abrasion of the infrastructure (brakes, wheels, lines).

8.2.6 Key Findings – Education buildings

Key findings from education buildings are presented in Table 16, for each of the contaminants of concern. Note that because of the bespoke nature of each study, the findings cannot necessarily be considered to be relevant to all education buildings in all locations. The specific reference associated with each key finding is provided.

The following sections summarise key findings that are not related to specific air pollutants.

8.2.6.1 Urban planning / location of education centres near main roads [62]

- All pollutants higher in early childcare centers located near heavy traffic areas [58].

8.2.6.2 Flued / unflued gas heaters [69]

- Mean NO_2 and CH_2O were substantially increased in classrooms during operation of unflued gas heaters.
- Studies can only assess short term effects.
- Classroom exposure to newer-style low-NO_2 unflued gas heaters increase respiratory symptoms, particularly in atopic children.
- In-class exposure to unflued gas heaters is associated with increased reporting of wheeze in the morning and possibly with increased cough and wheeze during the day; and in children with current asthma, an increase in air inflammation.
- Exposure to low-NOx unflued gas heaters causes increased respiratory symptoms, particularly in atopic children.

8.2.6.3 VOCs [79]

- 7 source categories explain 88% of indoor VOC data (with estimated contribution)
  - Outdoor traffic emissions (2%)
  - Off-gassing of building materials and stationaries (3%)
  - Decorating materials and computers, printers (5%)
  - Personal care products (5%)
  - Art and craft activities (21%)
  - Air fresheners (23%)
  - Cleaning products (41%)

Table 16 Overview of key findings for each pollutant in education buildings

Pollutant	Key findings
CO_2	The ratio of indoor and outdoor means ranged from 4.3 to 6.5, indicating that the indoor mean was significantly higher than the outdoor mean; consider mechanical ventilation improvements in newer classrooms to address air leaks [Ref 71] The three most important parameters for the carbon dioxide concentration of a school classroom during its occupancy periods are, the air change rate, carbon dioxide exhalation rate and the number of pupils in the classroom respectively [Ref 72] Passive ventilation systems based on manual interventions are most likely associated with sub-optimum environmental quality and extreme variability linked to occupancy patterns; low-cost, internet-enabled sensors can be used for real-time monitoring; smart controls could be implemented for air conditioning and door-opening cycles to prevent poor IAQ during hazardous outdoor conditions [Ref 73] CO_2 concentrations varied significantly between schools; highest average 2235 ppm; all 10 classroom showed max levels over 1700 ppm during school hours; highest max 5000 ppm [Ref 63] More than half of the classrooms exceeded 1,800 ppm multiple times, with some reaching nearly 5,000 ppm. 16 of 67 classrooms exceeded 1,800ppm that lasted 180 consecutive minutes or longer; 7 of 67 classrooms recorded continuous CO_2 concentrations above 2,500 ppm for 180 minutes or longer; the longest continuous exceedance of 2,500 ppm was 717 minutes [Ref 74] Classrooms with highest exceedances had mixed mode ventilation, and events occurred during cooler months. (issues: sealed windows, hard to reach ventilation controls; reluctance to open windows due to noise or energy efficiency concerns [Ref 74] In many cases assumptions that ventilation complied with relevant ventilation standards were incorrect [Ref 61]
PM_{10}	The 'low allergen' school did not effectively reduce the levels of $PM_{10.}$ 8% (of 113 samples of 2hr average concentrations) exceeded 24h standard of 50mg.m^3 [Ref 75]
$PM_{2.5}$	Average hourly $PM_{2.5}$ concentrations exceeded WHO thresholds 25% of the time [Ref 76] $PM_{2.5}$ in building foyers / entrances can be higher than ambient levels, even during significant pollution events [Ref 76] Ventilation systems should have strategies to adjust to severe air pollution scenarios [Ref 76] Ambient air quality monitoring stations are not a good indication / reference point for local outdoor $PM_{2.5}$ for individual building locations [Ref 76]
Ultrafine particles (UFP)	Children's mean indoor dose was never higher than the outdoors at any of the schools, indicating there were no persistent indoor particle sources in the classrooms during the measurements. Children's exposure during school hours was more strongly influenced by urban background particles than traffic near the school; different microenvironments (e.g. home and commuting) need to be monitored to quantify total daily dose [Ref 77] During schooling hours, grilling, heating, and printing led to indoor PNCs being elevated by a factor of more than four [Ref 71] PN concentrations associated with outdoor values and sometimes influenced by indoor sources [Ref 66] Under stable outdoor concentrations, ACH has a significant impact on PNC indoors (higher ACH associated with lower PNC) [Ref 65] Highest increases in UFPs related to art activities, followed by cleaning (use of detergents). Monoterpene in detergents reacted with O_3 to form secondary organic aerosols [Ref 68] Exposure to UFPs was not associated with asthma diagnosis or respiratory symptoms, but was positively associated with a biomarker for systemic inflammation [Ref 4]
NO_2	Geometric mean concentration of NO_2 almost twice as high in classrooms with low-NOx unflued gas heaters (60.4 $\mu g/m^3$) compared with classrooms with flued gas heaters (33.5 $\mu g/m^3$) [Ref 69]
CH_2O	Higher levels of Formaldehyde were recorded in the winter term than summer term; controlling CH_2O exposure in schools should be given a high priority so as to minimise potential risks of asthma and atopy [Ref 75] Formaldehyde concentrations, on average, 9,4 ppb higher during exposure to unflued gas versus flued gas heaters [Ref 69] All samples were below the WHO air quality guideline value [Ref 75] Median level in some classrooms was higher than NHMRC guideline (120 $\mu g/m^3$) and WHO threshold (100 $\mu g/m^3$) [Ref 78] 67% of new schools and 45% of old schools had concentration limits above NHMRC guidelines [Ref 78]
TVOC	No significant differences were found between the 'low allergen' school and standard schools [Ref 75] The overall cleaning products had the highest contribution of 41% indoors followed by air fresheners and art and craft activities; there is a need for a range of basic precautions during the selection, use and storage of cleaning products and materials to reduce the risk from these sources [Ref 70] During the bushfire season, TVOCs increased in every examined room because of biogenic emissions from biomass burning [Ref 73] Only 13.7% of samples monitored had levels of TVOCs exceeding 10 mg/m^3 [Ref 75] Most schools had indoor TVOC higher than outdoors [Ref 70]

Table 16 Overview of key findings for each pollutant in education buildings

- >90% of VOC mixtures were of low concern, indicating a low health risk to children.
  - For mixtures where toxicity is governed by single substances, the source of the substance needs to be identified and controlled
  - For mixtures where toxicity is due to combined effect of several substances, higher level risks assessment and management needs to be implemented

8.2.6.4 Decay rate of CO_2 [72]

- 2 factors influence CO_2 concentrations in classrooms: the airtightness / leakiness of the building envelope; and the intermittent behaviour of school children (e.g. children moving around the classroom or coming inside from outdoor activities)
- This paper argues that ventilation standards are based on assuming the attainment of a steady state, but this is not possible in a classroom situation. CO_2 concentrations at low air change rates will take time to settle to large steady-state values, but this settling time can be longer than actual classroom usage / occupancy times. The paper therefore argues for more advanced modelling techniques to better assess air movement and hence CO_2 concentrations.

8.3 Key Insights for Public Assembly Buildings

Collectively the studies provide three key insights for this class of buildings:

(i) the need to consider outdoor pollution sources associated with the location of the building and the vulnerability of intended users of the building;

(ii) the importance of eliminating indoor sources of pollutants (e.g. smoking, gas heaters, VOCs); and

(iii) the vital role of ventilation systems suited for the specific building use and variability in occupancy (e.g. design, operation, maintenance, scheduling, strategies to address high pollutant concentrations from indoor or outdoor sources).

8.3.1 Key considerations for design and operation of education facilities

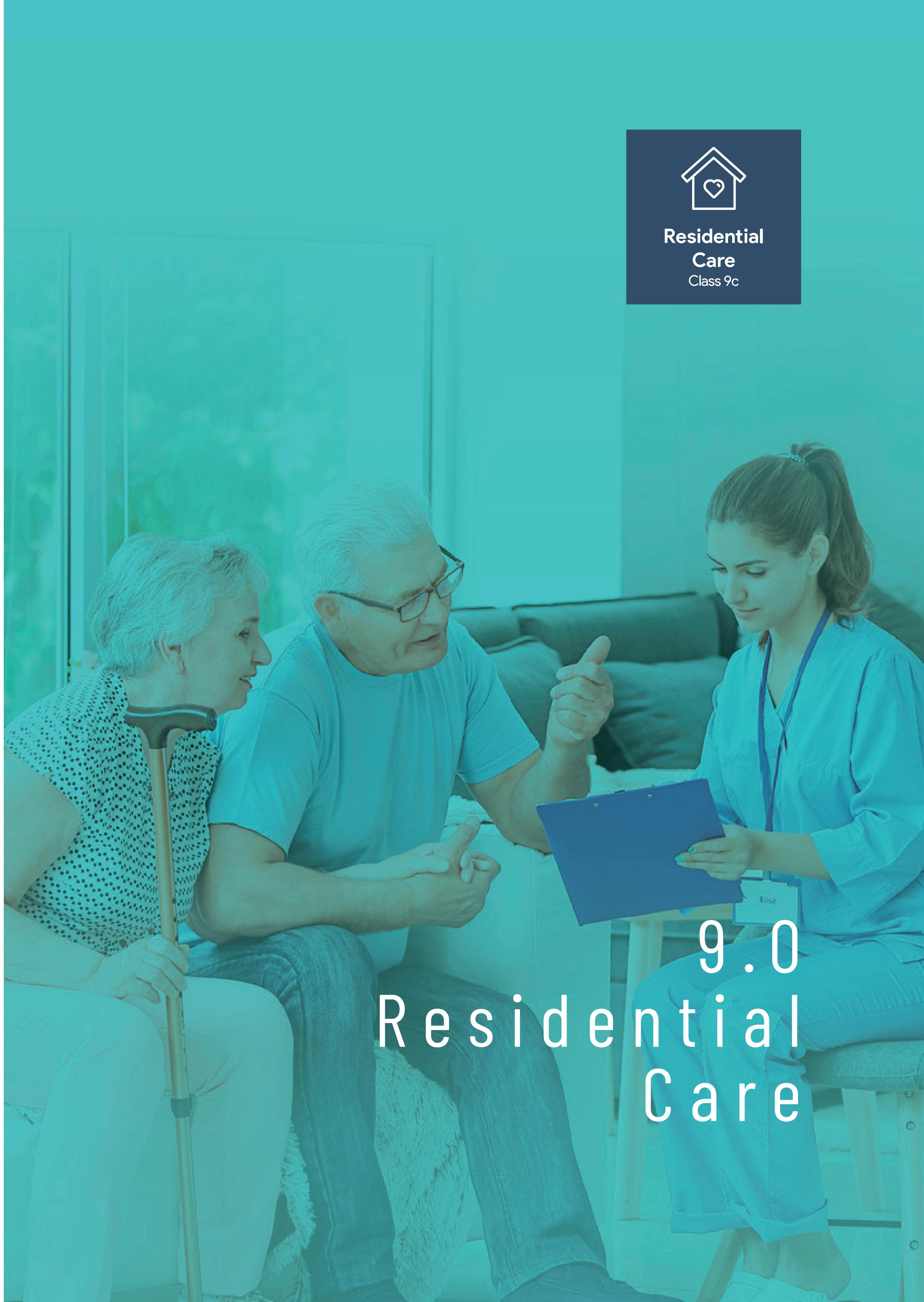
- What role does town planning play in protecting children, especially those in early childcare centres, from pollutant exposure?
- Are gas appliances being phased out of all school / early childhood facilities?
- Is there any benefit to measuring TVOCs? Are VOCs and CH_2O still a problem? Is more effort required in source control (beyond building products)?
- Do ventilation standards for education facilities need to be revisited, considering the issues raised about the decay rate of CO_2 and 'steady state' assumptions in the standards?
- How can classrooms be better protected during extreme events such as bushfires? Does this justify mechanical ventilation in all schools?

8.3.2 Key considerations for the health of children / staff

- Is there any benefit in reporting average / mean CO_2 concentrations, rather than real time readings? Should more attention be paid to peak concentrations and exposure?
- What strategies can be used to assist and enable students and teachers to proactively manage indoor air in response to monitored data?
- What strategies could be implemented in schools to minimise the VOC pollutants from classroom and cleaning activities?

8.3.3 Key considerations for policy and practice

- How can the design and operation of schools be incorporated into the National Preventive Health Strategy 2021 – 2030 and its principle of multi-sector collaboration?
- What further regulatory and/or market steps can be taken to ensure safe indoor air in non-education public assembly buildings? Is more regulation required, or more enforcement of existing regulation?
- What are the advantages and disadvantages of publicly visible CO_2 and $PM_{2.5}$ monitors in all public assembly buildings (even if they are not connected to demand control ventilation systems)?



9.0 Class 9c Buildings (Residential Care)

Residential Care
Class 9c

9.1 Scope

This is a sub-classification of public buildings that includes residential care buildings that may contain residents who have various care level needs. They are a place of residence where 10% or more of persons who reside there need physical assistance in conducting their daily activities and to evacuate the buildings during an emergency.

Aged care facilities, including nursing homes

Building Count 2021: 30,671[21]

Building Floor Area (m^2): 16,630,562

9.2 Current State

9.2.1 Overview and purpose of identified studies

Only three studies were identified through the literature review and each of these studies are recent. (There are a number of aged care studies that have concentrated on thermal comfort and have not specifically focused on measuring and analysing indoor air quality from the perspective of pollutants of concern). Each of the studies had a particular focus and scope of investigation. One study evaluated 5 facilities, but only 2 common rooms in each facility. Understanding common facilities is important, but given that many elderly persons spend much of their time in their own room, it only provides a limited picture.

Another study utilised a room in an unoccupied facility to evaluate the effectiveness of UV disinfection. Again this was valid for the purposes of the study but is of limited use in understanding the impact on air quality in residential care facilities in general.

Both of these studies were located in Victoria and the purpose of both was to evaluate the impacts of particular interventions: a ventilation retrofit and UV disinfection.

Neither study sheds light on how residential care facilities are designed, occupied and operated, making it difficult to understand pollutant exposure and risk for residents, visitors and staff.

The third study, undertaken in Adelaide, sought to investigate some of these issues. It monitored CO_2 levels in multiple zones within an aged care facility to identify potential 'super-spreader' zones and the efficacy of ventilation-based risk reduction strategies.

[21] Note that this data relates to buildings, not facilities. There are 2,622 residential aged care homes in Australia (2023-2024). A facility, similar to a university or school, will often have multiple buildings.

9.2.2 Geographic and temporal distribution of studies

Figure 24 Geographic distribution of Class 9c IAQ studies

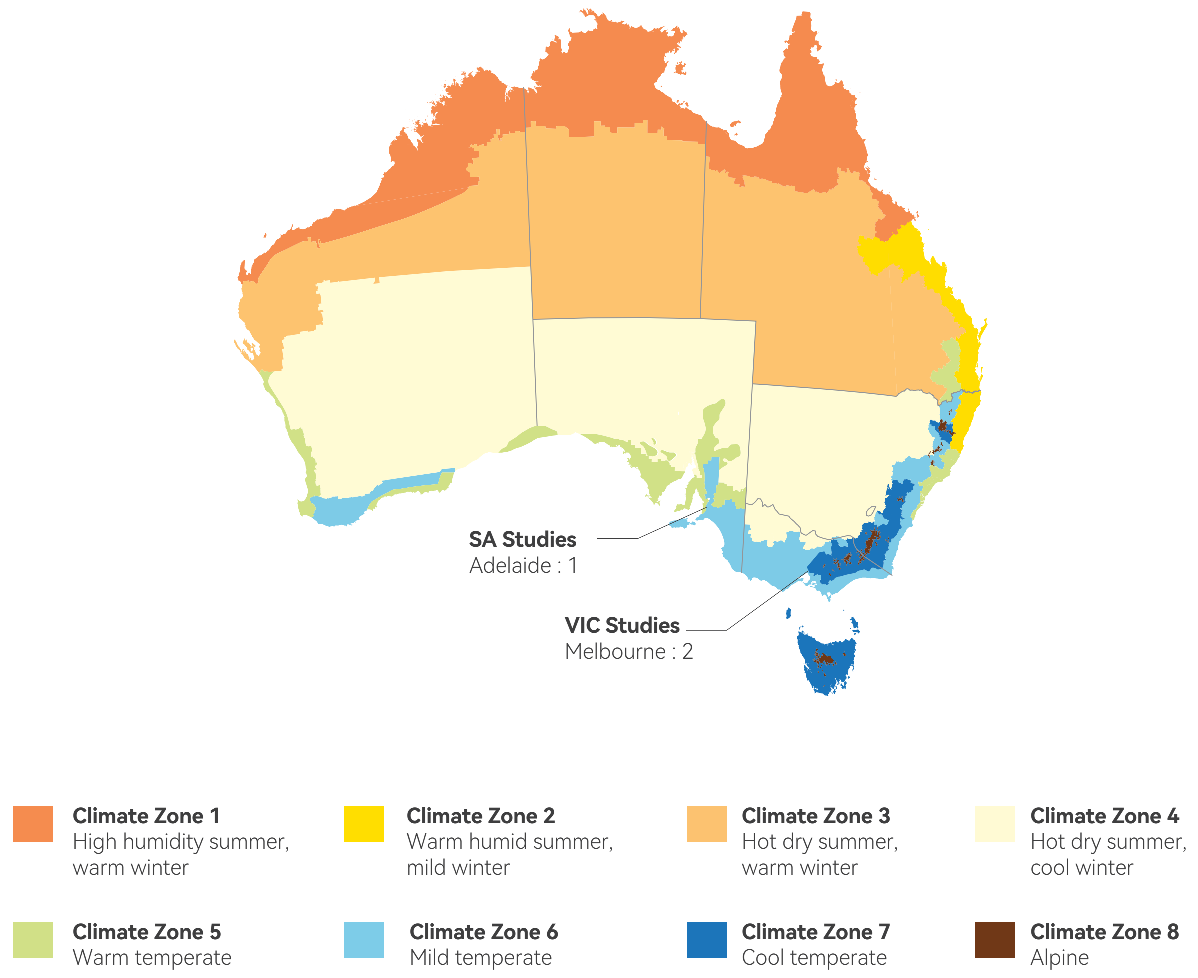
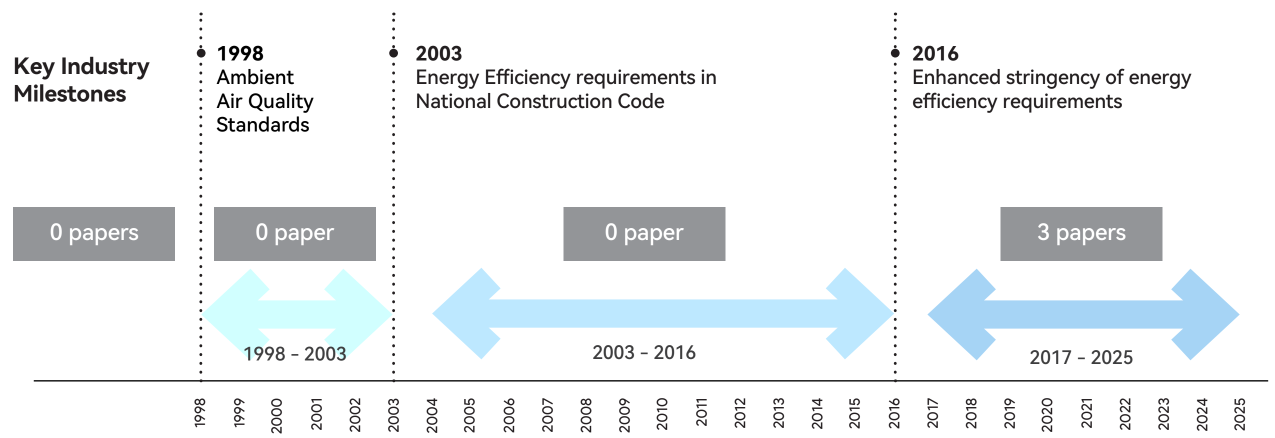


Figure 25 Temporal distribution of Class 9c IAQ studies



9.2.3 Measurement instruments and protocols

Indoor conditions (air temperature, relative humidity and CO_2) in the two studies of occupied RAC facilities were measured using Arenet4 Pro Sensors, Testo 480 and HOBO MX1102.

Particulate matter ($PM_{2.5}$ and PM_{10}) measurements in the five Victorian RAC facilities utilised a handheld Aerocet particle counter (Model 531S) and TSI DustTrak 8533.

Equipment used by the GUV Disinfection study (unoccupied facility), included:

- UV Photometric O_3 analyzer (Thermo Scientific Model 49i) for O_3
- Proton Transfer Reaction Mass Spectrometer (PTR-ToF 1000) for VOCs
- Cavity Ring-Down Spectrometry Picarro G2301) for CO_2, CH_4 and H_2O
- Condensation Particle Counter (TSI 3772) and Scanning Mobility Particle Sizer (TSI 3080 and 3081) for particle concentrations

9.2.4 Contaminant measurements and key findings

Four key findings were extracted from the identified papers.

High transmission risk, considered to be CO_2 levels >1000 for 15 minutes or more, was identified in 17.6% of staff only zones, and in none of the 45 common zones (staff and residents). Prolonged peaks corresponded to staff meal breaks. Simple ventilation interventions can reduce transmission risk in high risk rooms, for example an extraction fan in the lunchroom increased ventilation rate from 0.65 to 5.3 ACH [80].

As could be expected, occupant density in common rooms was associated with high CO_2 levels. Room density ranged from 0 – 33 during activities on normal days, and up to 52 for festive seasons and special events. Existing ventilation systems did not account for these variations in occupant density [81].

An independent supplementary ventilation system fitted to common rooms with a variety of existing ventilation systems decreased CO_2 concentrations by up to 1000 ppm but did not reduce PM_{10}. The supplementary ventilation system can operate manually or as demand- controlled ventilation (i.e. in response to CO_2 concentrations) [81].

The interventions examined in these studies had negative impacts on indoor air pollutants. In one study, the booster fans, which increased supply air velocity from 2.8 to 3.1 m/s resulted in increased $PM_{2.5}$ levels [81]. In another study, indoor ozone concentrations were shown to be tightly coupled to simultaneous outdoor concentrations, with indoor/outdoor ratios of 24% with HVAC on and 17% with HVAC off [82]. Low total room doses (~1.4 mW m−3) from GUV-222 devices however produced measurable effects on indoor ozone and OVOC (oxidized volatile organic compounds) but not on particle concentrations [82].

Table 17 Summary of pollutant measurements in residential care buildings vs exposure limits

Pollutant	Measurement range	Exposure Limits
CO_2	High prolonged peaks 1000 – 1400 and 1900 – 2200 ppm [Ref 80] Common rooms: Range of measurements 319 – 2066 ppm; range of maximums 667 – 2066 ppm; range of mean 466 – 553 ppm ACH 0.84 – 3.81; ventilation rates 5.52 – 30.95 L/s/pp [Ref 81]	~ 850 ppm (ambient + 450) [Ref 3]
UFP	Concentration range when HVAC on: 2,597±1,717 cm^{-3} (max 9,951) Concentration range when HVAC off: 4,606±2,168 cm^{-3} (max 12,503) [Ref 82] NOTE: unoccupied room	No existing limit [Ref 2]
O_3	Average concentrations 4.5±3.5 ppb; max 201 ppb [Ref 82] NOTE: unoccupied room	100 ug/m^3 (8 hr daily max) [Ref 2]

9.3 Key Insights for Residential Care Buildings

Residential care buildings are a unique class of buildings: 'home' to people with high levels of dependence and health vulnerability; public assembly /community venue for residents; daily workplaces for medical and non-medical staff; itinerant workplaces for medical and allied health professionals; and a 'pseudo-residence' for visiting family and friends. These buildings have multiple zones (e.g. resident only, staff only, communal) with varying occupant densities. The air quality focus is on the risk of spread of airborne pathogens, both from outside sources (e.g. staff / visitors coming into the facility) and indoor sources (e.g. between staff and residents).

9.3.1 Key considerations for ventilation design

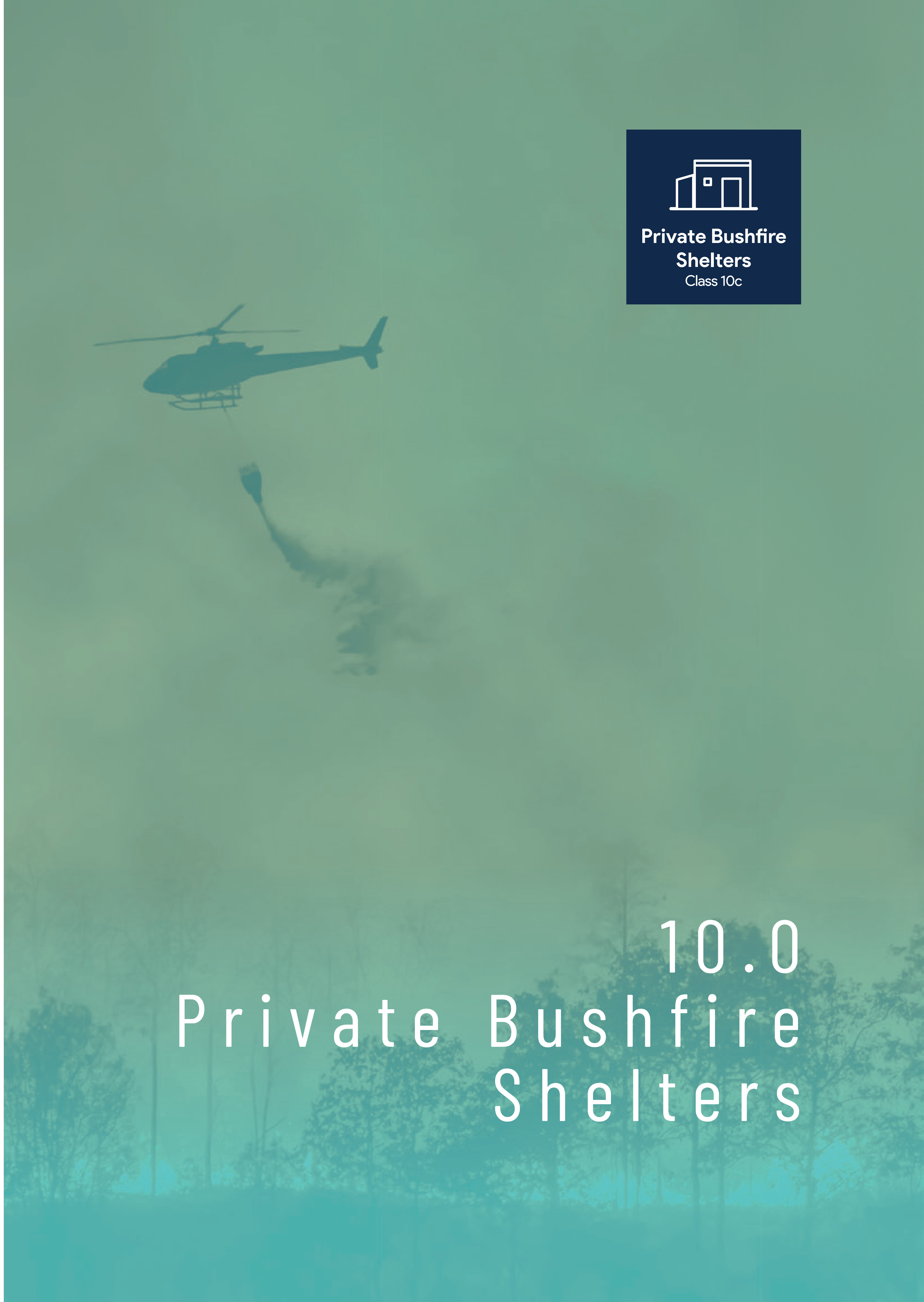
- Are ventilation systems in residential care buildings designed similar to those in hospitals (e.g. taking into account different zones and the need for isolation in some instances)?
- What are the highest risk zones? Staff only areas, resident rooms or communal zones? How have these been identified? What ventilation strategies are applied to each of the different zones to reduce transmission risk (e.g. source control, dilution, filtration)? Are these strategies static (i.e. scheduled) or dynamic (e.g. responsive to CO_2 measurements)?

9.3.2 Key considerations for the design and testing of interventions

- How can unexpected consequences be avoided when designing and implementing strategies for improving one aspect of IAQ (e.g. ventilation rate and CO_2 concentration)? Should solutions that result in trade-offs (e.g. lower CO_2 concentrations but higher UFPs or O_3) be accepted? Is there a hierarchy of IAQ pollutants that could / should be applied to a risk management process?

9.3.3 Key considerations for regulators

- The NCC requires occupied spaces to be ventilated with outside air to maintain adequate air quality. What does 'adequate' mean for vulnerable people? How are appropriate ACH rates determined for different zones, occupancy rates, occupant vulnerability and occupancy times?
- What further evidence does the ABCB require regarding biological contaminants (i.e. modelling, sampling, testing, measurement, and acceptable limits), in order to include them in verification methods in the IAQ Guidelines?
- How are the risks and needs of workers and residents managed?



10.0 Class 10c Buildings – Private Bushfire Shelters

Private Bushfire Shelters
Class 10c

10.1 Scope

A private bushfire shelter associated with, but not attached to, a Class 1a building.

10.2 Current State

There are no published papers relating to private bushfire shelters.

10.3 Key Insights for Emergency Shelters

10.3.1 Key considerations for private bushfire shelters

- Given what we know about leaky buildings, infiltration and the indoor pollution potential from bushfires and prescribed burns, what IAQ sensors / monitors are required / should be required in such shelters?
- How can such shelters be optimised to limit infiltration and maximise air tightness while providing appropriate clean air, thermal comfort and energy efficiency?
- What energy sources are used to power such shelters and do they present an air quality risk?
- What appliances are used in the shelters and do they present an air quality risk?
- What timeframe are these shelters designed for? and what occupancy density?

10.3.2 Key considerations for emergency shelters / evacuation centres / post-recovery buildings

- What are the implications for emergency shelters in general given that such shelters may be buildings that have been designed for a different purpose, occupant density and occupancy duration (e.g. shopping centres, libraries, community halls)? Are specific classes of buildings more suitable as potential evacuation centres?
- What IAQ protections are applied, or should be applied, to post-recovery accommodation?
- Should time limits be imposed on insurers to assess water damaged buildings (e.g. storm, cyclone, flood) to limit the potential for mould to grow / spread? How should water damaged buildings be repaired to limit the potential for future IAQ problems from the water damage?

11.0 Conclusion

11.0 Conclusion

This report identified 106 peer-reviewed scientific papers that have quantified some aspects of indoor air quality in Australian buildings in the period 2000 – 2025. Combined with NABERS IEQ ratings for office buildings, the data represents snap-shots in time of about 2,500 buildings, less than 0.03% of Australian building stock.

Table 18 summarises the number of papers and buildings identified for each building class, allowing comparison with the indicative total number of buildings for each class.

Each of the previous chapters, focusing on a particular class of building, has provided an overview of the papers relevant to that building class, and geographic distribution maps and timelines that provide insight into where and when studies have been conducted. The maps clearly show the very uneven distribution of studies between state jurisdictions, between urban and regional settings, and between different climate zones. The timelines reveal trends in research focus, possibly related to funding opportunities.

The comparison of the sections on measurement instruments provide insights into the evolution of technology over time, as well as the differences in technologies utilised in different building classes.

The tables showing pollutant measurements are not indicative or representative of current indoor air quality nor of air quality in all buildings in a particular class. By showing a range of measurements, however, they are useful in highlighting pollutant concentrations of concern.

The selected key findings, however, are conceivably still relevant to each building class today, and in many cases are relevant to other building classes.

The concluding section of each chapter is provided as a means of stimulating thoughtful discussion and debate on what the data means for various stakeholders, and how the various findings can be used to inform the development and implementation of a national strategy on indoor air quality.

It is the intention of this report that it is seen as the beginning of a process, not the end. Periodic (e.g. triennial) iterations of this report are expected, adding to the body of knowledge that provides the scientific evidence for the development of policy and practice. It is hoped that this evidence comes not only from peer-reviewed scientific publications, but also from other reputable sources.

Table 18 Summary of papers/buildings by Building Class

Building Class	Number of papers (number of buildings)	Indicative number of buildings per class
Class 1 and 2 – Residential	43 (1700)	11,500,000
Class 3 and 4 – Other residential	2 (9)	88,500
Class 5 – Offices	14 (110) 1673 NABERS IEQ ratings (450)	140,000
Class 6 and 7 – Retail and wholesale	2 (18)	210,000
Class 8 – Factories	5 (5)	128,000
Class 9a – Healthcare	5 (7)	22,700
Class 9b – Public assembly	35 (227)	185,000
Class 9c – Residential care	3 (7)	30,500

12.0 Summary tables of all studies

12.0 Summary tables of all studies

Table 19 Summary of Class 1 and 2 (residential) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of dwellings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Brown [27]	1998 (2001)	VIC (Melbourne)	1	Air toxics in a 'healthy house'	4 samples over 8 months	TVOC, CH_2O, NO_2
Morawska et al. [8]	1999 (2001)	QLD (Brisbane)	16	Relationship between particle number distribution and concentration	Simultaneous and non-simultaneous indoor / outdoor sampling during winter	UFP / fine PNC, $PM_{2.5}$
Brown [29]	1996 (2002)	VIC (Melbourne)	27	Decay rate of VOCs post construction / renovation	Various times post construction / renovation	VOCs
Lee et al. [18]	1999 (2000)	QLD (Brisbane)	57 (47 detached, 10 other)	Impact of microenvironmental NO_2 concentration of ambient, workplace and household combustion-activities on personal exposure level	2 days of simultaneous measurements over winter (time of active combustion)	NO_2
Dingle et al. [83]	~ mid 1990s (2002)	WA (Perth)	185 (160)	Formaldehyde exposure in four rooms per house (living room, kitchen, small and large bedroom)	Passive sampling over 3 days, with repeat in 4-7 months	CH_2O
Hargreaves et al. [7]	1999 (2003)	QLD (Brisbane)	14 houses	Relationship between fungal and airborne particle concentration		$PM_{2.5}$, UFP / fine PNC, Fungal species
Morawska [9]	1999 (2003)	QLD (Brisbane)	15 (kitchens only)	Effect of ventilation conditions on particle deposition	Continuous for 48 hrs during winter	$PM_{2.5}$, CO_2, UFP / fine PNC
He et al. [24]	1999 (2004)			$PM_{2.5}$ measurements corresponding to different household activities		
He et al. [23]	1999 (2005)			Particle deposition rate		
Yang et al. [17]	1999 (2004)	QLD (Brisbane)	28	Investigate ventilation rates and pollutant source strength	Daily indoor and outdoor samples for 30 consecutive days April-May	NO_2
Rumchev et al. [28]	Unknown (2004)	WA (Perth)		Association between VOC exposure and childhood asthma		VOCs
Sheppeard [21]	1999 (2006)	NSW (Sydney / regional)	140 (90 Sydney, 50 regional)	Prevalence, sources and concentrations of indoor air pollutants in homes	Passive sampling over one week (winter)	NO_2, PM_{10}, CH_2O, nicotine
Sheppeard et al. [12]	1999 (2006)	NSW (Sydney / regional)	136 subset of above	Comparison of IAQ in smoking / non-smoking dwellings		
Sheppeard et al.	1999 (2006)	NSW (Sydney / regional)	140 (same set as above)	Estimate NO_2 exposure based on indoor and outdoor concentrations		
Franklin et al. [19]	Unknown (2006)	WA (Perth)	53 (kitchens only in detached, semi-detached houses and flats)	Investigate relationship between average and short-term peaks of NO_2 and use of gas appliances	3 consecutive days (for averages); 1-8 hrs over 3 days (for peak)	NO_2
Dunne et al. [84]	2004 (2006)	VIC (Melbourne)	1	Quantify pollutant mass balance	Two 8 week sampling periods	NO_2, CH_2O, BTEX, O_3

Table 19 Summary of Class 1 and 2 (residential) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of dwellings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Jones et al. [85]	Unknown (2007)	WA (Perth)	77	Spatial variation (vertical / rooms) in particulate concentrations	24 hour period	PM_{10}, $PM_{2.5}$, Total Suspended Particles (TSP)
Sjodin et al. [86]	Unknown (2008)	QLD (Brisbane)	10	Concentrations levels of seven types of PBDE <2mm	Dust samples from vacuum cleaners	PBDE
Galbally et al. [87]	2003 (2009)	TAS (regional)	77	Contribution of wood heater emissions to indoor BTEX pollutants	7 day period in winter and summer	BTEX
Lazanby et al. [88]	2006/7 (2012)	WA (Perth)	41	Formaldehyde exposure in children	Summer and winter sampling periods	CH_2O
Loveday et al. [89]	2007/8 (2010)	WA (Perth)	79	Exposure risk of gas heaters for elderly occupants	Two 12-week periods during winter	NO_2, CH_2O , VOCs
Reisen et al. [25]	2006–08 (2011)	VIC (regional)	4	Ambient and indoor contaminants during biomass burning	Continuous sampling over 5 days	$PM_{2.5}$ and O_3
Maisey et al. [90]	2006 – 2011 (2013)	WA (Perth)	(homes from other studies)	Baseline indoor/ambient VOCs	Various	VOCs, CH_2O
Lawson et al. [16]	2008/09 (2011)	VIC (Melbourne)	40	IAQ – seasonal variation and distance from major roads	Winter/spring and Summer/Autumn; continuous sampling for CO and $PM_{2.5}$	PM_{10}, NO_2, BTEX, CO, $PM_{2.5}$
Galbally et al. [91]	2008/9 (2011)	VIC (Melbourne)	40 (possibly same homes as above)	IAQ in suburban homes	7 day monitoring in winter/spring 2008 and summer/autumn 2009	$PM_{2.5}$, PM_{10}, CO, CH_2O, VOCs, NO_2, O_3, Fungi
Molloy et al. [15]	2008/9 (2012)	VIC (Melbourne)	40 (possibly same homes as above)	NO_2 – seasonal variation	Winter/Spring and Summer/Autumn	NO_2
Cheng et al. [92]	2008/9 (2016)	VIC (Melbourne)	40 (possibly same homes as above)	VOC measurements +IAQ and ambient conditions		VOC
Hamidin et al. [30]	2009 (2013)	QLD (Brisbane)	32		Simultaneous continuous I/O sampling March – July	
He et al. [93]	2011 (2014)	QLD (Brisbane)	41 (24 flood affected, 17 non-flood affected)	Effect of riverine flooding and prompt cleaning activities	Mar-May (2 months post flood) and July – Aug (6 months post flood)	PM_{10}, bioaerosols
Sercombe et al. [94]	Unknown (2014)	NSW (Sydney)	39	Focus on inhalable fungal aerosols	Homes of people diagnosed with Chronic Fatigue FC	Fungal aerosols
Reisen et al. [95]	2014/15 (2019)	VIC (regional)	21	To assess if remaining indoors is effective to escape air pollution during biomass burning	Continuous (5 minute) sampling I/O	$PM_{2.5}$
Wang et al. [31]	2015 (2019)	QLD (Brisbane) ACT (Canberra)	14	Identification of levels, profiles and distribution of select contaminants	2-3 month sampling period for each location; simultaneous sampling of gas, airborne particles and dust	PAHs, PCBs, pesticides
Pacitto et al. [96]	2016 (2018)	QLD (Brisbane)	75 (assumed)	Measurement of personal exposure (measured by personal belt mount particle counters	3 days of continuous monitoring per volunteer	PN, concentration and size
Franklin et al. [97]	Unknown (2019)	WA (Perth)	262	Maternal exposure to indoor air pollutants	7 days at 34 weeks gestation	CH_2O, NO_2, VOCs

Table 19 Summary of Class 1 and 2 (residential) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of dwellings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Gilbey et al. [98]	2017 / 18 (2023)	WA (Perth)	111	IAQ in non-smoking homes and group dwellings with shared walls	1 x 24-h continuous sample per household	TVOC, CH_2O, NO_2, CO, CO_2, PM_{10}, PM_4, $PM_{2.5}$, PM_1
Gilbey et al. [10]	2017/18 (2023)	WA (Perth)	40	Impact of $PM_{2.5}$ and UFPs; non-smoking adults and cardiovascular risk	5 minute intervals continuously for 24 hours	$PM_{2.5}$ (at home) and UFP / fine PNC (at work)
Rumchev et al. [20]	2018 (2018)	WA (Perth)	63 (assumed, based on number of volunteers)	IAQ in primary living spaces	24hr continuous monitoring on weekdays	PM (1, 2.5, 4, 10)
Pettit et al. [22]	Unknown (2019)	NSW (Sydney)	1	Test efficiency of active green wall in reducing TVOC and PM from a room	Tested lavender oil in an airtight residential room	TVOC, PM
Xiong et al. [99]	2019 (2020)	NSW (Sydney)	48 (bedrooms only)	To derive association of bedroom temperature and ventilation with sleep quality	Measurements over 5 consecutive days	CO_2
Brambilla et al. [100]	2020 (2022)	ACT (Canberra)	1	Relationship between IAQ and mould growth; early detection of mould growth	Jul – Aug (winter); air and surface sampling	CO_2, PM_{10}, $PM_{2.5}$, TVOC
Wheeler et al. [26]	2021 (2023)	VIC (regional)	10	Effectiveness of HEPA filters	Continuous monitoring (I/O) for 2-4 weeks during prescribed burn periods	$PM_{2.5}$
Gilbey et al. [13]	2022 (2022)	WA (Perth)	111 (assumed, based on number of participants)	Associations between residential VOC exposure and subclinical measures	Continuous measurements (30 minute intervals) over 24 h period	VOCs
Boulic et al. [14]	Unknown (2024)	VIC (Melbourne)	1	Ventilation efficiency in removing CO_2	4 hr periods during winter and summer	CO_2, airflow velocity

Table 20 Summary of Class 3 (other residential) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of dwellings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
He et al. [32]	2013-14 (2016)	NSW (regional)	1 (correctional facility)	Impact of smoking ban on IAQ and staff exposure	48 hrs in each of 4 locations, pre and post smoking ban	$PM_{2.5}$, UFP / fine PNC, VOCs (markers of smoking)
Bott et al. [33]	(2017)	QLD (Brisbane and regional)	8 (dormitory facilities at workplace)	Impact of fire station activities on IAQ	2 minute sampling rate over two 10 hr day shifts, including start of shift, turnout response and return to station activities	DPM and PAH

Table 21 Summary of Class 5 (offices) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Dingle et al. [39]	Unknown (2000)	WA (Perth)	18 conventional, 20 portable	Impact of plants in reducing formaldehyde concentrations	3–4 days total (pre and post introduction of plants)	CH_2O
Jamriska et al. [36]	1997 (2000)	QLD (Brisbane)	1	Fractional performance of building filtration/ventilation systems and relationship between outdoor/indoor particle characteristics	10 hours, 5 minutes	PNC, ACH
Lee et al. [18]	1999 (2000)	QLD (Brisbane)	6	Personal exposure to NO_2 exposure in ambient conditions and at work and home	2 days of simultaneous measurements over winter (time of active combustion)	NO_2
Dingle et al. [34]	Unknown (2002)	WA (Perth)	5	Correlation between traffic emissions and IAQ	Continuous over 1 week	TVOCs, CH_2O
He et al. [38]	2006 (2007)	QLD (Brisbane)	1	Quantify submicrometer particulate emissions from office printers	48 hours (20 second sample time)	UFP / PNC
Morawska et al. [35]	2003–4 (2009)	QLD (Brisbane)	1 (4 rooms in a radio station)	Impact of HVAC redesign on particle concentrations	36 hours, 5 hours / 2 min	UFP / fine PNC, $PM_{2.5}$
Quang et al. [37]	2009/10 (2013)	QLD (Brisbane)	3	Optimisation of HVAC to address energy efficiency and reduce indoor pollutants	Continuous (10-sec intervals for 2-3 weeks)	CO_2, $PM_{2.5}$, PNC
Quang et al. [101]	2009/10 (2013)	QLD (Brisbane)	2	Optimisation of HVAC to address energy efficiency and reduce indoor pollutants	Continuous (10-sec intervals for 2-3 weeks)	CO_2, PN, $PM_{2.5}$
Taylor et al. [102]	2011/12 (2014)	SA (Adelaide)	18	Fungal spore variability		CO_2, pollutants in general, airborne fungi
Irga and Torpy [103]	2013–14 (2016)	NSW (Sydney)	11	Impact of different ventilation types on I/O pollutant ratios	Year long	CO_2, CO, NO_2, TVOCs, SO_2, PM_{10}, $PM_{2.5}$, airborne fungi
Wang et al. [31]	2015 (2019)	QLD (Brisbane) ACT (Canberra)	14	Identification of levels, profiles and distribution of select contaminants	2–3 month sampling period for each location; simultaneous sampling of gas, airborne particles and dust	PAHs, PCBs, pesticides
Goodman et al. [40]	2016 (2018)	VIC (Melbourne)	1 campus, multiple buildings	Concentrations and prevalence of VOCs and aldehydes in a range of indoor environments, including within a green certified building	Sampling (2.5 hrs, 7 hrs) over 2 months (summer, autumn)	VOCs, 41 pollutants (esp CH_2O and BTEX)
Woo et al. [104]	2019 (2021)	VIC (Melbourne)	7	Comparison of IAQ in different building typologies	Continuous	CO_2
Brambilla et al. [105]	2019/20 (2021	ACT (Canberra)	1	Impact of bushfires on office IAQ	Continuous (1 minute intervals over 3 months)	CO_2, PM_{10}, $PM_{2.5}$

Table 22 Summary of Class 6 and 7 (retail and wholesale) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Dingle et al. [48]	(2002)	WA (Perth)	10 (coffee shops, restaurants)	Indicators of tobacco smoke	5–15 minute samples over 2 hrs (general) and 4 hours (peak time)	Nicotine, CO, $PM_{2.5}$, PM_{10}, CO_2
Bott et al. [33]	(2017)	QLD (Brisbane and regional)	8 (fire stations)	Impact of fire station activities on IAQ	2 minute sampling rate over two 10 hr day shifts	DPM and PAH

Table 23 Summary of Class 8 (factories) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Rumchev et al. [52, 106]	2002 (2003)	WA (Perth)	15 (laboratories – chemistry, biology, engineering)	Evaluate IAQ in university laboratories	4 hr sampling on 2 occasions (semester and semester break)	VOCs, PM_{10}, $PM_{2.5}$, UFP
Agranovski et al. [51]	(2004)	QLD (Regional)	1 (animal confinement building)	Viability of UVAPS measurement process	1 min sampling periods over 2 hrs; and 5 second continuous sampling over 4 sampling periods	PM (viable and non-viable)
Rumchev et al. [52]	(2001)	WA (Perth)	1 (bakery)	Occupational dust exposure and size distribution	5 minutes (over 8 hrs)	PM
Hawchar et al. [49]	(2022)	NSW (Sydney)	1 (brewery)	Test IoT sensor network	2 months (dynamic measurements during different work cycles)	CO_2

Table 24 Summary of Class 9a (healthcare) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Morawska et al. [56]	1996 (1998)	QLD (Brisbane)	2 Hospitals (15 different units)	Concentration and distribution of submicrometer particles in relation to ventilation and filtration systems	2 hrly sequential indoor / outdoor measurements	PM (large particles 0.5 – 30 µm; submicrometer particles 0.017 – 0.7 µm) UFP / PNC/ PNSD
Knibbs et al. [54]	(2011)	QLD (Brisbane)	1 Hospital (Lung Function Laboratory; pressure isolation room in ED; outpatient consulting rooms)	Effect of ventilation on risk of airborne infection from 3 common pathogens (influenza, TB, rhinovirus)	Not applicable	ACH (infection spread was modelled, not measured)
He et al. [55]	2014 (2017)	QLD (Brisbane)	1 hospital (Paediatric intensive care unit)	Understand PM distribution, type and sources	Continuous indoor and outdoor sampling over 2 weeks	PM (bioaerosols) UFP / PNC
Pereira et al. [53]	Unknown (2017)	QLD (Brisbane)	2 hospitals (3 units each)	Characterisation of indoor bioaerosols	Several days over 3 weeks	PM (bioaerosols)
Pisaniello et al. [57]	2023 (2024)	SA (Adelaide)	1 hospital (surgery recovery suite)	Evaluation of advanced filter system	6 days (3 days prior and post installation); continuous (PM) and periodic (bacteria and fungi)	PM (multiple sizes), VOCs, CH_2O, CO_2, bacteria, fungi

Table 25 Summary of Class 9b (public assembly buildings – entertainment, sport, transport and cultural venues) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Entertainment venues						
Dingle et al. [48]	(2002)	WA (Perth)	10 (Taverns, nightclubs, sporting clubs, hotel)	Indicators of tobacco smoke	5–15 minute samples over 2 hrs (general) and 4 hours (peak time)	Nicotine, CO, $PM_{2.5}$, PM_{10}, CO_2
Sporting venues						
Rajagopalan & Luther [60]	Unknown (2012)	VIC (Regional)	1 (Sports Hall in Aquatic Centre)	Develop guidelines for practical retrofitting of multipurpose indoor sports facilities	1 week in March (15 min intervals 4 times daily)	CO_2
Public transport / transit stations						
Mohsen et al. [59]	2015/16 (2018)	NSW (Sydney)	4 stations (35 platforms, 1 concourse, train carriages)	Measure PM in underground and ground level platforms	15 min sampling over 6 weeks (during weekday rush hours)	PM_{10} and $_{2.5}$, dust samples
Cultural venues						
Afroz et al. [107]	(2020)	WA (Perth)	1 (library)	Evaluation of demand-controlled ventilation	Unknown	CO_2, VOCs
Wheeler et al. [58]	2019 (2021)	NSW (Regional)	1 (Library)	Effectiveness of library as a 'cleaner indoor air shelter'; efficacy of portable air cleaners	5 months	$PM_{2.5}$

Table 26 Summary of Class 9b (public assembly buildings – education) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Childcare / Kindergarten / Early Childhood						
Christian et al. [108]	2016 (2022)	WA (Perth)	22 (early childhood)	Effect of proximity to high-traffic areas and children's physical activity	48–72hrs	$PM_{2.5}$
Munckton & Rajagopalan [109]	2022 (2024)	VIC (Melbourne)	5 (kindergartens)	Interaction between thermal comfort and IAQ	15 minute intervals during winter	CO_2
Gilbey et al. [62]	2022 (2024)	WA (Perth)	22 (childcare centres)	Location and seasonal impacts on IAQ	Summer and winter seasons	PM (10, 4, 2.5, 1), UFP, CO_2, CO, NO_2, TVOC
Schools						
Zhang et al. [75]	2022 (2006)	WA (Perth)	4 schools	To investigate whether a newly opened 'low allergen' school can effectively improve IEQ in classrooms	Passive or active sampling at four times (summer term, winter term, autumn holiday, and winter holiday)	PM_{10}, TVOCs, CH_2O, Dust
Rumchev et al. [78]	Unknown (2007)	WA (Perth)	6 schools (20 classrooms)	Compare exposure levels between new and old schools	1 week (8 hrs at beginning and end of a week)	CH_2O, $PM_{2.5}$, UFP
Guo et al. [65]	2006 (2008)	QLD (regional)	1 school (1 classroom)	Impact of ventilation scenario on ACHs and PNC in air conditioned classroom	2 weeks, 10 second	PNC
Guo, H et al. [66]	2006 (2010)	QLD (Brisbane)	1 school (2 classrooms)	Characterisation of PNC and $PM_{2.5}$	10 days, 5 minutes	PNC
Morawska, et al. [68]	(2009)	QLD (Brisbane)	(3 classrooms)	Relationship between UFP concentrations and classroom activities	2 periods over 60 days)	UFP (PNC)
Marks et al. [69]	2009 (2010)	NSW (regional)	22 schools (20 classrooms)	Compare respiratory health effects of exposure to unflued gas heaters	6 periods of 1 week	NO_2, CH_2O
Salonen et al. [110]	2010 – 2012 (2013)	QLD (Brisbane)	25 schools	Endotoxin concentrations in indoor air and dust		Endotoxins
Mazaheri et al. [77]	2010 – 2012 (2014)			Personal exposure to ultrafine particles (UFP)	Wearable devices for continuous 24h sampling	UFP
Laiman et al. [71]	2010 – 2012 (2014)			Changes in particle number concentration (PNC) in naturally ventilated classrooms	Continuous sampling 24 h/ day for two weeks	CO_2, UFP
Salonen et al. [111]	2010 – 2012 (2014)			Prevalence and baseline concentrations of culturable fungi		Fungi
Crilley et al. [112]	2010 – 2012 (2014)			Elemental composition of PM_1 in urban schools		PM_1
Mishra et al. [70]	2010 – 2012 (2015)			Quantify indoor/outdoor VOC concentrations and sources	Continuous sampling (4 times daily) in spring, autumn, winter	VOCs
Mishra et al. [79]	2010 – 2012 (2015)			Health risks driven by a single substance or a mixture of substances	4 sampling periods each day	VOCs, Carbonyls
Mazaheri et al. [67]	2010 – 2012 (2016)			Daily cycles of indoor/outdoor PNC		UFP (PNC)
Crilley et al. [113]	2010 – 2012 (2014)		(subset of 11 schools)	Identification of sources of primary organic aerosols in urban schools		Organic aerosols

Table 26 Summary of Class 9b (public assembly buildings – education) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Toms et al. [114]	2011 – 12 (2015)	QLD (Brisbane)	(subset of 10 schools)	Determine concentrations of PBDE in dust in primary schools	4 sample sections per classroom; 28 samples from 16 classrooms	PBDE
Clifford et al. [4]	2010 – 2012 (2018)		(655 children from 25 schools)	Determine if exposure to UFP is associated with respiratory health status	30 s sampling intervals over 2 consecutive weeks	UFP (PNC)
Luther et al. [72]	Unknown (2018)	Victoria (Melbourne, Woodend, Broadmeadows, Wallan, Mildura)	6 schools (24 classrooms)	How classroom usage affects the build up and decay of CO_2	Continuous sampling during the winter period	CO_2
Haddad et al. [64]	2018/19 (2021)	NSW (Sydney)	1 school (2 classrooms)	Demand controlled ventilation and thermal comfort	1 year	CO_2, TVOC
Woo et al. [115]	2019 (2022)	VIC	5 Schools (10 classrooms, natural and mechanical ventilation)	Relationship between IAQ and student performance	1 year	$PM_{2.5}$
Rajagopalan et al. [63]	2019 (2022)	VIC		IAQ and ventilation effectiveness	1 year	CO_2, PM
Andamon et al. [116]	2019 (2023)	VIC		Effectiveness of ventilation strategies	1 year	CO_2
Snow et al. [74]	2021 (2022)	QLD (Brisbane)	13 early childhood, primary and secondary schools (67 classrooms)	Influence of occupant behaviour on IAQ and ventilation effectiveness	4–8 weeks (covering winter and summer)	CO_2
Universities						
Goodman et al. [40]	2016 (2018)	VIC (Melbourne)	1 university (20 locations)	Investigate VOCs	Active sampling over a two month period	CH_2O
Ulpiani et al. [73]	2019–2020 (2021)	NSW (Sydney)	1 university (1 building)	Spatial heterogeneity and temporal variability of environmental quality	Short term sampling	CO_2, TVOCs
Samandi et al. [76]	2021 (2023)	NSW (Sydney)	1 university (1 building)	Effect of hazard reduction burning and vehicular traffic	5 months; 24/7 at 2 min intervals	$PM_{2.5}$
McGarry et al. [61]	2021–2024 (2025)	(Undisclosed)	1 university (1439 occupied rooms across 78 buildings)	Pilot a method to characterise indoor CO_2 concentrations in occupied mechanically ventilated spaces		CO_2

Table 27 Summary of Class 9c (residential care) IAQ studies

Author / Title	Year of study (year of pub.)	Location State (city)	Number of buildings	Purpose / focus of study	Measurement timeframe	Pollutants Measured
Rajagopalan et al. [81]	2019 (2024)	zVIC (indeterminate)	5 aged care homes (2 common rooms each)	Evaluation of economic value of ventilation retrofit	1 year (6 months pre and post retrofit); 15 min sampling	CO_2, PM_{10}, $PM_{2.5}$
Brass et al. [80]	2022 (2022)	SA (Adelaide)	1 (25 communal rooms, 17 staff only areas, 20 connecting sites)	Identify potential ‘super-spreader’ zones and the efficacy of ventilation-based risk reduction strategies	4 weeks (summer)	CO_2
Franklin et al. [82]	(2025)	VIC (Melbourne)	Room in unoccupied aged care facility	Evaluate effectiveness of germicidal ultraviolet disinfection	11 days prior to GUV; 21 days post (continuous)	O_3, VOCs and PM

13.0 Literature Review Methodology

13.1 Systematic Literature Review

The ten pollutants selected for study formed the basis of a structured systematic literature search strategy in four scientific publication data bases (Scopus, PubMed, Scopus, Embase) for peer reviewed journal articles published since 2000. To be included, studies had to report onsite measurements of at least one of the named pollutants within buildings in Australia. Papers were excluded if measurements were conducted in buildings not in Australia, or if results were derived solely from modelling. Books, book chapters and conference papers were excluded, as were government or industry reports.

Duplicate papers were excluded, as were some older studies where the full text could not be accessed.

The identified papers were then sorted by building class before the full papers were read and relevant data extracted.

To minimise the likelihood of missing key papers, the reference lists of the identified papers were scanned, and additional online searches of key authors were conducted.

Some identified studies measuring the ten pollutants also measured pollutants such as specific VOCs, mould, fungi, organic compounds (e.g. PAHs) and manmade organic compounds (e.g. PCBs) because of their presence in gaseous form or in particulate matter. Reporting on these papers focuses on the ten pollutants of interest; findings about these additional contaminants are not robustly analysed in this report.

13.1.1 Limitations

The ten pollutants shown in Table 3 were the main key words used in the search strategy. Future editions of this report may expand on the list of contaminants.

Despite a rigorous literature review process, it is possible that the search terms and strategy did not identify all papers relevant to the ten pollutants of interest and measurements in Australian buildings. Any papers that have been inadvertently omitted in this report can be added in future editions.

No attempt was made to critically analyse or rank the scientific merit of each paper, for example by using citation based metrics such as Journal Impact Factor, or author H-index. Each identified paper has been subject to the relevant journal's peer review process prior to publication.

13.2 Additional Data Sources

Building classifications are based on those utilised in the National Construction Code. This enables indoor air quality to be examined and addressed for different occupancy modes, pollutant risks, exposure limits, health and economic consequences, and policy responses.

The estimated number of buildings per class are derived from the Commercial Building Baseline Study 2022. The total number of buildings and the floor area are both important for understanding the scale and challenges of monitoring indoor spaces and managing indoor air quality.

Data from NABERS Indoor Environmental Quality ratings was included for analysis, as it presents a discrete industry-lead data source of IAQ measurements in Australian office buildings.

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