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Is poor air quality in day-care centres' affecting our children's health? A study of indoor air quality in childcare facilities located in Perth, Western Australia

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Abstract

Poor indoor air quality (IAQ) can adversely affect children's health; however, limited studies have quantified indoor air pollutants in day-care centres (DCCs) where infants and young children are increasingly spending more time from a younger age. The aim of this study was to investigate seasonal IAQ in Western Australian childcare facilities at both heavy traffic and low traffic locations. In 22 centres, total volatile organic compounds, formaldehyde, nitrogen dioxide, carbon dioxide, and carbon monoxide, particulate matter (PM) measured in six size fractions (total PM, PM_{10}, PM_4, $PM_{2.5}$, PM_1, ultrafine particles), and meteorological parameters (temperature and relative humidity), were continuously sampled over a 24-h period, in the cold season and repeated in the warm season. All contaminants (other than formaldehyde) in the summer and/or winter collections, or averaged over both seasons, were found to be above contemporary air quality standards, guidelines, best practice statements, or other available guidelines developed to protect human health. Furthermore, all contaminants were present at higher concentrations indoors where a DCC was located within 100 m of a heavy traffic roadway. The findings of this study suggest that children who attend these facilities on a regular basis may be chronically exposed to a range of health damaging contaminants during critical stages of their development. The findings support the need for measures to reduce concentrations of air pollutants in DCCs. Preventative actions such as attention to DCC siting, selection of appropriate building materials and furnishings, improvement in ventilation, and usage of 'green' cleaning products should be considered to reduce children's exposures to harmful airborne contaminants.

Keywords Exposure · Air pollution · Road traffic · Asthma · Particulate matter · Health

Introduction

Across Australia, as in most industrialised countries, increasingly many parents and caregivers use formal paid childcare to support participation in employment, education, and training; to meet children's developmental needs; or to supplement care from the primary caregiver for other reasons (Australian Bureau of Statistics 2022; St-Jean et al. 2012). As such, day-care centres (DCCs) have become one of the most important environments for many infants and young children under the age of six, and their primary places for social activity and early learning (Branco et al. 2019; Madureira et al. 2016; St-Jean et al. 2012). With the evidence indicating that young children are spending greater periods of time in childcare environments, this study aimed to increase the currently limited body of knowledge relating to indoor air quality (IAQ) in day-care settings, by quantifying indoor concentrations of particulate matter (PM) and selected gas concentrations, in a cohort of Western Australian childcare facilities.

The impact of both indoor and outdoor air pollution exposure on human health has been the subject of considerable scientific effort in recent years, with PM and a range of gaseous pollutants implicated as potentially serious threats to human health (Brook et al. 2010; Kelly 2003; Kelly and Fussell 2015a, b, 2019; Landrigan et al. 2018; United States Environmental Protection Agency 2022a). PM is a complex mixture of solid and liquid particles suspended in air that exist in various shapes and sizes and originate from different sources, resulting in diverse compositions. They

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are considered amongst the most health-relevant pollutants with effects being directly related to their ability to easily penetrate the human respiratory system (Brook et al. 2010; Kelly and Fussell 2019; Landrigan et al. 2018; Mannucci et al. 2015; Oliveira et al. 2019; Rumchev et al. 2015; World Health Organisation 2010, 2021). Similarly, gaseous pollutants which can include nitrogen dioxide (NO_2), carbon dioxide and monoxide (CO_2 and CO), total volatile organic compounds (TVOC), and formaldehyde (HCHO) are also implicated as a concern to human health (Mannucci et al. 2015; Rumchev et al. 2002, 2004, 2015; World Health Organisation 2010, 2021).

Compared to adults, it is likely that exposure in infants and young children will result in more marked adverse health effects due to their higher breathing rate relative to their body size, their breathing of larger volumes of air per unit body weight, and their underdeveloped respiratory, immunological, physiological, and neurological systems (Bluyssen 2017; Buonanno et al. 2013a, b; Faustman et al. 2000; Hoang et al. 2017; Landrigan and Goldman 2011; Quirós-Alcalá et al. 2016; Seltenrich 2013; Sly and Flack 2008; United States Environmental Protection Agency 2022a; World Health Organisation 2021, 2022; Zhang et al. 2021). Additionally, because infants and young children engage in higher levels of physical activity, they tend to breathe more frequently through their mouths, allowing a greater volume of pollutants to be inhaled, thus bypassing a level of filtration provided by nasal breathing (Oliveira et al. 2019; Quirós-Alcalá et al. 2016; United States Environmental Protection Agency 2022a; World Health Organisation 2021, 2022).

Furthermore, this age group engages in exploratory behaviours that place them in direct contact with contaminants. This includes hand-to-mouth behaviours along with crawling and playing on the ground where dust accumulates. This places their breathing zone close to the floor, resulting in higher inhaled doses of some pollutants (particularly those that are denser and layer closer to the floor) compared to adults who might be in the same room (Annesi-Maesano et al. 2013; Bradman et al. 2012; Landrigan and Goldman 2011; Quirós-Alcalá et al. 2016).

Indoor air is a multifaceted mixture of gaseous and airborne contaminants, and recent epidemiological studies have identified various pollutants in childcare facilities, across a range of countries, which are considered a serious health threat to exposed children. The pollutants derive from various origins, vary over time, and include both PM and gases such as NO_2, CO_2, CO, TVOC, and HCHO (Branco et al. 2015, 2019; Fonseca et al. 2014; Gaspar et al. 2018; Hoang et al. 2017; Hwang et al. 2017; Kelly and Fussell 2019; Nunes et al. 2015; Zhang et al. 2021). In DCCs, potential sources of contaminants include building materials and furnishings (e.g. treated and pressed wood including off-gassing from these materials); paints, glues, and art supplies; carpets/flooring; consumer products (e.g. electronics and toys); cleaning supplies (e.g. disinfecting, sanitising, and deodorising products); and cooking and heating appliances (Australian Government 2021; Bradman et al. 2012; Branco et al. 2015, 2019; Hoang et al. 2017; Majd et al. 2019; Morawska et al. 2017; United States Environmental Protection Agency 2022a, b; Vardoulakis et al. 2020; Zhang et al. 2021). Additionally, concentrations of contaminants can be influenced by the infiltration of outdoor pollutants, proximity to traffic-dense roadways, the age and structure of the facility, maintenance and cleaning practices, and levels of ventilation (Australian Government 2021; Bradman et al. 2012; Branco et al. 2015, 2019; Hoang et al. 2017; Kelly and Fussell 2019; Majd et al. 2019; Morawska et al. 2017; United States Environmental Protection Agency 2022a, b; Vardoulakis et al. 2020; Zhang et al. 2021). PM and gaseous pollutants have consistently been associated with significant health effects including asthma, allergic rhinitis, increased allergen sensitisation, upper and lower respiratory diseases, decreased lung function, damage to liver, kidneys and central nervous system, systemic inflammation, and cancer (Annesi-Maesano et al. 2013; Bradman et al. 2012; Buonanno et al. 2013a, b; HEI Review Panel on Ultrafine Particles 2013; Kim et al. 2015; United States Environmental Protection Agency 2022a, b; World Health Organisation 2021). In more recent years, the findings of cross-sectional and longitudinal studies have highlighted adverse effects of air pollution and in particular the smaller sized fractions of PM, which are capable of translocating to the circulatory system to cause adverse cardiovascular effects (Brook et al. 2010, 2017; Schulz et al. 2019).

Consequently, children who attend child care facilities on a regular basis may be chronically exposed to a range of health damaging contaminants, during critical stages of their development (Bradman et al. 2012; Branco et al. 2019; Oliveira et al. 2017, 2019; Quirós-Alcalá et al. 2016; Zhang et al. 2021).

However, it is well reported that there is a substantial and important lack of exposure data and guidance on indoor air quality (IAQ) in childcare settings, particularly across some geographical regions, including Australia (Branco et al. 2019; Nunes et al. 2015; Oliveira et al. 2019; Quirós-Alcalá et al. 2016; Roda et al. 2011; Zhang et al. 2021).

This study aimed to address some of the gaps in quantitative environmental data related to childcare environments, by measuring seasonal IAQ in a sample of Western Australian day-care facilities. Data were compared to relevant Australian legislation and World Health Organization (WHO) air quality standards, guidelines, best practice statements, and other available guidelines which are evidence-informed recommendations developed to guide and protect public health from the negative effects of air pollution exposure. Further evaluation was also undertaken to understand the influence of traffic on indoor concentrations of pollutants by stratifying the centres into those located in traffic-dense areas compared to those that were not.

Methodology

Study population and study visits

Forty-five DCCs, from a list of registered DCCs, were randomly selected and invited to participate in this project. Centre managers who expressed interest and requested further information were emailed a letter of introduction along with an information sheet explaining the nature of the study. Centres were contacted by telephone to confirm eligibility which included that the facility was located within the Perth metropolitan area and had a minimum attendance of 20 registered children. Small and/or family day-cares were excluded.

Overall, 22 geographically dispersed facilities across the Perth metropolitan area were eligible and agreed to participate in the study. These centres are shown as red squares in Fig. 1.

Study location

Perth is located on the western side of Australia and is the capital city of Western Australia. Perth has a warm and temperate climate, with an average maximum summer temperature of 29˚C and 13˚C in winter (Australian Government - Bureau of Meteorology 2022).

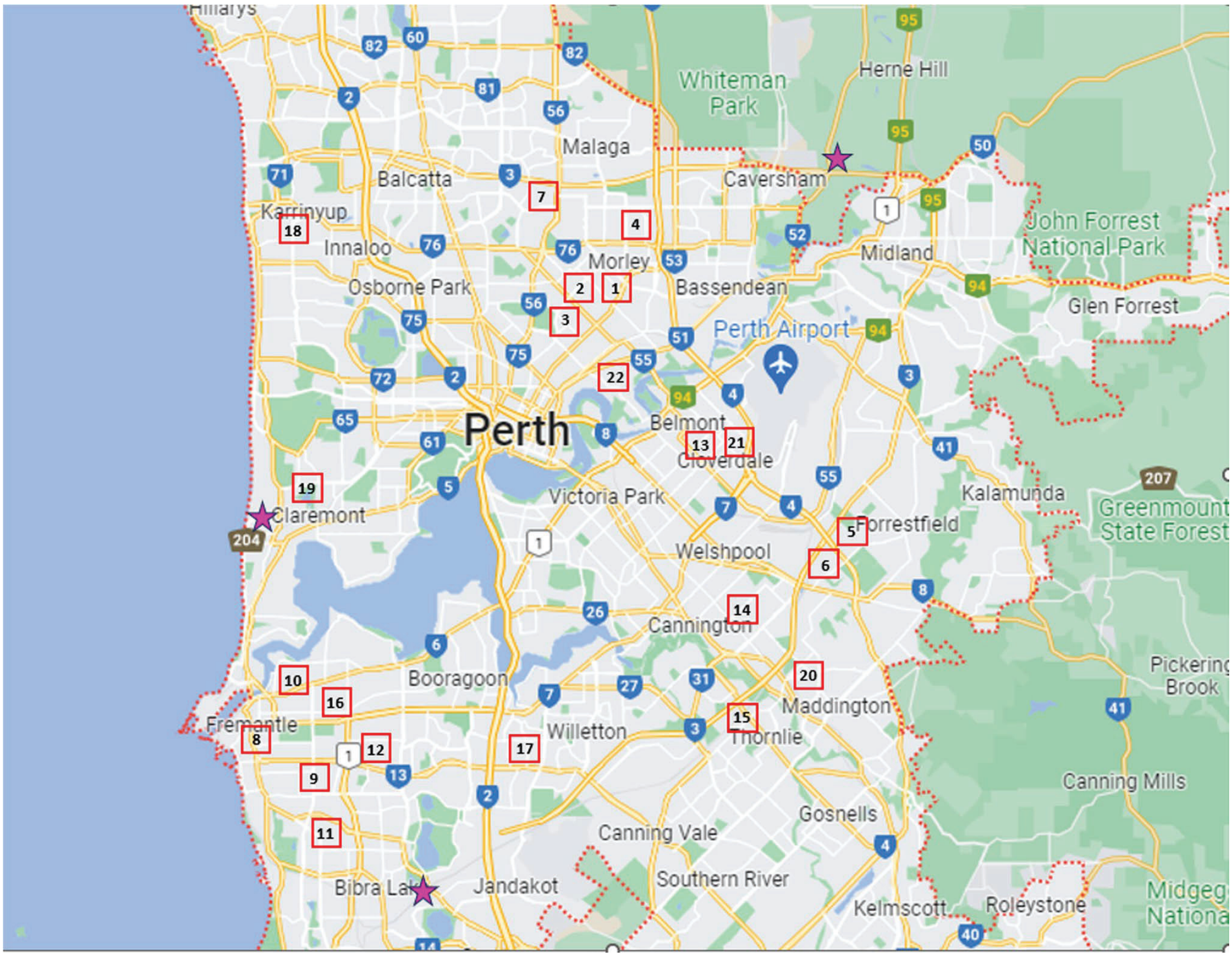


Fig. 1 Spatial distribution of monitored day-care centres (red squares containing location number) and fixed site ambient air monitoring stations (pink stars)

Indoor air quality monitoring

A total of 44 air samples (one at each DCC in winter and repeated in summer) was collected. At each facility, indoor air samples were collected in the main childcare room, out of children's reach, over a continuous 24-h period. The main childcare room at all facilities typically catered to preschool aged children (approximately 2–5 years). No sampling was undertaken in infant/baby rooms.

Indoor concentrations of CO_2, CO, NO_2, and TVOC, along with ancillary variables including temperature and relative humidity, were measured using the Gray Wolf AdvancedSense Pro (Gray Wolf Sensing Solutions, Shelton, CT, USA). HCHO concentrations were measured using a separate, supplementary sensor attached to the AdvancedSense Pro (Formaldehyde Multimode Monitor FM-801, Gray Wolf Sensing Solutions, Shelton, CT, USA). The HCHO sensor determines HCHO concentrations using photoelectric photometry (407–424 nm) as 30-min averages for continuous data monitoring. Sensors were calibrated for > 60 min prior to logging HCHO concentrations.

PM concentrations were measured for five size fractions (total PM (TPM), PM_{10}, PM_4, $PM_{2.5}$, and PM_1) using a DustTrak light scattering photometer (DRX 8533. TSI Inc., Shoreview, MN, Shoreview, MN, USA). Dust Trak is a real-time monitor that displays particle mass concentrations in units of micrograms per cubic metre (μg/m^{-3}; g × 10^{-6}). Data was logged at 5-min intervals. The measuring range of the instrument is 1 μg/m^3 to 150 × 10^3 μg/m^3 with accuracy of ± 0.1% of the reading or 1 μg/m^3, whichever is greater.

Mean concentrations for all pollutants and ancillary variables were calculated as the average over the entire 24-h monitoring period.

Numbers of ultrafine particles (UFP) were measured using a portable P-Trak 8525 (TSI Inc., Shoreview, MN, USA). P-Trak detects and counts UFP numbers in real-time with particle number concentration (PNC) being displayed in units of particles per cubic centimetre (particles/cm^3). This device has a limit of operation of 8 h at 21 °C and a measuring range of 0 to 5 × 10^5 particles/cm^3. This instrument detects and counts UFP ≤ 1 μm and was programmed to log data at 5-min intervals, for six hours from early morning to mid-afternoon when children were present in the centre. The mean concentration of UFP per DCC was calculated as the average of all measurements over the 6-h monitoring period.

All instrumentation was factory calibrated prior to the commencement of the winter and summer monitoring periods.

Outdoor air pollution

Concentrations of outdoor air pollutants including CO, NO_2, $PM_{2.5}$, and PM_{10} were obtained from the Western Australian Department of Water and Environmental Regulation, using data from three fixed monitoring stations (Caversham (north), South Lake (south), Swanbourne (west)). These fixed monitoring sites are depicted by a pink star in Fig. 1 and are considered to provide good representation of Perth's ambient air quality. Data from outdoor monitoring stations was matched to corresponding days of indoor air monitoring in day-care facilities to exclude contributions to pollutant concentrations in DCCs related to unusual events such as scheduled burn offs.

Questionnaires

At each visit, centre managers were requested to complete a questionnaire during the monitoring period to provide relevant information on building characteristics and sources of pollution within the centre. Questions included the age of the building (< 10 years or > 10 years), air conditioner for heating or cooling (yes or no), cooking appliances used (electric, gas, or a combination of both), and the distance of the facility to busy roads and industrial areas (< 100 m or > 100 m). Additional information was gathered on whether renovations had recently been undertaken (within the previous 3 months, including painting, new carpets, new furniture or building works), how they rated centre ventilation (very good or good, poor), and the type of flooring material used within the facility.

Informal independent observations were also made by the researcher. Typically, this included a brief notation of the general layout of the centre including where the kitchen was located relative to the main child care room, whether a reported air conditioning system was also used to ventilate (with fresh air) the centre, whether a hot meal was prepared using the cooking facilities during the monitoring period, and if the centre was a modified residential property or a fit-for-purpose facility.

Limitations of data

Data was not collected on explicit features of day-care centres such as the size of building/room, numbers of windows and doors, structural features of the building, or composition of furniture. Specific information was also not obtained related to the operational functioning of the centre such as window/door opening routines, duration of activities, or the number of children attending on a given day or present in a particular room, other than to note that child attendance changed daily, and that the numbers of children in the main childcare room (preschool aged children) at any given time, was reasonably fluid.

Ethics considerations

All study activities were approved by the Curtin University Human Research Ethics Committee (HRE2019-0036). Written informed consent was obtained from the manager of each participating DCC prior to the commencement of data collection.

Statistical analysis

Descriptive statistics were used to summarise pollutant concentrations and measurements of ancillary variables, overall, and for both the winter and summer collections. In the case of skewed distributions of variables, natural logarithm transformation was carried out before performing parametric tests. Non-parametric methods were used if normality was not achieved for transformed variables. Wilcoxon signed ranks test was used to assess the seasonal differences in the centre IAQ. To understand whether the pollutant concentrations were at a level of health concern, mean values were compared with appropriate international air quality standards, guidelines, and good practice statements. Alternative relevant indicators were used where a guideline or best practice statement was not available.

Confirmation of the reported 'distance to a busy roadway' (taken from the questionnaire) was carried out by accessing traffic density mapping data through the Western Australian Department of Main Roads. Traffic volumes at major roads or freeways located within 100 m of each DCC (Lindgren et al. 2009; Skrzypek et al. 2013) were examined and a 'heavy traffic' category was assigned to roadways where > 10 cars travelled per minute, based upon annual 24-h mean levels (Department of Main Roads Western Australia 2023; Lindgren et al. 2009). Mean pollutant concentrations between heavy- and light-traffic locations were compared for significant differences by Mann–Whitney *U* test.

Data from fixed air quality monitoring sites for outdoor pollutants CO, NO_2, $PM_{2.5}$, and PM_{10} were obtained for the equivalent days of indoor monitoring from the Department of Water and Environmental Regulation (DWER) (Department of Water and Environmental Regulation 2022). Outdoor data was compared to DWER air quality indexes to determine the quality of outdoor air.

Statistical analysis was performed using SPSS (IBM SPSS Statistics for Windows, version 26.0. Armonk, NY: IBM Corp.), and the statistical significance level was set at 0.05.

Results

In this study, seasonal variations of a selection of indoor airborne contaminants, along with meteorological parameters including temperature and relative humidity, were examined in 22 DCCs located across the Perth metropolitan area.

The facility characteristics of participating DCCs were self-reported by centre managers and are presented in Table 1.

Nineteen centres (86%) were 10 or more years old, and all centres other than one were modified residential properties (vs fit-for-purpose buildings). All centres consisted of a series of connected rooms, and most used an integrated, reverse cycle air conditioning system to heat, cool, and/or ventilate (with fresh air) the centre ($n = 21$; 95%). In 91% ($n = 20$) of centres, managers reported ventilation to be 'very good' or 'good'. All 22 facilities reporting to opening doors (usually when children were playing outside) and/or windows daily for all or some part of the day, in both seasons. Although specific details were not collected on room density, other than at set education or napping times, it was noted that numbers of children in the main childcare room at any one time were reasonably fluid as they moved between indoor, outdoor, and bathroom spaces.

Fifteen centres (68%) reported to be located within 100 m of a busy roadway. All facilities had kitchens located within the core of the centre and prepared a cooked lunchtime meal for children. Fifteen centres (68%) used a gas appliance for cooking. Twenty facilities (91%) had linoleum/carpet mat flooring, and all reported to clean (vacuuming, sweeping, mopping) daily. Notably, all centres reported an increase in the frequency of cleaning during the summer monitoring period, coinciding with the COVID-19 pandemic.

Exposure characteristics

An overview of the indoor pollutant exposure levels and ancillary meteorological variables, by season and overall, showing summary statistics including mean and standard deviation, median, and interquartile range is presented in Table 2. Statistically significant seasonal differences were observed in the daily means of NO_2 and HCHO, with the highest exposures occurring in summer. Other than HCHO, CO, CO_2, and NO_2, all concentrations of pollutants were found to be higher in winter than in summer.

Outdoor air

Concentrations of outdoor CO, NO_2, $PM_{2.5}$, and PM_{10} were obtained for the equivalent days of indoor monitoring and were used to confirm that no unusual events (such as prescribed burn offs) contributed to indoor concentrations of pollutants. Table 3 provides a summary of the outdoor data descriptive statistics. When compared to the air quality index for Western Australia provided by the Department of Water and Environmental Regulation, outdoor concentrations of these pollutants are rated as 'good' (Department of Water and Environmental Regulation 2022).

Table 1 Characteristics of the 22 participating day-care centres (DCCs) in Perth

DCC ID	Age (years)	Busy road?	Industry?	Floor covering	Cooking appliances	Renovations?	A/C	Ventilation
1	< 10	Yes	No	C/L	Electric	No	Yes	VG/G
2	> 10	No	No	C/L	Gas	No	Yes	VG/G
3	> 10	No	No	C/L	Gas	No	Yes	VG/G
4	> 10	No	No	C/L	Gas	No	Yes	VG/G
5	> 10	Yes	No	C/L	Both	Yes	Yes	VG/G
6	> 10	Yes	Yes	C/L	Gas	No	Yes	VG/G
7	> 10	Yes	No	C/L	Gas	No	Yes	VG/G
8	< 10	Yes	No	C/L	Electric	No	Yes	VG/G
9	> 10	Yes	No	C/L	Gas	No	Yes	Poor
10	> 10	Yes	No	C/L	Electric	No	Yes	VG/G
11	> 10	Yes	No	C/L	Both	No	Yes	VG/G
12	> 10	Yes	No	C/L	Gas	No	Yes	VG/G
13	> 10	No	Yes	C/L	Electric	Yes	Yes	VG/G
14	> 10	No	No	C/L	Gas	No	Yes	VG/G
15	> 10	No	No	C/L	Electric	Yes	Yes	VG/G
16	> 10	Yes	No	C/L	Gas	Yes	Yes	VG/G
17	> 10	No	No	C/L	Both	Yes	Yes	VG/G
18	> 10	Yes	No	Wood	Gas	No	Yes	VG/G
19	< 10	Yes	No	Wood	Both	No	Yes	VG/G
20	> 10	Yes	No	C/L	Both	No	Yes	VG/G
21	> 10	Yes	No	C/L	Electric	No	No	VG/G
22	> 10	Yes	No	C/L	Electric	No	Yes	Poor

DCC ID day-care centre identification number; *Busy road?* 'Is the centre located within 100 m of a busy road?'; *Industry?* 'Is the centre located within 100 m of an industrial area?'; *C/L* carpet/linoleum; *Renovations?* 'Has the facility been painted, had new carpet put down, got new furniture or been renovated within the last 3 months?'; *A/C* air conditioning; *VG/G* very good or good

Comparisons with standards and guidelines

In Australia, guidelines have not been established for indoor pollutants; however, the WHO has recently published global air quality guidelines (including PM_{10} and $PM_{2.5}$, NO_2, and CO) which provide evidence-informed, non-binding recommendations for protecting public health from the adverse effects of air pollution exposure (World Health Organisation 2021). Importantly, these guidelines are applicable to both outdoor and indoor environments. Additionally, qualitative statements on best practice have been provided for other pollutants, including UFP, for which the available information is insufficient to formulate a guideline level, but which indicates a degree of health risk (World Health Organisation 2021). Where appropriate, these guidelines and best practice statements are used for the purposes of comparison in this study. Alternative relevant indicators are used where a WHO guideline or best practice statement is not offered.

Although no unified regulation exists for TVOCs, when compared to the Environmental Health Sourcebook general thresholds, the overall 24-h mean TVOC concentration of 951 ppb (SD: 1313 ppb) was shown to be in the upper range where symptoms of irritation and discomfort may develop in some adult individuals (between 120–1200 ppb) (Larsen 2010).

Of all seasonal observations ($n = 37$), only locations 1 and 3 recorded winter levels unlikely to cause symptoms (below 120 ppb), whilst location 5 recorded a winter TVOC concentration above 10 000 ppb. This is within the health risk range where comprehensive expressions of toxicity have been reported in adult populations (Larsen 2010) (Fig. 2).

The 24-h overall mean HCHO concentration was 22.2 μg/m^3 (SD: 5.5 μg/m^3), and all participating facilities had individual mean concentrations that were below Australia's 24-h ambient measure of 50 μg/m^3 (National Environment Protection Council 2004) (Fig. 3) and the WHO guideline for indoor air quality of 100 μg/m^3 (based on 30-min average concentration) (World Health Organisation 2010). Concentrations of HCHO were observed to be significantly higher in summer when compared to winter ($p = 0.017$) (Table 2).

The 24-h overall mean CO concentration was 2.1 ppm (SD: 3.4 ppm) which is below the WHO air quality guideline (AQG) of 3.4 ppm (converted from 4 mg/m^3). Four facilities (2%) recorded levels above this guideline in summer and one in winter (Fig. 4).

Table 2 Exposure distributions of all indoor pollutants and ancillary meteorological variables for summer and winter and with seasons combined (overall)

	Overall		Summer		Winter		
	Mean ± SD	Median (25–75% quartile)	Mean ± SD	Median (25–75% quartile)	Mean ± SD	Median (25–75% quartile)	*p*-value*
Gaseous pollutants							
TVOC (ppb)	951 ± 1313	431 (331 – 969)	891 ± 1214	514 (397 – 764)	1074 ± 2490	329 (132 – 597)	0.562
CO (ppm)	2.1 ± 3.4	1.0 (0.6 – 2.3)	3.3 ± 7.2	1.3 (0.2 – 3.2)	1.2 ± 1.6	0.8 (0.6 – 1.1)	0.404
CO_2 (ppm)	647 ± 256	579 (507 – 723)	633 ± 268	594 (494 – 746)	591 ± 205	546 (467 – 644)	0.495
NO_2 (ppm)	0.067 ± 0.054	0.055 (0.028 – 0.071)	0.084 ± 0.056	0.066 (0.045 – 0.117)	0.029 ± 0.027	0.021 (0.005 – 0.51)	**0.002**
HCHO (μg/m^3)	22.2 ± 5.5	21.0 (17.0 – 25.6)	22.4 ± 7.4	22.5 (18.6 – 27.5)	19.4 ± 3.7	19.0 (15.0 – 24.8)	**0.017**
Particulate matter							
TPM (μg/m^3)	21.6 ± 8.0	19.5 (14.9 – 29.5)	18.9 ± 11.2	15.0 (11.8 – 22.5)	24.3 ± 12.7	20.5 (15.8 – 28.3)	0.062
PM_{10} (μg/m^3)	17.7 ± 7.1	16.0 (12.0 – 21.1)	15.4 ± 9.0	12.0 (9.8 – 19.3)	20.0 ± 12.1	16. 0 (13.0 – 23.5)	0.120
PM_4 (μg/m^3)	14.5 ± 6.4	13.0 (10.4 – 17.6)	12.4 ± 7.5	9.5 (8.0 – 16.0)	16.6 ± 11.3	13.0 (10.0 – 19.3)	0.153
$PM_{2.5}$ (μg/m^3)	14.0 ± 6.3	12.3 (9.5 – 17.1)	12.0 ± 7.4	9.0 (7.0 – 15.3)	16.0 ± 11.2	12.9 (9.8 – 19 – 0)	0.199
PM_1 (μg/m^3)	13.4 ± 6.2	11.8 (8.9 – 16.4)	11.3 ± 7.1	9.0 (7.0 – 14.3)	15.5 ± 11.2	12.9 (9.0 – 18.0)	0.189
UFP (particles/cm^3)	8547 ± 8403	7406 (2551 – 9902)	6875 ± 5339	6009 (2162 – 10085)	14445 ± 12804	9133 (4435 – 25223)	0.844
Ancillary variables							
Temperature (°C)	24.2 ± 2.0	23.7 (22.9 – 25.0)	27.3 ± 2.5	27.3 (25.3 – 28.7)	21.1 ± 2.8	20.5 (19.0 – 22.5)	**< 0.001**
RH (%)	41.7 ± 5.1	41.5 (39.9 – 46.0)	41.2 ± 10.7	39.4 (32.8 – 50.1)	42.1 ± 9.2	43 (36.0 – 50.0)	0.702

*Differences between winter and summer were assessed by Wilcoxon signed ranks test with significant *p*-values < 0.05 bolded

n = 22; *SD* standard deviation; *TVOC* total volatile organic compounds; *ppb* parts per billion; *CO* carbon monoxide; *ppm* parts per million; CO_2 carbon dioxide; NO_2 nitrogen dioxide; *HCHO* formaldehyde; *μg/m^3* micrograms per cubic metre; *TPM* total particulate matter; *μg/m^3* micrograms per cubic metre; PM_{10} particulate matter with an aerodynamic diameter < 10 μg/m^3; PM_4 particulate matter with an aerodynamic diameter < 4 μg/m^3; $PM_{2.5}$ particulate matter with an aerodynamic diameter < 2.5 μg/m^3; PM_1 particulate matter with an aerodynamic diameter < 1 μg/m^3; *UFP* ultrafine particles with an aerodynamic diameter < 0.1 μg/m^3; *particles/cm^3* particles per cubic centimetre; *°C* degrees Celsius; *RH* relative humidity

Table 3 Outdoor air quality concentrations taken from fixed monitoring sites corresponding to days of indoor air quality monitoring

	Mean ± SD	AQI 'good'
CO (ppm)	0.290 ± 0.091	0 – 6
NO_2 (ppm)	0.008 ± 0.003	0 – 0.08
$PM_{2.5}$ (μg/m^3)	7.5 ± 1.8	0 – 25
PM_{10} (μg/m^3)	15.4 ± 4.5	0 – 50

CO carbon monoxide; *ppm* parts per million; NO_2 nitrogen dioxide; $PM_{2.5}$ particulate matter with an aerodynamic diameter < 2.5 μg/m^3; *μg/m^3* micrograms per cubic metre; PM_{10} particulate matter with an aerodynamic diameter < 10 μg/m^3; *AQI* air quality index ranked according to the Department of Water and Environmental Regulation (Department of Water and Environmental Regulation 2022)

The 24-h overall mean NO_2 concentration was 0.067 ppm (SD: 0.054 ppm), and concentrations were observed to be significantly higher in summer when compared to winter (p = 0.002) (Table 2). All DCCs, other than location 15, recorded NO_2 concentrations above the WHO AQG of 0.005 ppm (24-h averaged, converted from 10 μg/m^3) in summer, and 10 locations recorded NO_2 levels above the AQG in winter (World Health Organisation 2021). Of greatest concern was that most of the guideline breaches were of many magnitudes higher than the WHO AQ recommendation (Fig. 5).

In the absence of other significant indoor sources (e.g. fuel combustion), CO_2 is mainly produced by human respiration and can be used as an indicator of occupancy of a play area and fresh air or ventilation in buildings. No specific guideline has been developed for recommended levels of CO_2 in DCCs; however, ANSI/ASHRAE Standards 62.1 and 62.2 provide a reference level of 1000 ppm which corresponds to the estimated CO_2 concentration based on ventilation rates in buildings having a mechanical ventilation system. This is also the recognised standard for acceptable IAQ (and comfort) to minimise adverse health effects for occupants (ASHRAE 2013; St-Jean et al. 2012).

Overall and in both seasons, DCCs had mean concentrations below the 1000 ppm recommended guideline; however, there were breaches in two individual centres (DCC locations 19 and 21) which are shown in Fig. 6. When linked to

Fig. 2 Comparison of summer and winter mean indoor TVOC concentrations (ppb) for each individual DCC location, with the Environmental Health Sourcebook general thresholds (Larsen 2010)

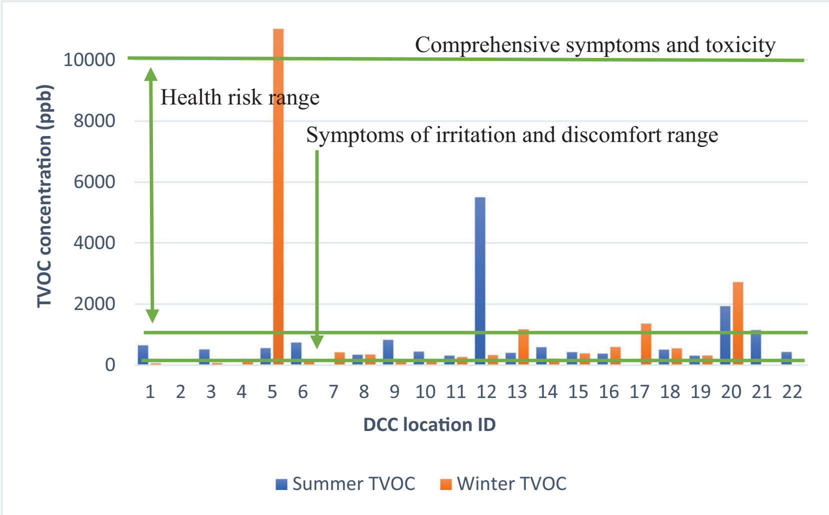


Fig. 3 Comparison of summer and winter mean indoor HCHO concentrations (μg/m^3) for each individual DCC location, with Australia's ambient air quality standard (National Environment Protection Council 2004)

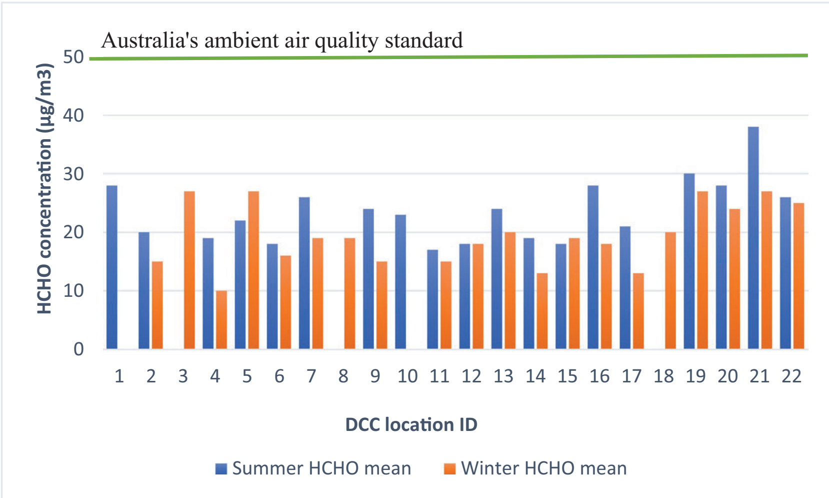
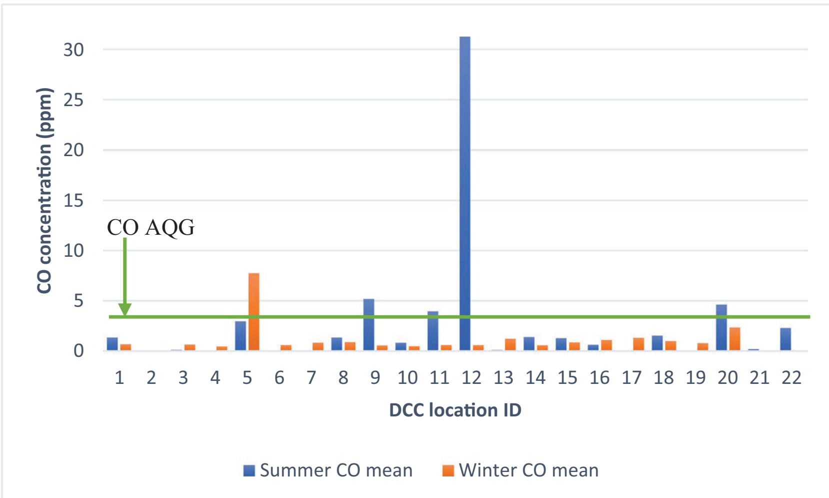


Fig. 4 Comparison of summer and winter mean indoor CO concentrations (ppm) for each individual DCC location, with the WHO AQG (World Health Organisation 2021)



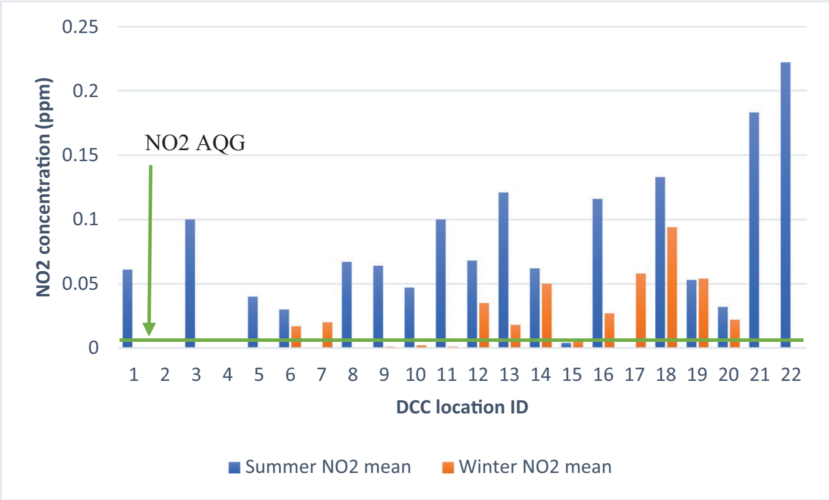


Fig. 5 Comparison of summer and winter mean indoor NO_2 concentrations (ppm) for each individual DCC location, with the WHO AQG (World Health Organisation 2021)

questionnaire responses related to ventilation, neither location reported to having 'poor' ventilation; however, location 21 stated there were no means of mechanical ventilation, such as air conditioning, in the centre.

In this study, the mean 24-h concentrations for PM_{10} and $PM_{2.5}$ were 17.7 μg/m^3 (SD: 7.1 μg/m^3) and 14.0 μg/m^3 (SD: 6.3 μg/m^3), respectively. Whilst the overall mean for DCCs for both PM_{10} and $PM_{2.5}$ was below the WHO short-term (24-h) AQG (PM_{10}: 45 μg/m^3; $PM_{2.5}$: 15 μg/m^3), two individual DCCs (9%) recorded a mean PM_{10} concentration above this guideline (47 μg/m^3 (summer) and 66 μg/m^3 (winter)) (Fig. 7). Similarly, for $PM_{2.5}$, seven DCCs (32%) recorded 24-h means above the WHO AQG in summer, and nine (41%) exceeded this in winter (Fig. 8).

The overall (8547 ± 8403 particles/cm^3) and summer (6875 ± 5339 particles/cm^3) mean for UFP were between the low (< 1000 particles/cm^3) and high (> 10 000 particles/cm^3) good practice statement guidelines provided by the WHO (World Health Organisation 2021). However, the winter mean (14445 ± 12804 particles/cm^3) for all DCCs was above the high PNC good practice statement guideline of > 10 000 particles/cm^3.

In this study, most individual DCCs ($n = 19$; 86%) recorded a mean UFP level above the WHO good practice guideline for low PNC in summer or winter or in both seasons. Furthermore, the high good practice guideline was exceeded by six DCCs (27%) for one or both seasons (Fig. 9).

Proximity to traffic-dense roadways

When concentrations of pollutants were stratified by proximity to a traffic-dense main road, all mean indoor pollutant concentrations were found to be higher in facilities located within 100 m of a busy road when compared to those DCCs located in less traffic-dense areas (< 100 m from a busy road) (Table 4). A significant difference was observed in CO_2 concentrations when the DCC was sited closer to a busy road when compared to those established in quieter traffic areas.

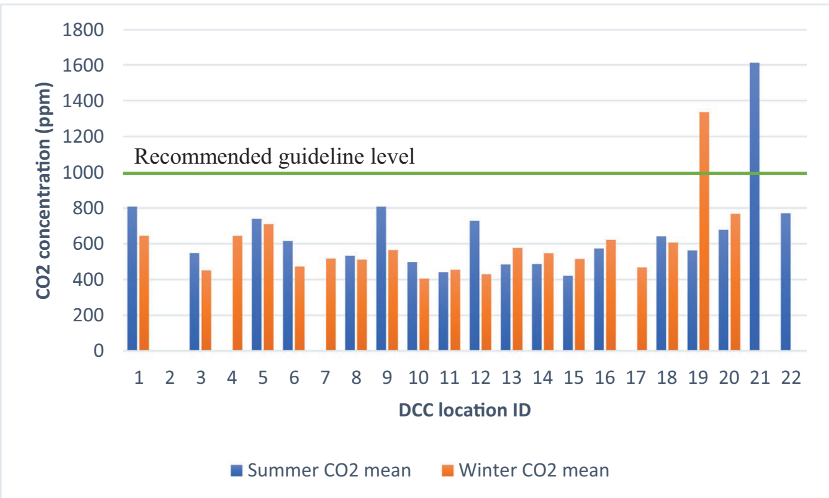


Fig. 6 Comparison of summer and winter mean indoor CO_2 concentrations (ppm) for each DCC location, with the ANSI/ASHRAE Standards 62.1 and 62.2 (ASHRAE 2013)

Fig. 7 Comparison of summer and winter mean indoor PM_{10} concentrations (μg/m^3) for each DCC location, with the WHO AQG (World Health Organisation 2021)

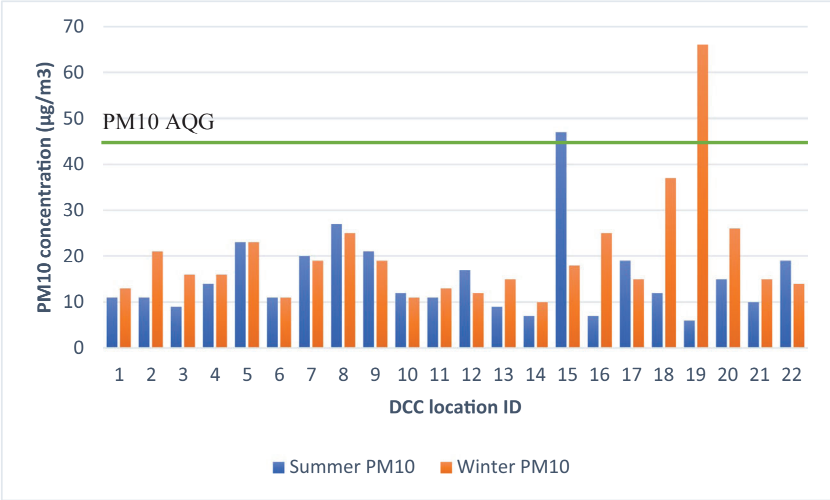


Fig. 8 Comparison of summer and winter mean indoor $PM_{2.5}$ concentrations (μg/m^3) for each DCC location, with the WHO AQG (World Health Organisation 2021)

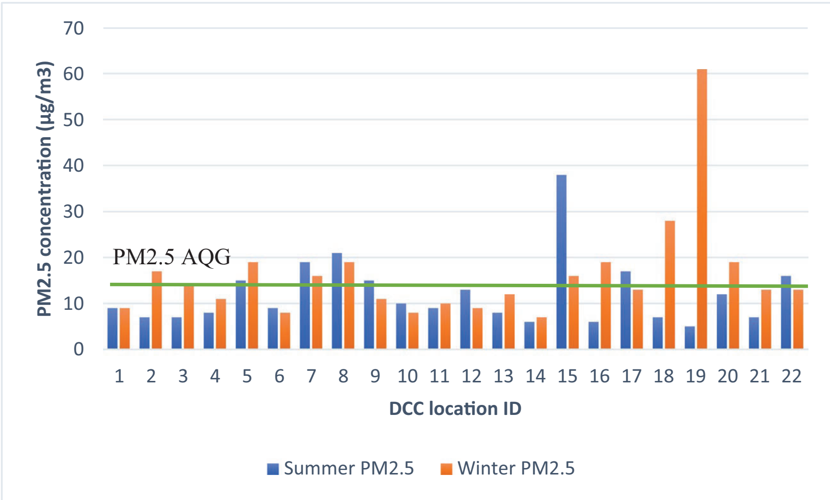
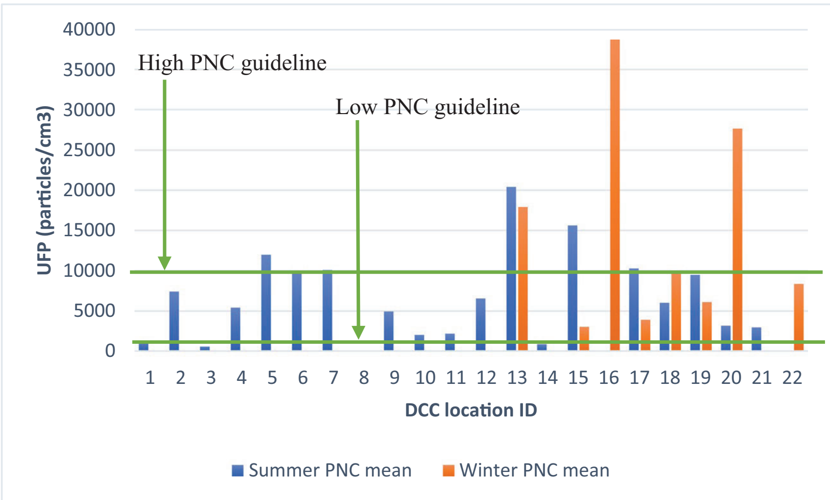


Fig. 9 Comparison of summer and winter mean indoor UFP concentrations (particles/cm^3) for each DCC location, with the WHO AQG (World Health Organisation 2021)



Discussion

This study investigated the indoor concentrations of airborne contaminants including a selection of gaseous pollutants and PM in six size fractions, in 22 randomly selected DCCs located in the Perth metropolitan area. As far as it is known, this study is the first to assess such a comprehensive panel of indoor pollutants in Western Australian DCCs over two seasons, whilst also considering their proximity to busy roadways and other building characteristics which may contribute to poor IAQ and thus trigger adverse health effects in children attending these facilities.

Despite that research has demonstrated the vulnerability of infants and young children's exposure to harmful airborne contaminants, applicable environmental air quality standards developed to protect the health of populations appear to be universally non-existent for childcare settings. Specific IAQ standards and guidelines exist in a minority of countries, although the WHO has recently published updated global air quality guidelines for selected pollutants, applicable for both indoor and outdoor settings (World Health Organisation 2021). In Australia, no standards or regulatory guidelines exist for acceptable pollutant concentrations within indoor environments, although some non-mandatory advice and guidance is provided by the Australian Building Codes Board with respect to workplace settings, commercial premises, and public buildings (Commonwealth of Australia and States and Territories 2021).

In this study, we found there were numerous instances where the concentrations of some hazardous indoor air pollutants in DCCs exceeded current standards, guidelines, and best practice statements developed by the WHO and other relevant agencies to protect adult human health.

TVOCs are ubiquitous in indoor environments and can be hazardous to health in a variety of ways. The term TVOC covers a broad range of individual subspecies of VOC, with TVOC concentration being the aggregation of all volatile components, without distinguishing between individual chemicals (Domínguez-amarillo et al. 2020). In DCCs, sources of TVOCs (including HCHO) include the use of glues and paints during typical children's activities, composite and pressed wood furniture materials (including off-gassing of these materials), carpets and carpet glues, building materials and furnishings, cleaning products, furniture fabrics, and personal care products (Bradman et al. 2012; Carreiro-Martins et al. 2016). All these items and products are common within childcare settings and can result in higher concentrations (Seltenrich 2013). Also contributing to the issue is that licencing guidelines and quality rating systems — which frequently emphasise infection control and cleanliness — can direct centres towards using economically favourable and potentially harmful substances such as bleach and other toxic cleaning agents (such as sanitisers and disinfectants) which add to the TVOC burden and are recognised as triggers for asthma (Franklin 2007; Paciência et al. 2016; Rumchev et al. 2004). Additionally, some VOC species such as terpenes (e.g. *d*-limonene) which are frequently used in cleaning products may also react with ozone to produce hazardous secondary pollutants such as HCHO and UFP (Australian Government 2021; Hoang et al. 2017; Morawska et al. 2013; United States Environmental Protection Agency 2022b).

Table 4 Comparison of mean indoor pollutant concentrations between DCCs, dependent on their proximity to a busy road way

	Pollutant concentration (± SD)		
	Centre located < 100 m of a busy road (n = 15)	Centre located > 100 m of a busy road (n = 7)	p-value*
TVOC (ppb)	1106 ± 1517	564 ± 448	0.47
CO (ppm)	2.6 ± 4.0	0.8 ± 0.4	0.30
CO_2 (ppm)	697 ± 287	520 ± 66	**0.05**
NO_2 (ppm)	0.069 ± 0.060	0.058 ± 0.030	0.80
HCHO (μg/m^3)	22.2 ± 5.8	18.9 ± 4.3	0.12
TPM (μg/m^3)	22.4 ± 7.8	19.9 ± 8.9	0.50
PM_{10} (μg/m^3)	18.4 ± 7.0	16.2 ± 7.7	0.48
PM_4 (μg/m^3)	15.0 ± 6.4	13.4 ± 6.7	0.52
$PM_{2.5}$ (μg/m^3)	14.5 ± 6.3	12.9 ± 6.7	0.48
PM_1 (μg/m^3)	13.8 ± 6.2	12.4 ± 6.6	0.52
UFP (particles/cm^3)	9267 ± 9428	7106 ± 6257	0.48

*Determined by Mann–Whitney U test; p-values < 0.05 bolded; *TVOC* total volatile organic compounds; *ppb* parts per billion; *CO* carbon monoxide; *ppm* parts per million; CO_2 carbon dioxide; NO_2 nitrogen dioxide; *HCHO* formaldehyde; *μg/m^3* micrograms per cubic metre; *TPM* total particulate matter; *μg/m^3* micrograms per cubic metre; PM_{10} particulate matter with an aerodynamic diameter < 10 μg/m^3; PM_4 particulate matter with an aerodynamic diameter < 4 μg/m^3; $PM_{2.5}$ particulate matter with an aerodynamic diameter < 2.5 μg/m^3; PM_1 particulate matter with an aerodynamic diameter < 1 μg/m^3; *UFP* ultrafine particles with an aerodynamic diameter < 0.1 μg/m^3; *particles/cm^3* particles per cubic centimetre

In general, exposure to VOCs in children represents a risk of irritation to the eyes, nose, and throat, headaches, nausea, and damage to the liver and kidneys as well as some neurological symptoms (Annesi-Maesano et al. 2013; Demirel et al. 2014; Le Cann et al. 2011; Paciência et al. 2016; United States Environmental Protection Agency 2022b; World Health Organisation 2010). Additionally, exposure can increase the risk and severity of asthma, rhinitis, eczema, and airway inflammation (Annesi-Maesano et al. 2013; Franklin 2007; Lee et al. 2014; McGwin et al. 2010; Paciência et al. 2016; Rumchev et al. 2004). Although no unified regulation exists for exposure to TVOCs, some general thresholds can be assumed as a result of physiological responses of and disturbances to individuals (Larsen 2010). In the range of 120–1200 ppb, symptoms of irritation and discomfort may appear in some adult individuals, with comprehensive manifestations and toxicity developing from 10,000 ppb dependent on the sensitivity of the individual. As a reference, > 1200 ppb is considered within a health risk range, with intermediate figures assumed as acceptable, but not risk-free in adult populations (Larsen 2010). It is presumed that infants and young children will be more vulnerable to TVOC exposure due to their higher susceptibility (Sly and Flack 2008).

In this study, the overall concentration of TVOCs (951 ± 1313 ppb) was at the upper range where symptoms of exposure may be observed. Four individual facilities (18%) recorded a summer or winter mean > 1200 ppb which whilst considered acceptable still indicates a health risk environment. Numerous centres recorded concentrations reported to cause irritation and discomfort (between 120 and 1200 ppb), and one centre recorded a 24-h mean winter concentration above 10,000 ppb, which is in the range where major displays and toxicity have been reported in some adult individuals, dependent on their sensitivity (Larsen 2010). Notably also was that the overall, summer, and winter mean concentrations were higher than that recorded in a sample of 111 domestic residences located in Perth, Western Australia, using the same measurement protocol, and where adverse associations with subclinical measures of cardiovascular risk were reported in a healthy adult population (Gilbey et al. 2022a).

In a further study, Carreiro-Martins et al. (2016) examined the estimated predisposition for asthma and actual wheezing susceptibility in children with the relationship to IAQ in DCCs. These authors found that exposure to TVOCs (and CO_2) was associated with wheezing and other respiratory symptoms (Carreiro-Martins et al. 2016). Although the observed concentrations in the current study were low, it is noted that exposure to VOCs even at low concentrations may constitute a significant health risk for some respiratory conditions (Carreiro-Martins et al. 2016; Viegi et al. 2004), particularly in vulnerable populations.

In the current study, it was also observed that the mean concentrations of TVOCs in facilities located closer to busy roadways were twice the magnitude of those located in quieter areas, although this relationship was not statistically significant.

HCHO is a pervasive environmental pollutant however, in childcare centres, will have origins in glues, paints, adhesives, building materials, furniture, and wooden products including off-gassing from original building materials or furnishings, electronic equipment (computers, photocopiers), cleaning products (disinfectants, liquid soaps), and other consumer items such as insecticides and paper products (Bradman et al. 2017; Commonwealth of Australia and States and Territories 2021; World Health Organisation 2010). HCHO is a VOC that has well-established links to irritations of the eye, nose, throat, and lower respiratory tract, inflammatory responses in the airways, allergies, and asthma (Commonwealth of Australia and States and Territories 2021; Franklin et al. 2000; Rumchev et al. 2002; World Health Organisation 2010) and is also considered to cause cancer in humans (IARC 2006).

In the current study, overall (22.2 ± 5.5 μg/m^3), summer (22.4 ± 7.4 μg/m^3), and winter (19.4 ± 3.7 μg/m^3) 24-h mean HCHO concentrations were below the WHO guideline for indoor air quality of 100 μg/m^3 (based on 30-min average concentration) (World Health Organisation 2010) and Australia's ambient air quality standard of 50 μg/m^3. HCHO concentrations observed in the present study were also consistent with levels measured in 21 DCCs located in Montreal, Canada (22.9 ± 8.2 μg/m^3) (St-Jean et al. 2012). In similar studies, Ruotsalainen et al. (1993) reported lower levels (15 ± 8 μg/m^3) in 30 Finnish DCCs although higher concentrations were measured in a study of 289 DCC located in Seoul, South Korea (40.6 ± 19.6 μg/m^3) (Hwang et al. 2017). The presence of mechanical ventilation in most centres may have contributed to lower concentrations of HCHO in the present study. This is consistent with the conclusions of St-Jean et al. (2012) who reported that the presence of a mechanical ventilation system was significantly correlated with lower HCHO levels (St-Jean et al. 2012). In a further study investigating the risk of asthma and respiratory effects of domestic HCHO exposure in young children aged between 6 months and 3 years, elevated concentrations of HCHO were associated with respiratory effects including wheeze (40.5 μg/m^3) and other symptoms related to asthma including runny nose (32.5 μg/m^3) and hay fever (32.7 μg/m^3). Asymptomatic children were found to be exposed to HCHO concentrations ≤ 26.8 μg/m^3 (Rumchev et al. 2002).

Nitrogen dioxide has well-established indoor sources including gas appliances, space, and water heaters (Demirel et al. 2014; World Health Organisation 2010) with contributions from infiltrating outdoor air sources including road traffic exhaust (including from carparks attached to the facility) and other fossil fuel combustion processes (Commonwealth of Australia and States and Territories 2021; World Health Organisation 2010). NO_2 can cause headaches and irritation to the eyes, nose, and throat and can cause decreased lung function, asthma, and other respiratory problems in children (Chen et al. 2022; Commonwealth of Australia and States and Territories 2021; Gaffin et al. 2018; World Health Organisation 2010). It has also been associated with autism spectrum disorder with prenatal traffic-related exposure (Flores-Pajot et al. 2016). In this study, the 24-h mean overall (0.067 ± 0.054 ppm), summer (0.084 ± 0.056 ppm), and winter (0.029 ± 0.027 ppm) concentrations of NO_2 were all above the WHO AQG of 0.005 ppm. Furthermore, of 32 valid samples collected from individual DCCs during summer and winter, 88% ($n = 28$) were greater than the AQG developed to protect human health. When compared to the Australian Child Health and Air Pollution Study examining outdoor NO_2 and children's respiratory health, an association was observed between relatively low levels of NO_2 exposure (0.0088 ± 0.0032 ppm), with current asthma and reduced lung function in a population-based sample of Australian children (Knibbs et al. 2018). Gaffin and colleagues investigating NO_2 exposure in school classrooms with respiratory health effects in American asthmatic children found signals of lung function impairment, and a trend towards more symptoms was found to be associated with lower NO_2 levels (mean: 0.0111 ppm; range: 0.0043–0.0297 ppm) than the current study, albeit in a particularly vulnerable paediatric population (Gaffin et al. 2018).

Particulate matter of all size fractions is recognisably one of the most relevant pollutants associated with significant health effects in children including asthma exacerbation; irritation of the eyes, nose, throat, and respiratory tract; allergic rhinitis; difficulty breathing; other upper and lower respiratory diseases including bronchitis; and a risk of lung cancer (Annesi-Maesano et al. 2013; Bradman et al. 2012; Commonwealth of Australia and States and Territories 2021; HEI Review Panel on Ultrafine Particles 2013; Kim et al. 2015; World Health Organisation 2022).

Indoor concentrations of PM can be airborne solid or liquid particles that are made up of many components including acids (such as nitrates and sulphates), organic and industrial chemicals, biological material, metals, and soil or dust particles (Bradman et al. 2012; Gaspar et al. 2018; United States Environmental Protection Agency 2022a). Their aerodynamic size can vary widely although most hazardous to health is consistently understood to include the fine inhalable fraction sized 2.5 μm or less (including UFP), due to their ability of being able to penetrate peripheral airways and translocate to the circulatory system (Commonwealth of Australia and States and Territories 2021; HEI Review Panel on Ultrafine Particles 2013; Tecer et al. 2008; World Health Organisation 2021). Sources of indoor PM in DCCs predominantly originate from the resuspension of indoor dusts such as soil particles, cloth fibres, and building material deterioration brought inside directly by children on their clothes and shoes and by their movement and activities. Other sources include cooking and cleaning processes (sweeping and other motions) (Domínguez-amarillo et al. 2020; Morawska et al. 2017; Oliveira et al. 2017). The health effects of exposure to PM are mostly related to their size and include asthma exacerbation, difficulty breathing, decreases in lung function, allergen sensitisation, allergic rhinitis, bronchitis (Bradman et al. 2012; Buonanno et al. 2013a, b; Tecer et al. 2008), and systemic inflammation in children (Clifford et al. 2018).

The WHO has recently further acknowledged the hazard of exposure to particles by releasing updated AQG for short-term (24-h) exposure to PM_{10} (45 μg/m^3) and $PM_{2.5}$ (15 μg/m^3) and a good practice statement (GPS) for high- (10 000 particles/cm^3) and low-level (1000 particles/cm^3) UFP exposure (World Health Organisation 2021). GPSs indicate there is insufficient data available to provide recommendations for an AQG; however, due to health concerns related to these pollutants, further research on their risks and approaches for improvement are necessary, and the application of a GPS is justified.

In this current study, two locations recorded concentrations above the WHO AQG for PM_{10}, and numerous breaches to the AQG were observed in both summer and winter for $PM_{2.5}$. Additionally, the overall mean concentration for UFP (8547 ± 8403 particles/m^3) was between, albeit on the upper range, of the low- and high-level GPS for this size fraction. Individually, all centres other than two locations in summer (excluding missing data) recorded UFP concentrations below the WHO GPS recommendation for low PNC of < 1000 particles/m^3. Of greater concern is that 30% of samples surpassed the high PNC guideline of 10,000 particles/m^3 with several further samples ($n = 3$) recording levels above 9000 particles/m^3. Based on the current evidence, this represents a significant health risk to infants and young children attending these facilities (World Health Organisation 2021).

Despite this, when compared to a Californian study of 40 childcare facilities, the current study recorded overall mean concentrations of PM_{10} (17.7 ± 7.1 μg/m^3), $PM_{2.5}$ (14.0 ± 6.3 μg/m^3), and UFP (8547 ± 8403 particles/cm^3) that were lower than the equivalent means in a study by Gaspar and colleagues (PM_{10}: 40 ± 27 μg/m^3; $PM_{2.5}$: 24 ± 28 μg/m^3; UFP: 17 000 ± 11 000 particles/cm^3). These authors concluded that children were receiving co-exposures to various sizes and compositions of particles, putting them at increased risk of health effects of early life particulate exposure (Gaspar et al. 2018).

The overall UFP concentration in the current study is also lower than those observed in 28 Californian centre-based facilities (11.997 particles/cm^3) (Bradman et al. 2012) and three Portuguese preschools (3–5-year-old children) assessing UFP number concentrations (11,500–18,200 particles/cm^3) (Fonseca et al. 2014). However, our winter mean (14,445 ± 12,804 particles/cm^3) was at the upper range when compared to other studies measuring UFP numbers (Bradman et al. 2012; Fonseca et al. 2014) and above the WHO GPS recommended high-level PNC. Notably, this PNC is also above the concentration reported by Gilbey et al. (2022b) (11,256 ± 8744 particles/cm^3), where adverse associations were demonstrated with selected subclinical haemodynamic markers of cardiovascular risk, in a population of healthy adults (Gilbey et al. 2022b).

Cooking emissions are an established source of UFP (Bradman et al. 2012; Buonanno et al. 2013a, b; Gaspar et al. 2018), and all centres in this present study cooked at least one daily hot meal for the children. All centres also consisted of contiguous rooms including the kitchen, which may have enabled easy penetration of cooking emissions. This can contribute to higher UFP numbers, particularly when combined with rooms made more 'airtight' to retain the thermal heat within the facility during the cooler months.

Ventilation and CO_2 levels

Ventilation has a significant influence on indoor pollutant levels and consequently on indoor exposure.

The measurement of CO_2 to evaluate ventilation in rooms has become a standard tool, suggested by ASHRAE Standard 62 as an indicator of IAQ and as a measure of the effectiveness of ventilation and renewal capacity of the indoor atmosphere (Bartlett et al. 2004; Domínguez-amarillo et al. 2020; Seppänen and Fisk 2004). CO_2 is therefore not considered a major indoor air pollutant; however, high levels (above 1000 ppm) are commonly used as an indicator of poor ventilation and the presence and possible accumulation of other harmful pollutants (Bekö et al. 2010; Domínguez-amarillo et al. 2020; Ruotsalainen et al. 1993). The main emission sources are the occupants of the indoor environments, although the frequent use of combustion equipment such as gas stoves, and potentially, the proximity to busy roadways, should be considered (Domínguez-amarillo et al. 2020). CO_2 at higher concentrations (than seen in the current study) can increase the risk of headaches, depression, and respiratory conditions such as asthma and wheezing (Carreiro-Martins et al. 2016).

In this present study, the overall, summer, and winter average CO_2 concentration measured in facilities ranged from 633 to 591 ppm with no statistically significant differences between summer and winter measured periods. Higher concentrations of CO_2 were observed in those DCCs located close to traffic-dense roadways when compared to those in quieter locations ($p = 0.011$). Higher levels measured in the warmer season may reflect restricted ventilation due to more frequently closed windows and doors, noting that 91% of all studied facilities reported using air conditioning (Table 2).

The individual CO_2 profiles of all DCCs shown in Fig. 6 indicate an acceptable air renewal situation, except for location 19 (winter) and location 21 in summer. Location 19 was noted to be the youngest of all the observed DCCs, and the relatively recent construction may have resulted in an 'airtight' building that when closed during colder winter days also resulted in limited air renewal of the indoor environment (St-Jean et al. 2012). In comparison, location 21 was an older, non-purpose-built facility consisting of an array of interconnected rooms. Potentially poor ventilation in the absence of any type of mechanical ventilation, a geographically inland location (lacking the usual daily afternoon breeze) and a facility design which limited the opportunity for cross-ventilation, might have contributed to higher concentrations of CO_2 observed in the summer collection. Furthermore, these results could be attributed to the activities of the children, including running indoors, which increases breathing and subsequently CO_2 concentrations (Oliveira et al. 2019; Quirós-Alcalá et al. 2016; United States Environmental Protection Agency 2022a; World Health Organisation 2021, 2022).

Relationship to busy streets

Traffic is one of the most important sources of air pollution in DCCs, and the literature provides evidence of a relationship between traffic-related air pollution with adverse health effects including asthma, rhinitis, and eczema, cardiovascular disease, and autism (Hoek et al. 2013; McConnell et al. 2010; Volk et al. 2013). In the present study, DCCs were open only on weekdays, during daytime hours. This is the most likely time for traffic flow to be high, contributing to increased concentrations of traffic-related air pollutants and thus high traffic pollution exposures for children attending these facilities. This is particularly applicable for those reporting to be located closer to busy roadways.

Using traffic density mapping accessed through the Department of Main Roads, DCCs were stratified into those that were in heavy traffic versus quiet traffic areas (> 10 cars per minute, based upon annual 24-h mean levels) (Department of Main Roads Western Australia 2023; Lindgren et al. 2009). Concentrations of all pollutants were observed to be higher in DCCs located near heavy traffic areas compared to those that were not, although only CO and CO_2 concentrations were statistically significant. This suggests that children who attend DCCs closer to busy roadways may be considered as vulnerable for adverse health outcomes related to traffic-related air pollution exposures.

Study limitations

The sample size of the current study was relatively small which might have limited the statistical power. Additionally, and common to several similar studies involving childcare facilities, participation rates were low and selection bias cannot be ruled out (Bradman et al. 2012, 2017; Gaspar et al. 2018; St-Jean et al. 2012). Reasons for a lack of interest to participate in this study may be associated with known air quality issues in the centre. In general, centre managers of enrolled DCCs were interested in environmental risks to children's health and may have actively employed strategies to mitigate the pollutant sources. Although the findings of this present study are plausible, they more realistically represent a broad cross-section of facilities providing childcare in the Perth metropolitan area.

Second, whilst the study observed several breaches to guidelines for individual pollutants, the guidelines and study observations do not address pollutant mixtures or the combined effects of pollutant exposures. In everyday life, people and children in DCCs are exposed to a mixture of air pollutants that vary in time and space. To fully understand the health risk implications for children presented by the IAQ observations in this study, comprehensive models are required to quantify the effects of multiple exposures on children's health. Despite this, as the main body of evidence on air quality and human health still focuses on the impact of single markers on the risk of adverse health outcomes, as a basic mitigation strategy, achievement of the recommended standards, guidelines, or good practice recommendations is necessary to minimise the health risk of air pollution exposure.

Finally, the study did not measure biological agents in the DCC air quality. Airborne bacteria and fungi are a well-known source of illness and infectious disease in DCC however have been well reported in other studies (Harbizadeh et al. 2019; Madureira et al. 2016).

Conclusion

This study found that in some centres, indoor pollutant concentrations of TVOC, CO, NO_2, CO_2, PM_{10}, $PM_{2.5}$, and UFP were above-established contemporary guidelines, standards, and best practice statements designed to protect human health. These findings highlight an important public health issue particularly as more parents and primary carers are returning to the workplace, and greater numbers of children are spending time in extended day-care.

In Australia, and in the context of a healthy indoor environment, there are no laws or licencing requirements designed specifically to protect the health of children in childcare centres under National Law or the National Quality Framework provided by the Australian Children's Education and Care Quality Authority. In WA, and most other states and territories, under the Education and Care Services National Regulations (2012), some provision is made for ventilation and natural light in indoor spaces with the legislation simply stating for centres to be 'well ventilated' and having 'adequate natural light' (Education and Care Services National Regulations 2012). However, this is the limit of consideration for the protection of 'children's health and safety' (Part 4.2) and the 'physical environment' (Part 4.3) within Australian child day-care facilities (Education and Care Services National Regulations 2012).

Given the overriding interest in providing safe and healthy environments for young children, additional research is required to identify strategies to reduce indoor sources of PM and gaseous pollutants. This information will be important for directed education and efforts to successfully improve the environmental and public health of young children receiving care in Western Australia's day-care facilities (Bradman et al. 2012).

In terms of controlling exposure, there are various options for reducing indoor air contaminants in DCCs. Source control is the universally preferred approach (Kelly and Fussell 2019) with strategies including attention to the selection of building materials, furnishings, craft materials and cleaning products, improvements to ventilation rates especially for new or newly renovated DCCs, and attentive siting of centres away from traffic-dense areas.

City planning and licencing criteria for DCCs should be reassessed to avoid air pollution burdens to infants and young children's attending childcare centres. It is acknowledged that criteria for DCC siting can be a contentious issue, and frequently centres are located due to convenience of access, economics, or availability of a site. Whilst it is difficult to understand the regulatory body's influence or role in this regard, it may be possible for intervention if child health is jeopardised. DCCs should be constructed and licenced away from trafficked roads and fitted out with materials, paints, and furniture with low emission VOC profiles (Hoang et al. 2017; Rivas et al. 2018; Walter et al. 2019). Greater attention is required to improve facility ventilation (natural and/or mechanical) with potential consideration for the use of an automated system (based on air quality sensor data) to determine window/door opening. Where traffic cannot be controlled, attention should be given to installing effective air filtration devices to improve IAQ especially at centres located closer to busy traffic ways, industrial areas, and other sources of outdoor pollutants, which are capable of infiltrating indoor environments (Oliveira et al. 2019; Sahin et al. 2022). Whilst increased cleaning activities may reduce PM resuspension, often cleaning products contain ingredients which can react to form new particles (in the range of UFP and VOC) and as such cleaning works are recommended when the centre closes to avoid infants and young children being exposed to additional concentrations of UFP and other pollutants. Alternatively, low reactive cleaning products could be selected including the use of 'green' cleaning options such as vinegar and baking soda (Hoang et al. 2017; Rivas et al. 2018). Increasing green and pedestrian spaces located closer to the facility would effectively reduce the number of cars using the area and would also result in lower levels of pollution (Rivas et al. 2018). However, intervention studies to evaluate the effectiveness of these recommended preventative measures also need to be implemented.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11869-023-01445-7.

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Author contribution S.E.G., Y.Z., A.L., and K.B.R. contributed to the study conception and design. S.E.G. and Y.Z. did the statistical analysis. The first draft of the manuscript was written by S.E.G. S.E.G., Y.Z., A.L., and K.B.R. read and approved the final manuscript.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethics approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Human Research Ethics Committee of Curtin University (HRE2019-0036).

Consent to participate All participants declared their written consent to participate in this study.

Conflict of interest The authors declare no competing interests.

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