Volatile organic compounds within indoor environments in Australia

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Abstract

Volatile organic compounds (VOCs) are pervasive indoor air pollutants. This paper systematically evaluates 25 years (1991–2016) of investigations of VOCs within indoor environments in Australia. Among 31 papers evaluated, the most frequently studied environment was domestic housing (61%), and the most frequently quantified compound was formaldehyde (81%). Active sampling techniques were used in 82% of studies of benzene, toluene, ethylbenzene, and xylene (BTEX), and in 38% of studies of formaldehyde and other carbonyls. New homes had the highest VOC levels among all studies of domestic housing. For nearly all pollutants, indoor levels were several times higher than outdoor levels. Among the most prevalent compounds indoors were terpenes, such as d-limonene and α-pinene. All studies were conducted at a regional or local level, and no study reported statistically representative indoor VOC data for the Australian population. The evaluation revealed a diversity of sampling approaches and techniques, pointing to the importance of a standard approach for collecting and reporting data.

Keywords

volatile organic compounds, indoor air quality, formaldehyde, BTEX, terpenes

Introduction

Australians spend over 90% of their time indoors in locations such as houses, apartments, caravans, schools, offices, public buildings, restaurants, and forms of transport (Australian Government, 2016). However, relatively little is known about the quality of air in these environments (Brown, 1997). In contrast to ambient air, indoor air is essentially unregulated and unmonitored, even though pollutant levels are usually several times higher indoors than outdoors (Brown et al., 1994; Galbally et al., 2009; Molloy et al., 2012; Cheng et al., 2016).

Volatile organic compounds (VOCs) are a main category of indoor pollutants (Environment Australia, 2001). VOCs can be considered as carbon-based chemicals with a relatively high vapor pressure at room temperature; i.e., greater than 0.01 kPa at 20°C (NPI, 2009). Major indoor sources of VOCs include consumer products and building materials (Brown, 2002; Wallace et al., 1991; Wheeler et al., 2013; Trantallidi et al., 2015; Campagnolo et al., 2017). Fragranced consumer products, for instance, emit numerous VOCs such as terpenes (e.g., limonene and α-pinene) which can generate secondary pollutants such as formaldehyde (Nazaroff and Weschler, 2004; Steinemann, 2015). Building materials such as engineered wood products, carpets, and paints can be substantial sources of indoor VOCs including benzene, toluene and formaldehyde (Brown, 2000; Guo and Murray, 2000; Guo et al., 2004). Concentrations are especially high in recently renovated, tightly sealed, or energy efficient buildings (Brown, 2001).

Indoor air quality (IAQ) refers to the air quality within buildings and structures that affect an occupant's comfort, health and well-being (US EPA, 2016; Wesolowski, 1987). In Australia, poor IAQ has been estimated to cost $12 billion per year from lost productivity and illness (Brown, 1998). Many VOCs frequently detected in indoor environments are associated with acute and chronic adverse health effects, such as sensory and skin irritation, headaches, breathing difficulties, asthma risk, and cancer (e,g., Mendell, 2007; Rumchev et al., 2004; Spengler et al. 2000). Australian research has shown that exposure to benzene, toluene, or formaldehyde can exacerbate asthma and respiratory problems (Franklin et al., 2000; Rumchev et al., 2002, Rumchev et al., 2004; Zhang et al., 2004). Approximately 10% of the Australian population suffers from asthma (over 2 million people), and collectively respiratory diseases accounted for approximately $3.3 billion (6%) of allocated health expenditure in 2008-2009 (Asthma Australia, 2015; ABS, 2012).

For indoor air, regulatory guidelines for acceptable VOC concentrations within indoor environments do not currently exist in Australia. Although national indoor air quality guidelines were recommended by the Australian National Health and Medical Research Council (NHMRC) in 1992, they were rescinded in 2002 (NHMRC, 2016). However, the NHMRC guidelines continue to be used discretionally by researchers, along with international guidelines (see Table 1). For outdoor air, the National Environmental Protection Measure (NEPM) sets legally binding national standards for ambient (outdoor) air pollutants, including the "air toxics" of formaldehyde, toluene, benzene, xylenes, and polycyclic aromatic hydrocarbons (NEPM, 2004; Australian Government, 2011).

Despite over two decades of VOC studies, there has been no published systematic evaluation of the peer-reviewed research of VOCs within indoor environments in Australia. This article addresses that gap. It examines and evaluates the sampling approaches, analytical techniques, and VOC data from indoor environments. It also compares results with health-based guidelines, where possible, and among studies that report similar sampling methods. The prevalence and concentrations of formaldehyde and BTEX compounds are a focus due to their classification as air toxics (Australian Government, 2011). Finally, the paper offers lessons and recommendations that can help improve indoor air quality studies in Australia and internationally.

Methods

A comprehensive literature search was conducted to identify any studies of VOCs within indoor environments in Australia from 1991-2016. Original research papers published in English language academic journals were obtained by searching electronic databases including Compendex, ProQuest, Web of Knowledge, and Scopus. The keywords used in these searches were: 'indoor air pollution' or 'indoor air quality' and a combination of 'VOC*', 'hazardous air pollutant*', 'carbonyl*', 'formaldehyde', 'BTEX', 'health', 'asthma', 'respir*'. The results were refined to identify authors and studies from Australia.

To be included in the evaluation, a study needed to (i) provide experimental data from sampling and analysis of VOCs from an indoor environment in Australia, (ii) report on an indoor environment that was non-industrial, and (iii) be published as a peer-reviewed journal article, book chapter, or official government report. For each study, results and data were evaluated according to the following 13 factors:

- (i) State or territory
- (ii) Year and focus of study
- (iii) Type of indoor environment
- (iv) Building operational status
- (v) Sampling methods
- (vi) Sampling duration
- (vii) Number of air samples

(viii) Analytical methods

(ix) Number and type of VOCs

(x) Concentration of compounds

(xi) Comparison of studies

(xii) Indoor to outdoor concentration ratios

(xiii) Seasonal variation

Within each study, data were categorised by the type of indoor environment. If a single study reported on multiple indoor environments (e.g., caravans, mobile houses, and conventional housing), each was considered a unique indoor environment. If an indoor environment (e.g., housing) reported on sampling in multiple locations (e.g., bedroom, kitchen, and living room), each location was considered to represent that environment. Because carbonyl compounds (e.g., formaldehyde) require different sampling and analytical approaches from other VOCs (e.g., BTEX), each approach was reported separately. If two journal articles referred to the same data, only the original reference was included in the analysis.

To summarize and compare VOC concentration data, a standard unit of $\mu g/m^3$ was chosen. Where parts per billion by volume (ppbv) or parts per billion (ppb) were reported, these were converted to $\mu g/m^3$. For conversion from ppb to $\mu g/m^3$, a standard formula was used: $\mu g/m^3 = (ppb) \times (MW) / (24.45)$, where MW is the molecular weight of the compound. For example, formaldehyde at 1 ppb = 1.23 $\mu g/m^3$. When total VOCs (TVOCs) were reported in ppb, the units were unchanged as conversion to $\mu g/m^3$ requires MW. Also, because the units of $\mu g/m^3$ are dependent on MW, temperature and pressure data must also be reported. In all cases, data were preserved in their original reported statistical format (i.e., arithmetic mean, median, geometric mean).

Results

A total of 31 papers were evaluated (Table 2). Each paper reported one or more sampling locations, approaches, or methods (Table 3). Data for VOCs (e.g., BTEX) and carbonyl compounds (e.g., formaldehyde) have been evaluated in greater detail (Tables 4-5).

(i) State or territory

The Commonwealth of Australia comprises six states and two territories: Victoria (VIC), New South Wales (NSW), Queensland (QLD), Tasmania (TAS), South Australia (SA), Western Australia (WA), Northern Territory (NT), and the Australian Capital Territory (ACT). The majority of the IAQ studies were completed in WA (39%) and VIC (42%), with fewer studies in NSW (10%) and QLD (10%) (Table 2). The most populated state, NSW (32% of national population), represented 10% of IAQ studies, while WA (11% of national population) represented 39% of the studies (ABS, 2016). These differences may arise from the locations of research institutions rather than specific IAQ problems in each of the states. Climate varies across the country, from cool/mild in south-eastern population centres (SA, TAS, VIC, NSW), to warm/mild in south-western WA, and subtropical/tropical in QLD and NT. Variations in temperature and humidity can significantly influence indoor concentrations of formaldehyde (Stock, 1987). None of the studies reported statistically representative assessments of indoor VOCs within each state or according to climatic zone.

(ii) Year and focus of study

As seen in Table 2, earlier studies exclusively sampled formaldehyde (i.e., McPhail, 1991; Godish et al., 1995; Garrett et al., 1997), and later studies included both formaldehyde and VOCs, the first in 1998 (Brown, 2001). In the most recent studies, in addition to formaldehyde, a larger group of carbonyl compounds has been investigated (Cheng et al., 2016; Mishra et al., 2015b).

Among all 31 studies, 42% measured formaldehyde only, 29% measured both formaldehyde and VOCs, 10% measured carbonyls and VOCs, and 19% measured VOCs only. Overall, formaldehyde has been a priority for 81% of all IAQ VOC research conducted in Australia. Despite the prevalence and concentrations of terpenes investigated in 26% of studies, these compounds have not been evaluated as frequently. Of the 18 papers published since 2006, half included both VOCs and formaldehyde. The most recent sampling was conducted in 2012. Consequently, no indoor air quality studies of VOCs in Australia with sampling conducted during the last five years have been identified in the literature.

(iii) Type of indoor environment

As shown in Tables 4 and 5, the most frequently studied indoor environment was housing (new and established) (61%), followed by primary schools (13%), office buildings (7%), caravans (7%), and other environments (12%) such as restaurants, vehicles, and gymnasiums. New housing was the focus of 13% of the papers (McPhail, 1991; Godish et al., 1995; Garrett et al., 1997; Brown, 2001; Brown, 2002; Dingle and Franklin, 2002). However, the definition of a "new house" varied from less than 12 months to less than 10 years old. Most studies of new homes reported higher formaldehyde and VOC levels compared to established homes. Moreover, homes in the first year after construction had the highest VOC levels among studies of domestic housing (Brown 2001; Brown 2002). Schools were the focus of several investigations (Zhang et al., 2004; 2006; Rumchev et al., 2007; Marks et al., 2010; Lazenby et al., 2012; Mishra et al., 2015a, 2015b), reflecting the vulnerability of children and the long periods of time spent at school. However, houses and schools are only some of the places where Australians spend considerable time (Australian Government, 2016), suggesting a need for evaluation of other indoor environments.

(iv) Building operational status

In this evaluation, building operational status is considered normal or extreme. A "normal" state means that doors or windows may be opened, and the building may be occupied during sampling. An "extreme" state means that doors and windows are closed prior to and during sampling, and the building may be occupied or unoccupied (CEC, 1989).

As detailed in Table 2, 19% of studies report the extreme state where the building was closed or unoccupied for a period of time (2 hours to 12 hours) prior to and during sampling, and 81% report normal state (or assumed to be normal). McPhail (1991) reported building status as both open (normal) and closed (extreme) and found formaldehyde levels 3–7 times higher in closed caravans or mobile homes compared with when they were open (Table 5). Among studies that enabled comparisons (e.g., McPhail, 1991; Dingle et al., 2000), levels of formaldehyde were higher during extreme state than normal state of operation.

(v) Sampling methods

Sampling methods can vary by approach, media, time, volume, and active or passive techniques (Table 3). Active sampling requires a pump whereas passive sampling is diffusion controlled. For VOCs, active sampling was used in 82% and passive sampling in 18% of all studies. Active sampling approaches included evacuated stainless steel SUMMA canisters, sorbent tubes, and multi-sorbent tubes. Passive sampling generally used single sorbents due to lower diffusion controlled sorbent adsorption rates. For formaldehyde and carbonyl compounds, active sampling was used in 38% and passive sampling in 62% of all studies.

Active sampling approaches were based on impingers or LpDNPH cartridges attached to a small pump. Passive sampling was in the form of a disc, radial or tape monitors.

Because active sampling can collect sufficient volumes for detection in shorter time periods than passive sampling, it can support comparisons to guidelines for acute health effects (e.g., 30 minute exposure period). However, only 38% of studies of formaldehyde used active sampling, whereas 82% of VOC studies used active sampling. Further, comparisons of sampling results to health-based guidelines are limited both by the paucity of guidelines and the mismatch between typical sampling periods and exposure guideline periods.

(vi) Sampling duration

Sampling duration is a critical consideration, especially if comparisons are to be made among studies and with health-based guidelines. A closer examination of formaldehyde studies (Tables 3 and 5) provides an example of the variation in sampling duration. Three papers had a sampling time of 8 hours (i.e., Rumchev et al., 2002; Zhang et al., 2006; Rumchev et al., 2007), four papers had a sampling time of up to 7 days (i.e., Ayers et al., 1999; Gillett et al., 2000; Sheppeard et al., 2006; Dunne et al., 2006), and five papers had a sampling time between 3 days and 5 days (i.e., Garrett et al., 1997; Dingle et al., 2000; Franklin et al., 2000; Dingle and Franklin, 2002; Loveday et al., 2010). Due to their differing sampling times, comparisons between these studies were limited.

However, some studies of housing reported the same sampling times that also were relevant to guidelines. For example, two studies evaluated formaldehyde levels for the same 1-day period (i.e., Zhang et al., 2004; Maisey et al., 2013). In these studies, the median or geometric mean values were below the NEPM guideline (50 µg/m^3, 1 day) although the geometric mean range in Zhang et al. (2004) (6–19 µg/m^3) was higher than the median value reported by Maisey et al. (2013) (5.3 µg/m^3). Maximum levels were almost identical for each study (126–130 µg/m^3) and exceeded the NEPM formaldehyde guideline of 50 µg/m^3.

In addition, two studies of schools (Marks et al., 2010; Lazenby et al., 2012) used identical sampling times and media (i.e., 24-hour passive sampling with UMEX tape monitors) to measure formaldehyde concentrations. Marks et al. (2010) reported the maximum range as 2.2–67 µg/m^3 with an arithmetic mean of 36 µg/m^3 collected in winter only in NSW. Lazenby et al. (2012) reported the maximum range of 5–13 µg/m^3 with an arithmetic mean of 9.7 µg/m^3 collected in winter and summer in WA.

Formaldehyde studies using active sampling over 1 to 1.5 hours (McPhail, 1991; Godish et al., 1995; Brown, 2001; Brown, 2002) (Table 3) offer sampling times close to former NHMRC guidelines (i.e., 1 hour, 120 µg/m^3). The use of relatively longer active sampling durations was likely due to the difficulties in collecting sufficient analyte volume. Two investigations reported 30-minute exposure assessments for formaldehyde using active sampling with impingers (Brown et al., 2006; Paevere et al., 2008). Results from these studies are unique in the Australian literature as they can be compared to WHO formaldehyde exposure guideline (100 µg/m^3 for 30 minutes). For instance, concentrations in a conventional office building ranged from 16–140 µg/m^3 (Brown et al., 2006), exceeding the WHO exposure guideline, and in a green office building from bdl–37 µg/m^3 (Paevere et al., 2008).

(vii) Number of air samples

The number of sites and samples collected are shown in Tables 4 and 5. Several studies report a relatively large number of sites (up to 224) and samples collected (up to 2,897). Among the studies that reported VOCs, 4% sampled more than 100 sites, and 22% collected more than 100 samples. Among studies that reported carbonyls including formaldehyde, 14% sampled more than 100 sites, and 43% collected more than 100 samples. However, most VOC studies reported 70 or fewer sites, with 4 or fewer samples.

For established housing (including caravans), five studies investigated more than 130 sites (i.e., Dingle et al., 2000; Franklin et al., 2000; Dingle and Franklin, 2002; Rumchev et al., 2002; Sheppeard et al., 2006). Other studies reported a relatively large number of samples (120 ≤ n ≤2,897) but with fewer locations (39≤ n ≤88) (Garrett et al 1997; Zhang et al., 2004; Maisey et al., 2013). Notwithstanding the larger sampling efforts, no single study or collection of studies reports statistically significant indoor VOC and carbonyl exposures relevant to the general population in Australia.

(viii) Analytical methods

As shown in Table 2, analytical methods were grouped according to studies of VOCs or studies of carbonyls. Analytical methods included protocols published by Australian agencies (e.g., Standards Australia), international authorities (e.g., the US National Institute of Occupational Safety and Health, NIOSH, 1994), and manufacturers of sampling or analytical equipment (e.g., Radiello, 2006). Since 2009, most authors cite US EPA Compendium Methods TO17 for VOCs and TO11A for carbonyls and formaldehyde (US EPA, 1999a; US EPA, 1999b).

For the analysis of VOCs, all studies reported gas chromatography (GC) / mass spectrometry (MS) as the principal method of analysis. The majority (78%) of studies used automated thermal desorption (TD) - gas chromatography (GC) / mass spectrometry (MS), and 17% of studies used a liquid phase desorption process. Flame ionisation detection was the principal mode of detection but was not uniformly specified.

For the analysis of carbonyls including formaldehyde, studies used high performance liquid chromatography (HPLC), with an ultraviolet (UV) or visible (VIS) detector or mass spectrometer based on US EPA Method TO11A (US EPA, 1999b). Early studies on formaldehyde used impinger sampling into a sodium bisulphite solution, subsequently quantified by visible spectroscopy (Standards Australia, 2014). If the formaldehyde sampling technique included chromotropic acid, formaldehyde concentration was determined by a UV/VIS spectrometer (24%). If the formaldehyde sampling technique utilised DNPH, quantification was from the hydrazone derivative detected with HPLC (76%). In general, the methods used for analysing VOCs and carbonyls are consistent with international protocols.

(ix) Number and type of VOCs

Table 2 shows the number and type of VOCs evaluated in each study. Overall, the median number of compounds was 10, and the maximum was 97 (Cheng et al., 2016). Most studies (84%) focused on 35 or fewer VOCs and carbonyls. Several studies reported a larger number (35–97) of VOCs (Brown, 2001; Mishra et al., 2015a; Maisey et al., 2012; Cheng et al., 2016).

Studies reported results in different ways, among them: (i) most commonly identified compounds (e.g., top 10 compounds) (Hinwood et al., 2006), (ii) number of VOCs that make up a percentage of the total (Cheng et al., 2016), (iii) number of VOCs (e.g., 5) that were observed in 50% of the locations (Maisey et al., 2013), (iv) functional groups of the compounds (e.g., aromatic hydrocarbons) (Mishra et al., 2015a), or (v) TVOCs (Brown, 2001; Zhang et al., 2004).

Benzene, toluene and xylene(s) were among the most commonly reported compounds, also in a variety of ways: (i) individual compounds (i.e., Maisey et al., 2013; Cheng et al., 2016), (ii)

TVOCs (i.e., Zhang et al., 2004), (iii) the sum of BTEX compounds (Galbally et al., 2009), or (iv) total xylene(s) (Hinwood et al., 2007). Additional VOCs such as alcohols and halogenated hydrocarbons were reported in 32% of the studies. Terpenes and terpenoids were reported in eight studies (26%) (Brown, 2001, 2002; Brown et al., 2006; Paevere et al., 2008; Maisey et al., 2013; Mishra et al., 2015a, 2015b; Cheng et al., 2016).

(x) Concentration of compounds

(a) VOCs

For BTEX compounds, the indoor maximum (MX), median (MD), geometric mean (GM), and arithmetic mean (AM) concentrations are reported in Table 4. Although MX values were consistently reported, MD values were reported only in some studies, and the AM and or GM reported in others. In order to compare investigations, differences in sampling approach and duration were not considered, and thus the analysis below is provided with that caveat.

Benzene concentrations in established houses exhibited a statistical range (i.e., the range of MD, GM, and AM values) of 1–25 $\mu g/m^3$. The maximum benzene concentration of 125 $\mu g/m^3$ was recorded in an established home using an un-flued gas heater (7-day sampling period) (Loveday et al., 2010). Relatively high benzene levels (MX up to 82 $\mu g/m^3$, MD up to 25 $\mu g/m^3$) were reported in studies of a new home (Brown, 2001), homes affected by ambient air pollution due to wood burning (Galbally et al., 2009), and homes of asthmatic children (Rumchev et al., 2004). In the latter study, each 10 $\mu g/m^3$ increase in benzene concentration was associated with a threefold increase in the risk of having asthma.

Toluene concentrations in established houses exhibited a statistical range of 3–73 $\mu g/m^3$. The highest toluene concentration of 692 $\mu g/m^3$ was recorded in a school (Mishra et al., 2015b). New homes and homes with recent renovations reported toluene levels of up to 240 $\mu g/m^3$

(30-minute sampling period), with a statistical range of 19–73 μg/m^3 (Brown, 2001). In an established home with an un-flued heater, a toluene concentration of 203 μg/m^3 (7-day sampling period) can be compared to the WHO guideline of 260 μg/m^3 (7 days) (Loveday et al., 2010). Toluene was the highest concentration VOC in 37% of indoor environments (range of 2.6–692 μg/m^3) (Table 4).

Ethylbenzene concentrations in established houses exhibited a statistical range of 1–46 μg/m^3. The maximum ethylbenzene concentration of 210 μg/m^3 was in a recently renovated office building (Brown, 2002).

Xylenes are more difficult to compare as not all studies reported the same isomer(s) (see footnotes Table 4). Xylene concentrations in established homes exhibited a statistical range of 4.4–12 μg/m^3. For newly constructed or renovated homes, the statistical range was higher, 19–36 μg/m^3, though with fewer studies (Brown, 2001, 2002). The maximum xylene concentration measured in a home was 320 μg/m^3 using active sampling (8 hours) (Rumchev et al., 2004). The highest xylenes concentration of 770 μg/m^3 was measured in a renovated office building (Brown, 2002).

Terpenes were also investigated in 26% of the studies, and found to be among the most abundant compounds. For example, in a study of domestic housing, limonene (45%) and pinene (32%) were the second and third most prevalent compounds detected after BTEX (Maisey et al., 2013). In another study of domestic housing, limonene was one of nine compounds comprising 68% of all VOCs reported (Cheng et al., 2016). Several studies reported limonene in schools at concentrations up to 213 μg/m^3 (Mishra et al., 2015a; Mishra et al., 2015b).

(b) Formaldehyde and carbonyls

For formaldehyde and carbonyl compounds, the MX, MD, GM, and AM concentrations are reported in Table 5. The statistical range of formaldehyde concentrations for new housing (15–90 µg/m^3) was nearly three times higher than for established housing (4.1–31 µg/m^3).

Primary schools were evaluated by five studies (Zhang et al., 2006; Rumchev et al., 2007; Marks et al., 2010; Lazenby et al., 2012; Mishra et al., 2015b) (Table 5), reporting formaldehyde concentrations with a range of 1.5–305 µg/m^3. A study of new schools (built after 1985) and older schools found higher MD formaldehyde concentrations in new (148 µg/m^3) than old (103 µg/m^3). Thus, some primary schools can have significant levels of formaldehyde.

Relatively high levels of formaldehyde were reported in caravans, with the maximum concentration in (unoccupied or closed) caravans ranging from 12–1,200 µg/m^3 (McPhail, 1991; Dingle et al., 2000), with AM ranging from 190–850 µg/m^3. Results indicate that much higher concentrations of formaldehyde have been observed in caravans compared to housing (new or established).

(xi) Comparison of studies

Studies that used similar methods for similar times are identified in Table 3. For example, similar sampling media and durations were reported in a set of four VOC studies (Brown, 2001; Brown, 2002; Mishra et al., 2015a, 2015b) and five formaldehyde studies (McPhail, 1991; Godish et al., 1995; Brown, 2001; Brown et al., 2006; Paevere et al., 2008). In addition, several sets of similar investigations allowed comparisons to exposure guidelines. Three studies of housing (Galbally et al., 2009; Loveday et al., 2010; Dunne et al., 2006) with passive sampling of VOCs for 7 days, provide results that can be compared to 7 day WHO guidelines (Tables 1 and 4). Three other studies of housing (Zhang et al., 2004; Lazenby et al., 2012; Maisey et al., 2013) with passive sampling of carbonyls for 24 hours, report formaldehyde concentrations ranging from bdl–130 µg/m^3, which can be compared to the 24 hour NEPM value of 50 µg/m^3.

Two similar studies evaluated formaldehyde concentrations in multi-story office buildings: one an established conventional building (Brown et al., 2006), and the other a new green building (Paevere et al., 2008), both in the same city, and both sampled in summer and winter. The conventional building concentrations ranged from 16–140 µg/m^3, exceeding the WHO exposure guideline (i.e., 100 µg/m^3), with MD summer (60 µg/m^3) greater than winter (34 µg/m^3). The green office building concentrations ranged from bdl–37 µg/m^3, with MD in both seasons of 7.5 µg/m^3. The authors suggest that lower formaldehyde levels in the green building were due to the selection of low-emitting building materials (Paevere, et al., 2008).

(xii) Indoor to outdoor concentration ratios

As shown in Table 2, of the 31 studies, 29% reported I/O ratios, 26% reported outdoor measurements only (although most did not designate whether they were concurrent), and 45% did not report outdoor air measurements. One study reported I/O ratios as well as differences between indoor and outdoor concentrations to investigate possible sources (Molloy et al., 2012).

For toluene (Table 4), the highest median I/O ratio was 30 in a new house (Brown, 2001). Ratios for established housing ranged from 1.4 to 3.6 (plus an attached garage ratio of 12.5), offices ranged from 0.8 to 2, and schools were 1.7. Ratios for established housing, offices, and schools were similar, whereas new housing was an order of magnitude higher.

For formaldehyde (Table 5), the highest median I/O ratios were 16 for new housing, and 40 for housing sampled in winter, which were the highest among housing studies (Brown, 2001; Dunne et al., 2006). The median I/O ratios for established housing ranged from 3.5–12 (across all seasons) (Lazenby et al., 2012; Cheng et al., 2016).

Evaluation of I/O ratios revealed that the majority of compounds sampled were several times higher indoors than outdoors. In general, median formaldehyde and toluene I/O concentration ratios were significantly higher in new homes than in any other indoor environment.

(xiii) Seasonal variation

Seasonal conditions can affect indoor VOC and formaldehyde levels (Campagnolo et al., 2017; Molloy et al., 2012). Among the studies, 35% reported VOC or formaldehyde data from a single season, 42% reported data from two or more seasons, distinguishing between warmer and cooler months, and 23% of the studies reported data from all four seasons (e.g., Molloy et al., 2012; Rumchev et al., 2002).

Of the studies that considered two or more seasons, 31% found that warmer months had higher formaldehyde levels than cooler months (Molloy et al., 2012; Brown et al., 2006; Dingle and Franklin, 2002; Rumchev et al., 2002). Also, 31% found higher levels of formaldehyde in winter compared to summer (Zhang et al., 2006; Zhang et al., 2004; Dingle et al., 2000; Garrett et al., 1997). Further, 31% found generally higher VOC concentrations in winter compared to summer (Maisey et al., 2013; Zhang et al., 2006; Dunne et al., 2006; Galbally et al., 2009).

For studies that reported sampling during multiple seasons, 60% found differences in VOC and formaldehyde levels among seasons. However, these differences were not consistently observed in cooler or warmer seasons. Although indoor VOC levels were likely to be higher in winter, formaldehyde levels were found to be higher in either winter or summer. In some instances, seasonal differences were found to have a negligible effect on formaldehyde levels (Dunne et al., 2006), VOC levels (Brown et al., 2006), or both (Paevere et al., 2008).

Discussion

This evaluation of 31 studies conducted across Australia during the past 25 years revealed that there is no standard approach for IAQ sampling or VOC reporting. Comparisons are frequently made among studies, but without consideration to the sampling methods. In particular, the sampling times are often different. This is rarely acknowledged and is a problem for researchers globally who wish to compare their findings. This paper demonstrates the need for a standard approach for collecting and reporting data.

The evaluation also showed that results from some investigations could be compared to former NHMRC and WHO health-based guidelines, and to NEPM ambient air quality guidelines. However, the use of passive sampling in 62% of formaldehyde studies limits the determination of concentrations relevant to short-term exposure and guidelines for acute effects. For VOCs, active sampling techniques were used in 82% of studies, which may better support the assessment of acute health effects. Sampling methods and time periods that are more consistent with exposure guidelines, as well as pollutant exposure guidelines that are more compatible with sampling patterns and occupant behavior, would enable a more rigorous assessment and comparison of potential health risks.

Relatively few studies investigated housing during the first year after construction, when most off-gassing of new materials typically occurs. For these studies, the number of buildings sampled and number of geographical locations were limited. In contrast, established housing has received considerable attention, with several studies reporting a relatively high number of buildings and samples. Levels of VOCs and formaldehyde in new housing were the highest among all studies of domestic housing in Australia, indicating a need for greater attention to new and renovated buildings.

Primary schools were evaluated in six of the studies, with formaldehyde concentrations of up to 288 $\mu g/m^3$. The implication is that some school environments may be a significant source of formaldehyde exposure.

Indoor VOC levels of other educational environments, such as preschools, high schools and universities, are not well understood in Australia. In addition, indoor VOC assessments of health care facilities, hospitals, day care centres, and aged care facilities are lacking. However, these environments are especially important because their occupants may be more vulnerable to the effects of VOC exposure.

The last Australian assessment of formaldehyde concentrations in caravans was conducted in 2000. Future assessments are needed to determine if levels have changed due to possible changes in engineered wood products and insulation materials (Brown and Johnson 2004). Furthermore, residences such as apartments comprise an increasing proportion of the Australian urban landscape (ABS, 2015). Though not yet adequately investigated, they offer an important area for future VOC studies.

Conclusion

In summary, IAQ research in Australia has evolved from evaluating only formaldehyde in early studies to including other carbonyls and a range of VOCs in later studies. Indoor concentrations of nearly all pollutants were higher indoors than outdoors, especially in new and renovated buildings. In some cases, concentrations of formaldehyde and toluene exceeded pollutant exposure guidelines. To enable comparisons among studies and with exposure guidelines, a standard approach for sampling and reporting VOC data is needed. Greater attention should be focused on indoor environments that are underreported and with vulnerable populations. Finally, what is also needed, and what has not yet been conducted, is a nationally representative study of indoor VOCs in Australia.

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Volatile organic compounds within indoor environments in Australia (Tables)

Table 1. Air quality guidelines for organic pollutants

Pollutant	Pollutant guideline (exposure period)		
	NHMRC 1992	NEPM 2004	WHO 2000/2010
Formaldehyde	120 µg/m^3 (ceiling)	50 µg/m^3 (1 day)	100 µg/m^3 (0.5 hour)
TVOC	500 µg/m^3 (1 hour)	n/a	n/a
Benzene	50% TVOC[a]	10µg/m^3 (1 year)	No safe limit[b]
Toluene	50% TVOC[a]	3770 µg/m^3 (1 day), 377 µg/m^3 (1 year)	260 µg/m^3 (7 day)[c]
Xylenes	50% TVOC[a]	1085 µg/m^3 (1 day), 870 µg/m^3 (1 year)	n/a
Dichloromethane	50% TVOC[a]	n/a	450 µg/m^3 (7 day)[c]
Styrene	50% TVOC[a]	n/a	260 µg/m^3 (7 day)[c]
Tetrachloroethylene	50% TVOC[a]	n/a	250 µg/m^3 (1 year)
Trichloroethylene	50% TVOC[a]	n/a	250 µg/m^3 (1 year)

[a] NHMRC specified that no VOC should exceed 50% of a TVOC mixture. [b] Geometric mean concentration estimated for lifetime cancer risk of 1/100,000 is 1.7 µg/m^3 (1 year). [c] Goals provided by WHO (2000) but considered to have insufficient evidence by WHO (2010).

Table 2. Australian IAQ studies of VOCs and carbonyls (C), including formaldehyde (F).

Reference	Year(s) of study	Organic compounds	# of VOCs	I/O Ratios or [Outdoor]	Building Operational Status	Location (Month / Season)
McPhail, 1991	1986, 1987	F[1]	1	n/a	Normal and Extreme	New South Wales (n/a)
Godish et al., 1995	1992	F[1]	1	n/a	Extreme, closed 12 h prior	Victoria (Winter)
Garrett et al., 1997	1994, 1995	F[2]	1	[Outdoor]	Normal	Victoria (Summer, Autumn, Spring)
Ayers et al., 1999	1997	F[2]	1	n/a	Normal (assumed)	Victoria (Spring)
Dingle et al., 2000	n/a	F[2]	1	n/a	Normal (assumed)	Western Australia (Summer, Winter)
Franklin et al., 2000	n/a	F[2]	1	n/a	Normal (assumed)	Western Australia (Summer, Winter)[b]
Gillett et al., 2000	n/a	F[2]	1	n/a	Normal (assumed)	Victoria (Autumn)
Brown, 2001	1998	F[1] and VOCs[3]	28	[Outdoor]	Extreme, closed 3h prior	Victoria (All Seasons)
Dingle and Franklin, 2002	n/a	F[2]	1	n/a	Normal	Western Australia (Summer, Winter, Spring)
Rumchev et al., 2002	1998, 1999	F[2]	1	n/a	Normal	Western Australia (All Seasons)
Brown, 2002	n/a	F[1] and VOCs[3]	35	[Outdoor] I/O	Normal, Extreme, closed 2h prior	Victoria (Summer, Autumn)
Rumchev et al., 2004	1998, 1999	VOCs[4]	10	n/a	Normal (assumed)	Western Australia (Winter, Summer)
Zhang et al., 2004	2002, 2003	F[2] and VOCs[4]	11	n/a	Normal	Western Australia (Winter, Summer)
Zhang et al., 2006	2002	F[2] and VOCs[4]	10	n/a	Normal	Western Australia (Summer, Winter),
Sheppeard et al., 2006	1999	F[2]	1	n/a	Normal	New South Wales (Winter, Spring)
Dunne et al., 2006	2004	F[2] and VOCs[3]	4	I/O	Normal, Extreme	Victoria (Summer, Winter)
Hinwood et al., 2006	2000	VOCs[5]	41	[Outdoor]	Normal	Western Australia (August to December)
Brown et al., 2006	2006	F[1] and VOCs[3]	20	I/O	Normal	Victoria (Winter, Summer)
Rumchev et al., 2007	n/a	F[2]	1	n/a	Normal, Extreme	Western Australia (Winter)
Paevere et al., 2008	2007	F[1] and VOCs[3]	20	[Outdoor]	Normal	Victoria (Summer, Winter)
Galbally et al., 2009	2003	VOCs[3]	6	I-O[c]	Normal	Victoria (Summer, Winter)
Markes et al., 2010	2009	F[2]	1	n/a	Normal	New South Wales (June to August)
Loveday et al., 2010	2007, 2008	F[2] and VOCs[3]	35	[Outdoor]	Normal	Western Australia (May to September)
Lawson et al., 2011	2008, 2009	VOCs[3]	6	I/O	Normal	Victoria (All Seasons)
Lazenby et al., 2012	2006, 2007	F[2]	1	[Outdoor]	Normal	Western Australia (Spring, Summer, Winter)
Molloy et al., 2012	2008, 2009	C[2] and VOCs[3]	8	I/O	Normal	Victoria (All Seasons)
Maisey et al., 2013	2010, 2011	F[2] and VOCs[3]	45	[Outdoor][a]	Normal	Western Australia (Summer, Winter)
Hamidin et al., 2013	2009	VOCs[3]	7	I/O	Normal	Queensland (Autumn, Winter)
Mishra et al., 2015a	2010 to 2012	VOCs[3]	62	I/O[a]	Normal	Queensland (All Seasons)
Mishra et al., 2015b	2010 to 2012	C[2] and VOCs[3]	73	[Outdoor][a]	Normal	Queensland (All Seasons)
Cheng et al., 2016	2008, 2009	C[2] and VOCs[3]	97	I/O	Normal	Victoria (All Seasons)

[a] Supplied as supplementary material to the original document. [b] Personal communication (15 November, 2016 e-mail from P Franklin to lead author).[c] Indoor minus outdoor. [1] Ultraviolet visible spectroscopy, [2] High performance liquid chromatography, [3] Thermal desorption gas chromatography mass spectrometry, [4] Carbon disulphide gas chromatography mass spectrometry, [5] Cryogenic concentration gas chromatography mass spectrometry.

Table 3. Sampling approach, media and methods for all studies

Sampling Approach	Media	Active/ Passive	Percentage Active/ Passive	Sample Volume (Sampling Time)	Percentage of Each Method (All Studies)	Reference(s)	Comparison of Sampling Time Within Each Group *(Match To Guidelines)*
Sorbent tubes *(VOCs)*	PerkinElmer Chromosorb 106	Passive	18%	6.7 to 10 litres* (7 days)	7%	Galbally et al., 2009; Loveday et al., 2010; Dunne et al., 2006	High, identical sampling times *(WHO)*
	Charcoal	Active		240 to 600 litres (4 to 10hours)	7%	Rumchev et al., 2004; Zhang et al., 2004; Zhang et al., 2006	Moderate, range between 4 and 10h
	Tenax TA	Active		4.5 litres (150 minutes)	2%	Hamidin et al., 2013	n/a
Multisorbent tubes *(VOCs)*	Tenax TA, Ambersorb XE 430, Tenax TA, Carbotrap	Active		6 to 10 litres (40 to 50 minutes)	7%	Brown, 2001; Brown, 2002; Mishra et al., 2015a, 2015b	High between these studies *(Approx. NHMRC)*
	Tenax, Ambersorb/ Corboxen, Activated C	Active	82%	2.4 to 4 litres (45 to 48 minutes)	5%	Brown et al., 2006 Paevere et al., 2008	High, very similar sampling times *(Approx. NHMRC)*
	Markes Carbograph 1TD/ Carbopack X	Active		16.8 litres (7 days, 2 x 1 hour intervals / day)	7%	Lawson et al., 2011; Molloy et al., 2012; Cheng et al., 2016	High, identical sampling times *(WHO)*
	PerkinElmer Air Toxics	Active		20 litres (100 minutes)	2%	Maisey et al., 2013	n/a
Canisters *(VOCs)*	SUMMA	Active		2.90 to 5.80 litres (6 to 12 hours)	2%	Hinwood et al., 2006	n/a
Impinger techniques *(Formaldehyde)*	Impinger bisulphite	Active	38%	60 to 90 litres (0.5 to 1.5hours)	14%	McPhail, 1991; Godish et al., 1995; Brown, 2001; Brown et al., 2006; Paevere et al., 2008	High to moderate, all studies between 30 and 90mins *(Approx. NHMRC), (WHO)*
Cartridges *(Carbonyl compounds)*	Sigma Aldrich Supelco DNPH	Active		80 to 3024 litres (40 minutes to 7 days)	7%	Molloy et al., 2012; Mishra et al., 2015b; Cheng et al., 2016	High between two studiesMolloy et al., 2012 and Cheng et al., 2016
Disc, radial or tape monitors *(Carbonyl compounds)*	Disc DNPH	Passive	62%	0.32 to 10.08 litres* (8 hours to 7 days)	33%	Garrett et al., 1997[4d]; Ayers et al., 1999[7d]; Dingle et al., 2000[3–5d]; Franklin et al., 2000[3–4d]; Gillett et al., 2000[3–7d]; Dingle and Franklin, 2002[3–5d]; Rumchev et al., 2002[8h]; Zhang et al., 2004[24h]; Zhang et al., 2006[8h]; Rumchev et al., 2007[8h];Sheppeard et al., 2006[7d]; Dunne et al., 2006[7d]; Loveday et al., 2010[3d]; Maisey et al., 2013[24h]	Wide range of sampling times; 8 hours, 1 day, 3 to 5 days, 3 to 7 days, and 7 days; moderate to high degree of similarity among some studies *(NEPM)*
	UMEX tape monitor DNPH	Passive		0.96 to 1.44 litres* (24 hours)	5%	Markes et al., 2010; Lazenby et al., 2012	High, identical sampling times *(NEPM)*
	Disc Bisulphite	Passive		0.96 to 1.44 litres* (24 hours)	2%	McPhail, 1991	n/a *(NEPM)*

* Volume based on a passive diffusion rate of 40 to 60 mL/min (Woolfenden, 2010)

Table 4. Sampling and concentration data (maximum-MX, geometric mean-GM, median-MD, arithmetic mean-AM) for BTEX compounds

Reference	Indoor environment	Number of sites	Number of samples	Sampling duration	Benzene (μg/m³)			Toluene(μg/m³)			Ethylbenzene (μg/m³)			o, m, p-xylene (μg/m³)			I/O ratio	Highest concentration (μg/m³)	
					Range	GM or MD	AM	Range	GM or MD	AM	Range	GM or MD	AM	Range	GM or MD	AM	For Toluene	Compound(s)	MX
Brown, 2001	House [n]	1	12	30 minutes	2–35	13[a]	15[a]	7–240	51[a]	73[a]	1–12	10[a]	10[a]	3–30	26[a]	19[a]	30	1,2-Propanediol	1600
Brown, 2002	Gymnasium	1	2	30–50 minutes	1–6.7	2.6[a]	3.2[a]	14–110	19[a]	39[a]	1.8–25	3.3[a]	8.5[a]	n/a	n/a	n/a	2.3	n-Heptane	2900
Brown, 2002	Houses	22	61	30–50 minutes	n/a	3	7	n/a	9	14	n/a	2	2	n/a	4	6.9	2.4	Texanol	160
Brown, 2002	Office Building	1	2	30–50 minutes	2–18	8	9	9–220	34	60	1.6–210	6	46	5–770	19	145	n/a	2-Methylpentane	2300
Brown, 2002	House [n] extension	3	16	30–50 minutes	2–10	5	5	6–63	18	24	n/a	n/a	n/a	2–110	21	36	2.4	Texanol	160
Rumchev et al., 2004	Houses	192	384	8 hours	0.01–82	25	n/a	0.8–150	12	n/a	0.01–15	1.4	n/a	0.01–320	1.4	n/a	n/a	m-xylene	320
Zhang et al., 2004	Houses	45	90	10 hours	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	TVOCs	575
Zhang et al., 2006	Schools	4	98	8 hours	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	TVOCs	94
Dunne et al., 2006	House	1	63	7 days	2.8–6.1	n/a	4	4.4–9.6	n/a	7.1	0.7–2.7	n/a	1.6	5.1–24[b]	n/a	12[b]	1.4	Xylenes	24.4
Dunne et al., 2006	Garage	1	63	7 days	2.6 – 4.3	n/a	4	7–16	n/a	11	1–3.7	n/a	2	6.7–17	n/a	9.7	2.2	Xylenes	17
Hinwood et al., 2006	Transport (car)	4	4	12 hours	6.7	n/a	n/a	26	n/a	n/a	4.3	n/a	n/a	27	n/a	n/a	n/a	Xylenes	27
Hinwood et al., 2006	Nightclub	2	4	6 hours	14	n/a	n/a	43	n/a	n/a	20	n/a	n/a	130	n/a	n/a	n/a	Xylene(s)	130
Hinwood et al.,	Houses	3	10	6 hours	0.7–2.2	n/a	n/a	1.6–11	n/a	n/a	0.3–1.3	n/a	n/a	1.3–7	n/a	n/a	n/a	Toluene	11

2006																			
Hinwood et al., 2006	Shopping centre	2	2	12 hours	5.4	n/a	n/a	15	n/a	n/a	0.9	n/a	n/a	6.5	n/a	n/a	n/a	Toluene	15
Brown et al., 2006	Office Building	11	22	40 minutes	1-5	4[w]	2	4-14	7.5[w]	8	2–8	n/a	4	6–19	n/a	12	2	Ethanol	170
Paevere et al., 2008	Green Office Building	7	14	40 minutes	0.9–7.7[d]	2.5	2.8	3.7–29	11.5	12.2	1.1–1.8	1.7	1.6	5.5–10	9.3	8.5	0.8	TVOCs	180
Galbally et al., 2009	Houses	57	171	7 days	2–34[k]	6.5& 3.8[k]	8.8[k]	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.4	BTEX	960
Loveday et al., 2010	Houses	79	79	7 days	bdl–125	1.6	n/a	bdl–203	7	n/a	n/a	n/a	n/a	bdl–83	3.5	n/a	n/a	Toluene	203
Lawson et al., 2011	Homes [<]	15	57	7 days	n/a	n/a	2	n/a	n/a	10	n/a	n/a	1	n/a	n/a	7.2[b]	2.7	Toluene	10.3
Lawson et al., 2011	Homes [>]	12	48	7 days	n/a	n/a	1	n/a	n/a	5.7	n/a	n/a	1	n/a	n/a	4.4[b]	2.2	Toluene	5.7
Molloy et al., 2012	Houses	40	150	7 days	2.3[i]	1	1	14[i]	6.1	8.8	n/a	n/a	n/a	10[i]	4.5	6.2	2.7	Toluene	14
Maisey et al., 2013	Houses	69	64	100 minutes	2.7–4.9	bdl–1.3[h]	n/a	37–51	3–10[h]	n/a	3–18	0.2–1.4[h]	n/a	8–61	1– 4[h]	n/a	1.7–3.1	Toluene	51
Hamidin et al., 2013	Houses	32	81	2.5hours	bdl–13	2	2	0.8 to 82	7.5	11	bdl–14	1.3	2	0.3 to 24[c]	2.8	3.7	3.6	Toluene	82
Hamidin et al., 2013	Garages	32	81	2.5hours	4–8	6	6	7–38	25	26	2–5	3.4	4	3–12[c]	8.8	8.1	12.5	Toluene	38
Mishra et al., 2015a	Schools	25	100	40 minutes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.7[j]	TVOCs	1100
Mishra et al., 2015b	Schools	25	250	40 minutes	2.7–3.7	3.2	n/a	1–692	11	n/a	2–4.1	3	n/a	1–50[c]	6[c]	n/a	n/a	Toluene	692
Cheng et al., 2016	Houses	40	145	7 days[f]	0.3–6.5	1.0&1.1	1.3	2.9–150	6.1&7.4	11	0.34–8.1	0.9& 1.0	1.2	0.57–23[e]	1.9&2.1	2.9	1.8	Ethanol	1200[g]

[w] Winter, [bdl] Below detection limit, [n] New houses, [>] Houses located 300 m from a road, [<] Houses located less than 50 m from a road. I/O ratios are derived from mean or median values. [a]Calculated value (with permission of authors),[b] All isomers (i.e., ortho, meta, para), [c] The isomers m,p-xylene, [d] Supplementary information used with permission of author, see Brown (2007), [e] The isomer p-xylene was presented here although each was reported separately in the original paper, [f] Two 1-hr intervals per day for 7 days, [g] Semi-quantitative, [h] Summer and winter median data reported. [i] The 90th percentile. [j] TVOCs ratio for GM, [k] Data from winter from homes with compliant wood heaters.

Table 5. Sampling and concentration data (maximum-MX, geometric mean-GM, median-MD, arithmetic mean-AM) for formaldehyde studies

Author, Date	Indoor Environment	No. of Sites	No. of Samples	Sampling time	Formaldehyde (μg/m^3)				I/O Ratio
					Range	GM	MD	AM	
McPhail, 1991	Houses	23	23	1 hour	10–40	n/a	n/a	n/a	n/a
McPhail, 1991	Houses [n]	8	8	1 hour	20–36	n/a	n/a	n/a	n/a
McPhail, 1991	Caravans [cl]	2	7	24 hours	n/a–1200	n/a	n/a	850	n/a
McPhail, 1991	Caravans [op]	16	16	24 hours	n/a–320	n/a	n/a	260	n/a
McPhail, 1991	Portable Houses [cl]	2	7	24 hours	n/a–1100	n/a	n/a	770	n/a
McPhail, 1991	Portable Houses [op]	4	7	24 hours	n/a–130	n/a	n/a	120	n/a
Godish et al., 1995	Houses [n]	20	20	1.5 hours	n/a–90	27	24	n/a	n/a
Godish et al., 1995	Houses	20	20	1.5 hours	n/a–89	20	n/a	n/a	n/a
Garrett et al., 1997	Houses [n]	39	720[a]	4 days	0.25–133	21	15	19	17
Garrett et al., 1997	Houses	40	720[a]	4 days	n/a	16	n/a	n/a	13
Ayers et al., 1999	Houses	9	18	7 days	2.2–32	n/a	3.1[a]	4.7[a]	n/a
Dingle et al., 2000	Caravans [u]	132	264	3 to 5 days	12–1050	120	189	190	n/a
Dingle et al., 2000	Caravans [o]	60	120	3 to5 days	10–214	36	43	43	n/a
Franklin et al., 2000	Houses	224	448	3 to 4 days	1–114[i]	12[i]	13[i]	18[i]	n/a
Gillett et al., 2000	Houses	6	17	4 to 7 days	2.5–25	7.2[a]	6[a]	9.2[a]	n/a
Gillett et al., 2000	Office	1	2	4 to 7 days	54–66[a]	n/a	n/a	60	n/a
Brown, 2001	Houses [n]	1	13	1 hour	5–134	90	87	85	16
Dingle and Franklin, 2002	Houses	185	1380	3 days	bdl–204	23–31[f]	n/a	4–113	n/a
Rumchev et al., 2002	Houses	192	768	8 hours	n/a–224[c] n/a–189[c]	n/a	24[b,s]–13[b,w]	27–30[c]	n/a
Zhang et al., 2004	Houses	88	196	24 hours	bdl–92[c] and bdl–126[c]	6–19[c]	n/a	n/a	n/a
Zhang et al., 2006	Schools	4	141	8 hours	1.5–56[g]	3–38	n/a	n/a	n/a
Sheppeard et al., 2006	Houses	139	139	7 days	0.16–58	n/a	4.1	n/a	n/a
Rumchev et al., 2007	Schools [n]	3	20	8 hours	13–288	n/a	148	n/a	n/a
Rumchev et al., 2007	Schools	3	20	8 hours	5–305	n/a	103	n/a	n/a
Dunne et al., 2006	Houses	1	64	7 days	2.3–6.1	n/a	n/a	4.4	40[w], 10[s]
Brown et al., 2006	Office Building	10	20	30 minutes	16–140	49	34[w] 60[s]	71	> 4
Paevere et al., 2008	Green Office Building	7	14	30 minutes	bdl–37[h]	8.3	7.5	10.2	1.5
Marks et al., 2010	Schools	22	44	1 day	2.2–67[f]	n/a	n/a	36	n/a
Loveday et al., 2010	Houses	79	324	3 days	bdl–39	n/a	5.3	35	n/a
Lazenby et al., 2012	Houses	41	75	1 day	5–46	12	n/a	15	3.5
Lazenby et al., 2012	School	4	7	1 day	5–13	n/a	n/a	9.7	1.5[d]

Molloy et al., 2012	Houses	40	160	7 days	8.3–24[g]	n/a	14.5	15	12[d]
Maisey et al., 2013	Houses	68	2897	1 day	bdl–130	n/a	5.3	n/a	n/a
Cheng et al., 2016	Houses	40	145	7 days[e]	4.8–33	15	15	16	12
Mishra et al., 2015b	Schools	25	100	0.7 hours	bld–80	n/a	4.2	n/a	n/a

[n] New house(s), [cl] closed, [op] open, [u] unoccupied, [o] occupied, [s] summer, [w] winter.[a] Calculated value (from data in paper), [b]Results from the living rooms of asthmatic children, [c] Results from the bedroom and living room, respectively, of asthmatic children, for summer and winter, [d] I/O ratio based on mean, [e] 7 day continuous sampling, [f] 95% CI based on the geometric range, [g] 10% and 95% quantiles. [h]Supplementary information used with permission of author, see Brown (2007). [i] Supplementary information used with permission of author (15 November, 2016 e-mail from P Franklin to lead author). I/O ratios are derived from mean or median values.