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Ventilation and indoor air quality in retail stores: A critical review (RP-1596)

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Identifying air pollutants that pose potential adverse health exposures in retail stores will facilitate exposure mitigation. Assessing the role of ventilation in mitigating this exposure is important to understand the energy implications of maintaining acceptable indoor air quality. In this work, we summarize results from 28 papers that report ventilation rates and/or pollutant concentrations in retail stores. These results were compared to available standards as well as data collected in non-retail environments. The findings of this review are: (1) half of the stores tested met/exceeded ASHRAE Standard 62.1-2010 (ASHRAE 2010a; or California Code of Regulations Title 24-2010) for ventilation; (2) $PM_{2.5}$, acrolein, formaldehyde, and acetaldehyde exceeded their established, most conservative limits/reference exposures for a few of the stores tested in the United States, and outside the United States, researchers reported PM_{10}, benzene, and trichloroethylene as additional pollutants found at concentrations that exceeded their limits; (3) alternative control methods would be more effective, and possibly more economical, than ventilation; (4) meeting or exceeding the ventilation requirements does not necessarily negate the presence of pollutants above their suggested limits; and (5) using disability-adjusted-life-year (DALY) as a metric of disease burden, two pollutants were identified as priority hazards in retail stores: $PM_{2.5}$ and acrolein. Control strategies should focus on decreasing exposure of retail employees to these pollutants generated indoors or infiltrated from outdoors.

Introduction

Among commercial buildings, retail buildings rank second in energy consumption and greenhouse gas emissions, after office buildings (Zhang et al. 2011, Kennedy et al. 2012). Within retail stores, HVAC systems have been identified as one of the largest energy users, accounting for 28% to 48% of the total building energy use (Alhafi et al. 2012). The retail sector employs 15 million workers, approximately 10% of the U.S. workforce (National Retail Federation [NRF] 2010), making the indoor air quality (IAQ) of retail buildings an important occupational exposure consideration. Additionally, the average American above the age of 15 years spends 0.48 hours per day purchasing goods and groceries (American Time Use Survey [ATUS] 2011), further highlighting the importance of IAQ in these environments. Ventilation is generally regarded as the most effective measure to improve IAQ when source control is not an option. However, there is a tradeoff between increasing ventilation to improve IAQ and saving fan and conditioning energy associated with ventilation. A sustainable approach to retail environment ventilation must also consider the occupant perceptions and health exposures for retail workers and customers.

Despite the importance of retail buildings, there have been no published reviews focusing on contaminants of concern in retail buildings, and whether ventilation can be used to control these contaminants below their reference or regulatory limits. Specifically this literature review addresses the following questions:

1. How do ventilation rates measured in retail stores compare to standards?
2. What are the dominant pollutants in different types of retail spaces?
3. How do different ventilation measurement methods affect the reported results?
4. What are the associations between ventilation and IAQ?
5. What are the contaminants of concern from an exposure perspective?

This article addresses these questions by summarizing ventilation rates and pollutants concentrations reported in the relevant literature. These data are also compared to the available standards and guidelines, as well as data collected in

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non-retail environments. The reported concentrations are contextualized with information about sampling and analysis approaches where possible. Furthermore, this investigation also discusses the available data linking ventilation and measured pollutant concentrations and, finally, evaluates contaminants of concern found in retail environments through a disability-adjusted-life-years (DALYs) loss assessment. The central objective of this approach is to provide baseline data for comparison of results from the ASHRAE RP-1596 project conducted between 2011 and 2013 (Siegel et al. 2013). The goal of the RP-1596 project was to characterize the ventilation, IAQ, and occupant perception in 14 retail stores located in Texas and Pennsylvania and this literature review serves as background to that investigation.

Methodology and search criteria

The literature review systematically searched the following online databases: the ISI Web of science, Compendex, ScienceDirect, government reports, and Google Scholar. The keywords used to guide the search included various combinations of "energy," "ventilation," "infiltration," "air exchange rate," "outdoor air rate," "IAQ," multiple pollutants (i.e "volatile organic compounds (VOCs)" "semivolatile organic compounds (SVOCs)," "aldehydes," "particulate matter," "bacteria," "fungi," "radon," "carbon monoxide (CO)," "nitrogen dioxide," and "sulfur dioxide") with "retail," "mall," "supermarket," "store," "shopping," and "commercial building." Other types of buildings were also included in the search for comparison purposes. Excluding those references included from other building types, papers had to report measured ventilation, IAQ, and/or occupant survey results for retail buildings. Records for approximately 118 papers were deemed to be the most relevant to the research questions of interest, and of those 28 publications specifically reported measurements in retail spaces. After the articles were selected they were sorted into one of the following categories: (i) ventilation; (ii) particulate matter; (iii) VOCs; and (iv) other pollutants (i.e., ozone, SVOCs, microbiological contaminants, radon, CO, NO_X, and SO_X).

Summary of literature review

The existing studies with reported ventilation raters and/or IAQ measurements provide data for retail ventilation rates, particulate matter, VOCs, and other pollutant concentrations. Some of the studies included investigations that considered the impact of ventilation on these concentrations. The studies that reported ventilation and/or pollutant concentrations in retail stores are categorized and summarized in Table 1.

Ventilation

The ventilation parameters measured in retail stores, comparisons with standards and non-retail environments, and potential implications of sampling approaches are discussed in the following section.

Measurements in retail stores

The studies that reported ventilation rates in retail stores typically measured the total outdoor air exchange rates (Chao and Chan 2001; Wargocki et al. 2004; Hotchi et al. 2006; Lee and Hsu 2007; Bennett et al. 2011, 2012; Chan et al. 2012). In addition, two studies measured the components of total outdoor air exchange rate: mechanical ventilation rate supplied by the roof top units (RTUs; Bennett et al. 2011, 2012), and the infiltration rate through retail entrance doors (Shaw 1981). Table 1 includes the summary on these two studies that examined ventilation rates in more details.

Total outdoor air exchange rates

The required minimum ventilation rates provided in the ASHRAE Standard 62.1 (ASHRAE 2010a) are determined based on space type, and occupancy density. Consequently, the standard separates minimum ventilation rate for grocery stores from retail since the building activity and function of grocery stores that offer mostly food products have a different type of potential internal contaminant sources than the potential sources in other retail stores. Several studies measured air exchange rates (AER) in retail stores in the United States, Europe, and Asia. Two of these studies investigated the impact of changing AER on measured indoor pollutant concentrations and/or environmental perceptions (Wargocki et al. 2004; Hotchi et al. 2006). The number of existing studies is limited, so the current AER findings are limited to specific case studies. The average ventilation rate found in grocery stores was 1.6 ± 1.3 L/s·m$^2_{floor}$ (0.32 ± 0.26 cfm/ft$^2_{floor}$; Bennett et al. 2011; Chan et al. 2012). The average ventilation rate found in retail stores other than groceries was 1.45 ± 1.3 L/s·m$^2_{floor}$ (0.29 ± 0.26 cfm/ft$^2_{floor}$; Chao and Chan 2001; Wargocki et al. 2004; Hotchi et al. 2006; Bennett et al. 2012; Chan et al. 2012). Most of these studies used tracer gas measurements to establish time-averaged AERs and, therefore, the relatively high standard AER deviations can indicate a relatively large temporal AER variability. A detailed description of the individual studies follows.

Currently, the most comprehensive study to report AER in retail stores examined typical U.S. commercial buildings in California (Bennett et al. 2012). The study included a total of 37 buildings; 10 of which were retail establishments. Bennett et al. (2012) used SF_6 as the tracer gas. The average of the measured retail AERs was 1/h $\pm$ 0.7/h, which corresponds to 1 ± 0.5 L/s·m$^2_{floor}$ (0.2 ± 0.11 cfm/ft$^2_{floor}$). The highest AER (2.33/h) was measured at a retail store that sold water filtration supplies. According to the authors, the infiltration rates were high since the doors were open most of the time, and contributed to the high AER observed.

In a recent pilot study that aimed to quantify the contaminant emission rates in retail stores, the outdoor air exchange rates were measured in two grocery stores and three furniture stores in northern California using SF_6 as the tracer gas (Chan et al. 2012). In the 2-day-long measurement, one

Table 1. Summary of measurement studies in retail stores.

Study	N	Store type*	Ventilation/ pollutant	Sampling method	Location
Shaw 1981	10	9 Supermarket 1 Shopping mall	Infiltration	Pressure difference	
Yu et al. 1996	10	Mall	Radon	Tsivoglou procedure (TN-WL-MS filter)	Hong Kong
Grimsrud et al. 1999	1	General merchandise	$PM_{2.5}$	Continuous particle counting (Atcor APC)	Minnesota, USA
Marley 2000	1	General merchandise	Radon	Continuous radon level (NITON Rad 7)	Northamptonshire, UK
Chao and Chan 2001	2	Computer	Air exchange rate 43 VOCs	Tracer gas decay (SF_6) 4-h canister sample	Hong Kong
Kim et al. 2001	5	2 Department 3 Perfume	15 VOCs	2-h sorbent tubes	Birmingham, AL, USA
Li et al. 2001	9	Mall	PM_{10} CO Bacteria	Continuous particle mass (TSI Dusttrak) Nondispersive infrared (Thermo Electron Model 48 Analyzer) Culturing	Hong Kong
Rea et al. 2001	1	Retail (unspecified)	$PM_{2.5}$	Integrated gravimetric particle mass (PEM, MSP)	Baltimore, MD, USA
Sakai et al. 2002	1	Department	PM_{10}, PPAH	Continuous particle mass (TSI Dusttrak, AQM)	Tokyo, Japan
Hartman et al. 2004	5	2 Furniture 3 Electronics	SVOC	Polyurethane foam (PUF) plugs	Zurich, Switzerland
Wang et al. 2004	8	Supermarket/office	Radon	Passive detector (SSNTD of CR-39) Active detector-continuous radon level (SNC 1027)	China
Wargocki et al. 2004	1	Department	Air exchange rate	Outdoor air duct pressure differential	Germany
Liu et al. 2004	5	General merchandise	PM_{10}, $PM_{2.5}$, PM_1	Continuous particle mass (Dustmate)	Beijing, China
Tang et al. 2005	7	2 Supermarket 4 Department 1 Book	11 VOCs	30-min sorbent tubes	Guangzhou China
Hotchi et al. 2006	1	General merchandise	Air exchange rate 34 VOCs	Tracer gas decay (PMCH) 30-min sorbent and DNPH tubes	San Francisco, CA, USA
Loh et al. 2006	113	17 Hardware 12 Multipurpose 16 Grocery 8 Drugstore 14 Sporting goods 11 Furniture 16 Housewares 10 Department 9 Electronics	16 VOCs	1- to 3-h composite sorbent and DNPH tubes	Boston, MA, USA
Lee and Hsu 2007	12	Photocopy	$PM_{2.5}$, ultrafine particles (<0.1 μm) 5 VOCs Ozone	Continuous particle mass (Dusttrak), particle sizer (SMPS/CPC Model 3025A & APS) 2-h sorbent tubes Ecotech ML9810B	Taiwan
Bruno et al. 2008	4	2 Supermarket 2 Pharmacy	15 VOCs	24-h diffusive samplers	Bari, Italy

(Continued on next page)

Table 1. Summary of measurement studies in retail stores (*Continued*).

Study	*N*	Store type*	Ventilation/ pollutant	Sampling method	Location
Eklund et al. 2008	4	1 Jeweler 1 Clothing rental 1 Optician 1 Video rental	28 VOCs	8-h canister	New Jersey, USA
Tringe et al. 2008	2	Malls	Bacteria	DNA sequencing and cloning	Singapore
Caselli et al. 2009	2	Printing	23 VOCs	24-h diffusive samplers	Bari, Italy
Maskey et al. 2011	1	Mall	Chemical analysis of particles 1–2.5 μm and 2.5–10 μm	X-ray Microanalysis (low-Z particle Electron probe)	Korea
Bennett et al. 2011	10	2 Grocery 1 Florist 1 Cabinet 1 Water filters 1 Art supplies 1 Bookstore 2 Sporting goods 1 Convenience/gas station	Air exchange rate PM_{10}, $PM_{2.5}$, sub-3micron particles (<3 μm)	Tracer gas decay (SF_6) Steady-state PFT CO_2 equilibrium Integrated gravimetric particle mass (Harvard cascade impactors), Continuous particle counting (Met One Model 237B, TSI CPC Model 3781)	California, U.S.
Grimsrud et al. 2011	3	General merchandise	Air exchange rate 20 VOCs	Tracer gas decay (CO_2) 48-h formaldehyde and passive organic vapor badges	Minnesota, Florida, Maryland, USA
Wu et al. 2011	9	2 Grocery 7 Retail (unspecified)	Air exchange rate 30 VOCs SVOC (DEP)	Tracer gas decay (SF_6) 4-h sorbent and DNPH tubes Sorbent tubes	California, USA
Brown et al. 2012	2	1 Bookstore 1 Grocery	$PM_{2.5}$, submicron particles (<1 μm)	Continuous particle mass (TSI Dusttrak) number (TSI P-Trak Model 8525)	Atlanta, GA, USA
Chan et al. 2012	5	2 Grocery 3 Furniture	Air exchange rate PM_{10}, $PM_{2.5}$ 46 VOCs Ozone	Tracer gas decay (SF_6) Integrated gravimetric particle mass (SKC PEM) 1 and 2-h sorbent, DNPH and PFP tubes 2B Tech Model 205	California, USA
Bennett et al. 2012	10	2 Grocery 1 Florist 1 Cabinet 1 Water filters 1 Art supplies 1 Bookstore 2 Sporting goods 1 Convenience/gas station	Air exchange rate, mechanical air exchange rate	Tracer gas decay (SF_6), calibrated variable speed fan with integral airflow meter	California, USA
Dong et al. 2013	1	General merchandise	$PM_{2.5}$	Integrated gravimetric particle mass (TH-16A)	Jinan, China

*As characterized by the authors.

grocery store showed an average AER of 0.6–0.7/h (1.4 $L/s{\cdot}m^2_{floor}$, 0.28 cfm/ft^2_{floor}) while the other grocery store showed a higher average AER of 1.8/h–2.0/h (3.5 $L/s{\cdot}m^2_{floor}$, 0.7 cfm/ft^2_{floor}). The furniture stores were naturally ventilated and their AER ranged from 0.3 to 3.9/h (0.4–1.3 $L/s{\cdot}m^2_{floor}$, 0.08–0.26 cfm/ft^2_{floor}). The doors in furniture stores were kept open most of the time and the entrance and loading doors in one of these stores had a large opening area.

Another study evaluated the impact of reduced ventilation rates on indoor air quality to develop a peak load shedding strategy for a general merchandise store located in California (Hotchi et al. 2006). The study measured the ventilation rate during regular operation before shutting down a certain number of RTUs. Their study used perfluoromethylcyclohexane (PMCH) as the tracer gas. The AERs were 0.71/h and 0.95/h measured in 2 separate experiments on 2 different days.

A European study examined the relationship between AERs and occupant perception of air quality in seven buildings, one of which was a department store (Wargocki et al. 2004). In their study, the ventilation measurements were conducted under constant air volume (CAV) operation of the air handling unit. AERs were determined from the pressure differential in the outdoor air supply duct under the assumption that the building was positively pressurized, so the potential infiltration rates were neglected. The total AERs or floor area were not reported. The measured AER normalized by the floor area was 3.5 $L/s{\cdot}m^2_{floor}$ (0.7 cfm/ft^2_{floor}), and constituted 50% of the total airflow supplied to the building.

Chao and Chan (2001) investigated the relationship between typical AER and VOC concentrations in a total of 20 buildings in Hong Kong, of which 2 were computer shopping centers in 2 different shopping malls. The study used the SF_6 tracer gas decay method to measure the AER. The 2 computer shopping centers had the same AER of 0.9/h, which corresponds to 0.5 $L/s{\cdot}m^2_{floor}$ (0.1 cfm/ft^2_{floor}). The reported AER was lower than the AERs in offices (1.69/h) and public buildings (2.17/h) measured by the same study.

Lee and Hsu (2007) reported the air exchange rates for 12 photocopy centers located in Taiwan that had an average AER of 7.34/h. The study did not mention how the AER was measured.

Mechanical system ventilation rates

Only one study measured the mechanical ventilation rates in retail stores (Bennett et al. 2012). Bennett et al. (2012) reported that on average 71% of total AER was supplied mechanically. This averaged percentage for mechanically supplied air included buildings with 100% of outdoor air brought in through the HVAC system and excluding buildings with doors open most of the time and the buildings that have no mechanical ventilation. Therefore, their study indicated that even in fully mechanically ventilated buildings, unintentional ventilation, such as infiltration, makes a significant contribution to the total AERs.

Infiltration rates through entrance doors

Retail stores are usually assumed to have a tight building envelope. However, Shaw (1981) tested air leakage in 10 retail stores and found that the range of infiltration rates in these stores was greater than other building types: double the infiltration rates measured in school and quadruple the infiltration rate measured in high-rise office buildings. Although, retail ventilation systems are often designed to minimize air infiltration by pressurizing the building interior, air infiltration through door usage in entrance/exit lobbies and loading docks make a significant contribution to the whole building air leakage rate (McGowan et al. 2006). The infiltration rates through entrance doors in standalone retail and strip mall buildings have been identified as one of the significant contributors to the total energy use. For example, Bennett et al. (2012) found that buildings with the doors kept open had an average AER of 2/h, which was significantly greater than the rate of 1/h that was found when the doors were closed. To decrease infiltration through entrance doors, ASHRAE Standard 90.1-2010 requires the use of vestibules (ASHRAE 2010b). For a prototype well-sealed standalone retail building, Cho et al. (2010) estimated that the infiltration rate was 3375 m^3/h (1986 cfm) for peak hours and 442 m^3/h (260 cfm) for off-peak hours through doors with vestibules. The infiltration rate was 1.5 times the rates observed for doors without vestibules. Cho et al. (2010) also estimated potential national weighted-average site energy saving from the use of vestibules to be 2.4% and 5.6% for standalone retail and strip mall buildings respectively, higher than any other type of commercial buildings except restaurants.

Comparison to standards

Recommended outdoor ventilation rates for different building types are provided in several standards including ASHRAE Standard 62.1-2010 (ASHRAE 2010a), the European Standard CEN CR 1752-1998 (European Committee for Standardization [CEN] 1998), and the California Code of Regulations Title 24-2010 (California Energy Code 2010). ASHRAE Standard 62.1-2010 (ASHRAE 2010a) and CEN CR 1752-1998 (CEN 1998) define two required ventilation components. One ventilation component is based on the occupancy rates and the other is based on the floor area. The differentiation between the occupancy and the area requirements provide flexibility when using occupancy-based control, such as demand control ventilation with CO_2 sensors. While the California Code of Regulations Title 24-2010 recommends outdoor airflow rate no less than the larger of the ventilation rate per conditioned of floor area or 15 cfm per person. Table 2 contains a summary of the required outdoor ventilation rate for the different standards.

Table 2 shows that ASHRAE Standard 62.1-2010 recommends a combined design ventilation rate for general retail sales double of that required for grocery stores (ASHRAE 2010a). The European Standard CEN CR 1752-1998 (CEN 1998) differentiates between low polluted buildings and non-low polluted buildings. For both cases, the European Standard CEN CR 1752-1998 (CEN 1998) requires higher outdoor ventilation rates than the ventilation rates required by ASHRAE Standard 62.1-2010 (ASHRAE 2010a). In the California Code of Regulations Title 24-2010 (California Energy Code 2010), the recommended ventilation rate based on the floor area is

Table 2. Comparison of ventilation standards requirements for retail stores and supermarkets.

Standards	People outdoor air rate, L/s·m$^2_{floor}$ (cfm/ft$^2_{floor}$)	Area outdoor air Rate, L/s·m$^2_{floor}$ (cfm/ft$^2_{floor}$)	Combined outdoor air rate, L/s·m$^2_{floor}$ (cfm/ft$^2_{floor}$)
ASHRAE 62.1-2010 (ASHRAE 2010a)			
Retail sales	0.57^A (0.11)	0.6 (0.12)	1.2^A (0.23)
Supermarket	0.3^A (0.06)	0.3 (0.06)	0.6^A (0.12)
CEN CR 1752 (CEN 1998)			
Low polluted building			
Type A^B	2.1 (0.4)	2 (0.38)	4.1 (0.78)
Type B^B	1.5 (0.29)	1.4 (0.27)	2.9 (0.55)
Type C^B	0.9 (0.17)	0.8 (0.15)	1.7 (0.32)
Non-low polluted building			
Type A^B	2.1 (0.4)	3 (0.57)	5.1 (0.97)
Type B^B	1.5 (0.29)	2.1 (0.4)	3.6 (0.69)
Type C^B	0.9 (0.17)	1.2 (0.23)	2.1 (0.4)
California Code of Regulations Title 24 (California Energy Code 2010)	2.6^C (0.5)	1 (0.2)	Max (people rate, conditioned area rate)^D

^{A}To make a comparison of total outdoor air rate requirements, these values are multiplied by the occupancy density per floor area (retail 15 people/100m^2, supermarket 8 people/100m^2) provided in ASHRAE Standard 62.1-2010 (ASHRAE 2010a).
^{B}Type A corresponds to 15% of occupants dissatisfied; Type B corresponds to 20% of occupants dissatisfied; and Type C corresponds to 30% occupants dissatisfied.
^{C}From Section 1004 Occupant Load in 2010 California Building Code Title 24, Part 2 (California Energy Code 2010), the space with a design occupant density is 60 ft^2/person. Since the space is without fixed seating, the default occupant density will be one half of the maximum occupant load that is 30 ft^2/person.
^{D}California Title 24 (California Energy Code 2010) recommends the outdoor air rate to be no less than the larger of people outdoor rate and area outdoor rate.

between the values recommended by ASHRAE for retail sales and supermarkets; however, when considering the ventilation rate based on the occupancy rates, the standard California Code of Regulations Title 24-2010 (California Energy Code 2010) requires higher outdoor ventilation rate than the rates required by ASHRAE Standard 62.1-2010 (ASHRAE 2010a).

For grocery stores, the range of ventilation rates in the stores reported by Chan et al. (2012) and Bennett et al. (2011) met the minimum performance required by the ASHRAE Standard 62.1-2010 (ASHRAE 2010a) and the per floor area requirement in California Code of Regulations Title 24-2010 (California Energy Code 2010). For the non-grocery stores, two of the eight retail stores measured by Bennett et al. (2011) and two of the three retail stores measured by Chan et al. (2012) and the store measured by Hotchi et al. (2006) met both ASHRAE Standard 62.1-2010 (ASHRAE 2010a) and the floor area minimum required in California Code of Regulations Title 24-2010 (California Energy Code 2010). One retail store measured by Chan et al. (2012) met the ventilation rate per floor area recommended in California Code of Regulations Title 24-2010 (California Energy Code 2010). For retail stores measured outside the United States, measurements reported by Wargocki et al. (2004) met the ASHRAE and California standards requirements and the European Standard for type C buildings (30% of occupants dissatisfied). The measurements reported by Chao and Chan (2001) in Hong Kong did not meet the requirements of both ASHRAE and California standards.

Comparison to other environments

In order to put retail environments in context, Figure 1 shows a summary of AERs found in literature for various environments. As in all similar plots in this article, the bottom of the box indicates the 25th percentile; the horizontal line indicates the median and the top of the box the 75th percentile. The whiskers indicate the data range within 1.5 times the interquartile range of the 25th and 75th percentile. If present, any filled circles are outliers.

The investigations shown in Figure 1 showed that the ventilation rates in retail stores are generally less than bars/restaurants and healthcare facilities and comparable to other environments (i.e., fitness centers, residences, offices, and schools). The high ventilation rates found in bars and restaurants may be driven by the use of kitchen exhaust fans. This finding is expected since the outdoor airflow required by area for restaurants in ASHRAE Standard 62.1-2010 is higher than the requirement of outdoor air flow by area required for retail and grocery stores (ASHRAE 2010a). Also, the healthcare category shown in Figure 1 encompasses both treatment rooms for dentists, as well as rooms for surgery and critical care. The requirements for surgery and critical care in ASHRAE Standard 170-2008 are significantly higher than other environments (ASHRAE 2008). The published studies cited in Figure 1 demonstrated that the ventilation rates within a single category varied widely. The wide range of ventilation rates is influenced by the building envelope leakage, operation of ventilation control systems, and the approach used to calculate the ventilation rate. Commercial buildings that have a relatively large envelope area and frequently used entrance doors tend to have high ventilation rates due to infiltration.

Implications of sampling approaches

The studies cited earlier used a variety of different tracer gas techniques to measure ventilation. Several studies eval-

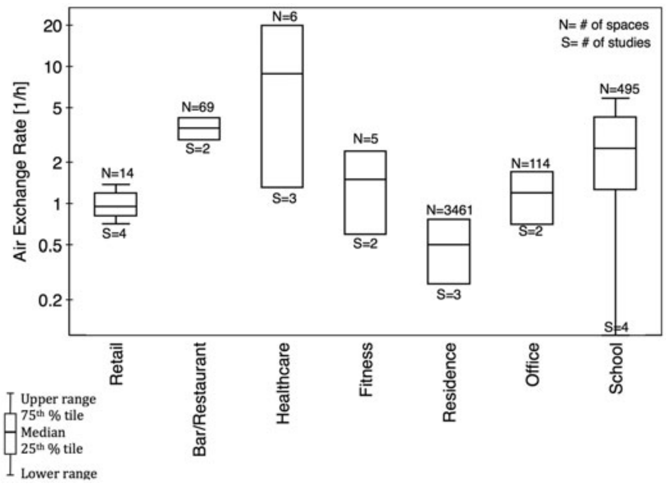

Fig. 1. Summary of air exchange rate for different environments (N = number of spaces, S = number of studies). Data for retail stores from Chao and Chan (2001), Hotchi et al. (2006), Bennett et al. (2011), and Chan et al. (2012). Data for bars/restaurants from Bennett et al. (2011) and Bohac et al. (2012). Data for healthcare facilities from Qian et al. (2010), Bennett et al. (2011), and Knibbs et al. (2011). Data for fitness from Bennett et al. (2011) and Chao and Chan (2001). Data for residences from Murray and Burmaster (1995), Offermann (2009), and Yamamoto et al. (2010). Data for offices from Chao and Chan (2001) and Parthasarathy et al. (2013; analyzed values from the BASE Study: Persily et al. 2005). Data for schools from Godwin and Batterman (2007), Apte et al. (2012; including results from two studies), and Ramalho et al. (2012).

uated sources of uncertainties when conducting tracer gas measurements. Axley (1991) found that the significant uncertainty of tracer gas measurements came from incomplete air mixing and unsteady airflow rates. Sandberg (1989) investigated the effect of airflow rates on the measurement errors for both constant concentration and decay methods, and demonstrated good agreement between the two tested methods. Sandberg (1989) also concluded that the measurement errors resulting from the changes in airflow rates during the experimental time period could generally be neglected when compared to the large errors due to poor air mixing in the tested environments. Poor mixing was estimated to contribute an error of 12% to 18%.

Previous studies demonstrated good correlation between the tracer gas constant injection and decay methods (Kumar et al. 1979; Sandberg 1989; Axley 1991; Heidt and Werner 1986) and between constant concentration and decay methods when the measurement was conducted for fixed airflow rates (Kumar et al. 1979). However, various analytical approaches might provide different ventilation rates and uncertainties. Sherman (1990) reported that each analytical approach provided strong results at specific environmental conditions. The study compared many different approaches including regression, integral, averaging, and transient techniques with various measurement time intervals and airflow rates. The averaging decay method presented high uncertainties when the measurement time interval increased because the tracer gas concentrations tended to be low and variable at the end of the experiment. The regression and integral decay methods reduced the errors found in the averaging decay method, and both methods had the same level of uncertainty. The constant concentration requires preparations of the system controls for real time tracer gas injection to maintain the concentration at the same level. The uncertainties from this technique depended on the measurement time interval and the accuracy of system controls, but not on the changes in the airflow rates.

Due to high instrumentation expenses and/or labor intensity in measuring AERs with the typical tracer gas decay method using SF_6, and the fact that SF_6 is potent greenhouse gas, there is an interest in understanding CO_2-based ventilation rate measurements. One particular area of interest is the use of metabolic CO_2 as the tracer for continuous ventilation rate measurements. The CO_2 generation rate per occupant is correlated with the metabolic rate, respiration quotient and body surface area that depend on factors such as occupant activity type and physical condition. If the occupancy rates are known, the CO_2 generation rate can be calculated, and measurements of CO_2 levels can be used to calculate AER and percentage of AER supplied mechanically.

The successful application of CO_2 as the tracer gas has been demonstrated in residential and commercial buildings (Aglan 2003; Asadi et al. 2011; Grimsrud et al. 2011). In general, these studies were performed in single zone settings with easily determined occupancy rates. While the single zone assumption could be used for well-mixed retail floors, the difficulty in using CO_2 as a tracer in retail buildings comes from transient and difficult-to-account-for occupancy rates.

Grimsrud et al. (2011) measured ventilation rates in three large retail stores located in three climate regions of the United States (Minnesota, Florida, and Maryland) using the CO_2 decay method. Hourly occupancy data for 48-hour periods, including employees, were used together with continuous CO_2 measurements taken in 6 to 12 locations in the stores to determine the hourly ventilation rates. Results agreed with SF_6 tracer-decay measurements and measurement results for the rooftop ventilation systems with an uncertainty of 10%.

Instead of using CO_2 decay method to measure the ventilation rate, Bennett et al. (2011) used the CO_2 equilibrium (steady-state) method and showed that the findings from this method are unreliable. In some of the test sites, the CO_2 concentrations never reached steady state. In other buildings, the occupancy profiles were not consistent and in other buildings the difference between the indoor and outdoor CO_2 concentrations was small and caused large uncertainties. The authors recommended the use of the tracer decay method instead of the CO_2 steady-state method for future studies. Beside using CO_2 equilibrium to measure ventilation rates, Bennett et al. (2011) also used SF_6 decay method and perfluorocarbon tracer (PFT) steady-state method. The R^2 value for the correlation between the SF_6 decay method and the PFT method was 0.76, between the PFT and CO_2 equilibrium was 0.84, and between the SF_6 and the CO_2 equilibrium was 0.74. According to the authors, the AER measured by steady state PFT was lower than the AER determined by SF_6 decay, probably because the steady state is influenced by the nighttime period, which tends to have lower ventilation rates than during the day. Another reason is related to the poor mixing in some buildings. The poor mixing lead to higher ventilation rates determined by SF_6 decay as the SF_6 sampling was done in areas in the building with significant airflow. Nonetheless, the SF_6 decay method was considered as the most accurate method to measure ventilation rates in retail stores.

IAQ

The following sections summarize the literature on contaminants measured in retail stores: particulate matter, VOCs, and other pollutants (i.e., ozone, SVOCs, microbiological contaminants, radon, and CO). For each contaminant, the average observed concentration, comparisons to standards, and non-retail environments, as well as the implications of collection methods, is summarized.

Particulate matter

There is reason to believe that certain retail environments have particulate matter sources that are of indoor origin. Many groceries, general merchandise, and malls include food preparation areas or food courts. Cooking events can generate fine and ultrafine particles (e.g., Abt et al. 2000; Wallace et al. 2004). Other retail sites that sell new clothing can be a source for textile particles (Maskey et al. 2011). Additionally, retail environments usually have high foot traffic areas that contribute to indoor particles through movement of people, transport of outdoor dust, and resuspension of previously deposited particles (e.g. Abt et al. 2000; Lee et al. 2002). Frequent cleaning and other activities, such as the use of forklifts to move merchandise or a propane-powered floor burnisher, may also contribute to elevated particle concentrations (e.g. Abt et al. 2000; Grimsrud et al. 1999).

Although short in duration, nonoccupational exposures occurring during time spent in retail buildings can be significant contributors to 24-h personal exposures (Chang et al. 2000; Rea et al. 2001). Rea et al. (2001) suggested that up to 35% of particle exposure takes place in microenvironments (primarily retail buildings, restaurants, and coffee shops) where people spend only 4% to 13% of their time. Exposure to particulate matter has been associated with serious health effects (e.g., lung cancer, cardiovascular morbidity and mortality, ischemic heart disease mortality, nonfatal myocardial infarction, heart rate variability, and systemic inflammation) in several epidemiological studies (e.g., Dockery et al. 1993; Pope et al. 2003; Pope and Dockery 2006; Weichenthal et al. 2008; Brook et al. 2010). The USEPA considers both PM_{10} and $PM_{2.5}$ as criteria pollutants that can cause serious health effects. The World Health Organization (WHO) air quality guideline asserts there is no threshold below which particulate matter is not associated with adverse health effects (WHO 2005). It should be noted that PM standards/guidelines are established for outdoor concentrations. In the absence of IAQ standards, we assume that ambient standard/guidelines also apply to indoor concentrations. The comparisons between indoor concentrations and outdoor standards are used for reference only. The average particulate matter concentrations found in retail

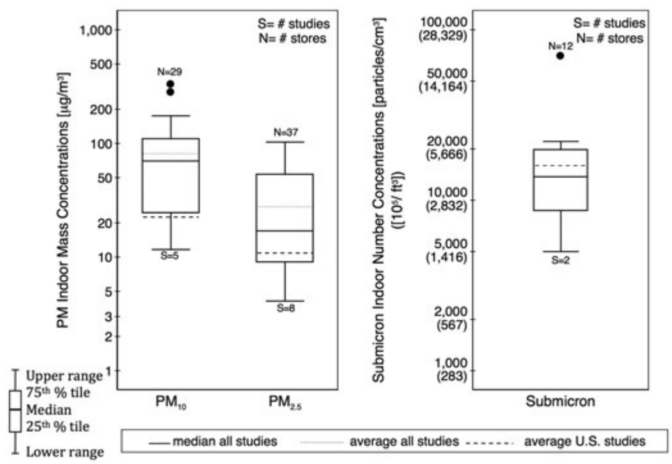

Fig. 2. Summary of PM_{10}, $PM_{2.5}$ mass concentrations and submicron particle number concentrations. The horizontal line represents the median concentration, the dotted line represents the mean concentration, and the short-dashed line represents the mean concentration reported only by U.S. studies. Data for PM_{10} from Li et al. (2001), Sakai et al. (2002), Liu et al. (2004), Bennett et al. (2011), and Chan et al. (2012). Data for $PM_{2.5}$ from Grimsrud et al. (1999), Rea et al. (2001), Liu et al. (2004), Lee and Hsu (2007), Bennett et al. (2011), Brown et al. (2012), Chan et al. (2012), and Dong et al. (2013). Data for submicron particles from Bennett et al. (2011) and Brown et al. (2012).

stores, possible indoor sources, comparisons with standards and other environments, and implications of sampling approaches are discussed in the following section.

Measurements in retail stores

Indoor particulate matter concentrations in retail spaces was reported in 11 articles (Grimsrud et al. 1999; Li et al. 2001; Rea et al. 2001; Sakai et al. 2002; Liu et al. 2004; Lee and Hsu 2007; Bennett et al. 2011; Maskey et al. 2011; Chan et al. 2012; Brown et al. 2012; Dong et al. 2013). Of those studies, five studies reported PM_{10}, eight studies reported $PM_{2.5}$, one study reported PM_1, and one study reported particle with attached polycyclic aromatic hydrocarbons (PPAH) mass concentrations. Additionally, Lee and Hsu (2007) Bennett et al. (2011), and Brown et al. (2012) reported ultrafine or a proxy for ultrafine (submicron, sub-3 μm) number concentrations. Also, one study reported chemical analysis of fine and coarse particles (Maskey et al. 2011). Among these studies, only three (Lee and Hsu 2007; Bennett et al. 2011; Chan et al. 2012) also reported the ventilation rates of the retail spaces. Figure 2 summarizes PM_{10}, $PM_{2.5}$, and submicron particle concentrations from these studies. In addition to the figure features described for Figure 1, the dotted line represents the mean concentration and the short-dash line represents the mean concentration reported only by U.S. studies.

PM_{10} and $PM_{2.5}$. Median PM_{10}, shown in Figure 2, is dominated by studies conducted in Hong Kong, Taiwan, Japan, and China, where the outdoor air was an important contributor to indoor PM_{10} (Li et al. 2001; Lee and Hsu 2007; Dong

et al. 2013). Bennett et al. (2011) and Chan et al. (2012) are the only studies that reported PM_{10} concentrations in U.S. retail stores. These two studies reported an average PM_{10} mass concentration for the 15 retail stores of 24.3 $\mu g/m^3$. Using data from Grimsrud et al. (1999), Rea et al. (2001), Bennett et al. (2011), Brown et al. (2012), and Chan et al. (2012), the average $PM_{2.5}$ mass concentration calculated for U.S. retail sites is 11.6 $\mu g/m^3$. Approximately half of all the stores tested had an indoor-to-outdoor (I/O) ratio larger or equal to 1, while the remaining stores had I/O ratio less than 1. This suggests that indoor PM_{10} and $PM_{2.5}$ can originate either indoors, outdoors, or both. The reported indoor sources include: cleaning (Grimsrud et al. 1999), cooking (Li et al. 2001; Bennett et al. 2011; Brown et al. 2012), and smoking (Li et al. 2001). Additionally, there is evidence that grocery stores exhibit higher particle concentrations than other types of stores: $PM_{2.5}$ mean concentration recorded in grocery stores measured in the United States was 31.7 $\mu g/m^3$, with a maximum concentration of 90 $\mu g/m^3$ (Bennett et al. 2011; Brown et al. 2012; Chan et al. 2012). The main contributor to elevated concentrations in these grocery stores is cooking events. Besides grocery stores, the data available for U.S. sites is insufficient to draw conclusions about specific indoor particle sources for different store types.

Submicron particles. Figure 2 contains a graph showing the submicron particle number concentrations reported by two studies conducted in the United States (Bennett et al. 2011; Brown et al. 2012). The average submicron concentration was 17,000/cm^3 ($481 \cdot 10^6$/ft^3). It is worth noting that the submicron concentration measured in these studies is a good proxy for ultrafine particles since the particle number concentration is typically dominated by small particles. Another non-U.S. study reported only the highest ultrafine number concentrations observed during photocopying of 10^8/cm^3 ($3{,}000 \cdot 10^9$/ft^3; Lee and Hsu 2007); thus, the number reported in Lee and Hsu (2007) is not included in Figure 2. These investigations associated submicron particle number concentrations with in store cooking, cleaning, photocopying, and specific activities (presence of silk screening area; Lee and Hsu 2007; Bennett et al. 2011; Brown et al. 2012).

PPAH. Sakai et al. (2002) measured particles with diameters under 1 μm with PPAH, and reported an indoor average concentration of 3.5 ng/m^3 and an outdoor average concentration of 45.2 ng/m^3 in the parking lot of the store. Sakai et al. (2002) reported that the average concentration of PPAH in the department store was low compared to levels measured by their study in restaurants, near garages, and in smoking rooms.

Chemical analysis of coarse and fine particles. Maskey et al. (2011) reviewed the chemical make-up of 7900 particles in 1–2.5 μm and 2.5–10 μm diameter bins in an underground mall in Korea. Maskey et al. (2011) reported that soil derived particles were the most common, followed by (in order) primary soil-derived, carbonaceous, iron-containing, secondary soil derived, and secondary sea-salt particles. Given the proximity of the underground mall to subway terminals, their results for iron-containing particles correspond well with other studies in subway terminals (e.g., Aarnio et al. 2005). A significant baseline concentration of larger, thread-like textile particles with the chemical constituents of carbon, nitrogen, and oxygen were also observed in some of the samples.

Comparison to outdoor standards

Comparison of the measurements reported in the literature to the standards and guidelines is difficult, owing to the difference of averaging periods (1-year average or 24-hour average for regulatory/reference levels vs. 8 hours or less reported in literature studies), location (ambient vs. indoor), and different measurement methods. Given these limitations, comparison with the National Ambient Air Quality Standards (NAAQS; http://www.epa.gov/air/criteria.html) limit (24-hour PM_{10} limit = 35 $\mu g/m^3$, and annual $PM_{2.5}$ limit = 12 $\mu g/m^3$) reveals that both PM_{10} and $PM_{2.5}$ mean mass concentrations measured in retail stores in the United States were below outdoor regulatory levels. However, the mean concentration measured in grocery stores in the United States for $PM_{2.5}$ mass concentration was 31.7 $\mu g/m^3$, which is 2.6 times higher than the NAAQS value.

Comparison to non-retail environments

PM_{10} and $PM_{2.5}$. Figure 3 shows a summary of PM_{10}, and $PM_{2.5}$ mass concentrations found in the literature for

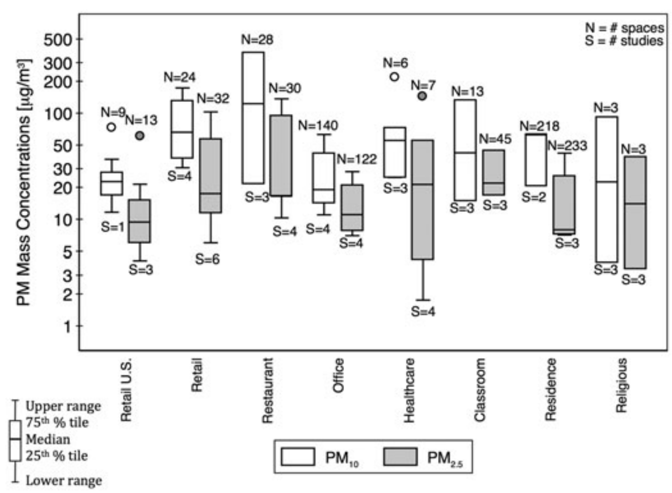

Fig. 3. Summary of PM_{10}, $PM_{2.5}$ mass concentrations (N = number of spaces, S = number of studies). Data for retail stores from Grimsrud et al. (1999), Li et al. (2001), Rea et al. (2001), Sakai et al. (2002), Liu et al. (2004), Lee and Hsu (2007), Bennett et al. (2011), Brown et al. (2012), Chan et al. (2012), and Dong et al. (2013). Data for restaurants from Liu et al. (2004), Buonanno et al. (2010), Bennett et al. (2011), and Brown et al. (2012). Data for offices from Turk et al. (1989), Burton et al. (2000), Liu et al. (2004), and Bennett et al. (2011). Data for healthcare facilities from Tsai et al. (2000), Helmis et al. (2007), Bennett et al. (2011), and Brown et al. (2012). Data for classrooms from Liu et al. (2004), Branis et al. (2005), and Weichenthal et al. (2008). Data for residences from Ozkaynak et al. (1997), Long et al. (2000), and Wheeler et al. (2011). Data for religious facilities from Bennett et al. (2011), Daher et al. (2011), and Chuang et al. (2012).

various environments, none of which included (legal) smoking activities. Considering other environments, PM mass concentrations measured in U.S. retail stores are comparable to offices, religious buildings, healthcare facilities, and residences, and generally less than restaurants and classrooms. The wide range of values is largely the result of differences in averaging periods, ventilation rates, source strengths, outdoor concentrations, and sampling techniques used in the studies.

Submicron particles. Submicron number concentrations reported in retail environments were lower than concentrations (average > 50,000/cm^3 [>10^9/ft^3]) observed in restaurants or residences during cooking events (Buonanno et al. 2010; Bennett et al. 2011; Wallace and Ott 2011), in photocopy centers (Lee and Hsu 2007; Morawska et al. 2009), and near freeways or busy roads (Zhu et al. 2002, 2008; Kaur et al. 2005). Other environments where the submicron concentrations were lower than values reported for retail stores include residences measured overnight or with no cooking events, and classrooms (Zhu et al. 2005; Weichenthal et al. 2008; Mullen et al. 2011).

Implications of sampling approaches

Broadly, the sampling techniques used to measure particle mass concentrations can be divided into two categories: filter-based integrated gravimetric methods and real-time methods.

For the 10 studies found in the literature (Grimsrud et al. 1999; Li et al. 2001; Rea et al. 2001; Sakai et al. 2002; Liu et al. 2004; Lee and Hsu 2007; Bennett et al. 2011; Chan et al. 2012; Brown et al. 2012; Dong et al. 2013), 4 studies used a gravimetric technique (Rea et al. 2001; Bennett et al. 2011; Chan et al. 2012; Dong et al. 2013), 3 studies used a laser photometric instrument combined with gravimetric technique for calibration (Li et al. 2000; Lee and Hsu 2007; Brown et al. 2012), and 3 studies used a photometric instrument without any calibration (Grimsrud et al. 1999; Sakai et al. 2002; Liu et al. 2004). Since gravimetric methods directly measure the mass of particles accumulated during a sampling period, it is considered the most reliable method. However, there are many difficulties in conducting this type of measurement. Bennett et al. (2011) reported issues that arose during sampling such as the filter ripped during sampling and poor seal of the impactor. Bennett et al. (2011) also reported differences between results obtained when sampling $PM_{2.5}$ and PM_{10} directly through one impactor compared to summing PM masses through multiple stages of impactors.

For the studies that used laser photometer instruments with no calibration (Grimsrud et al. 1999; Sakai et al. 2002; Liu et al. 2004), reported concentrations are less accurate than the studies that used gravimetric technique. Laser photometers are generally calibrated at the factory against a gravimetric reference using a specific test dust. Aerosols with different physical/optical properties compared to the calibration dust can produce photometer responses differing by as much as a factor of 3 (Jiang et al. 2011). Ramachandran et al. (2000) demonstrated that the readings of TSI DustTrak (see Table 1) could exceed the true $PM_{2.5}$ values by a factor of 5 to 10. In addition to the calibration issue, the studies that employed a real-time particle counter and then converted the particle concentration to a mass concentration must assume a particle density, which increases the uncertainty (Kim et al. 2001; Chao and Chan 2001; Tang et al. 2005; Hotchi et al. 2006; Loh et al. 2006; Lee and Hsu 2007; Bruno et al. 2008; Eklund et al. 2008; Caselli et al. 2009; Wu et al. 2011; Grimsrud et al. 2011; Chan et al. 2012).

Ultrafine particle measurements were monitored using condensation particle counters (CPCs): TSI ultrafine particle counters Model 3781 (0.006–3 μm; Bennett et al. 2011), Model 3025A (0.003–3 μm; Lee and Hsu 2007), and Model 8525 (0.02–1 μm; Brown et al. 2012). Given the differences in particle size range and instrument responses to environmental conditions and aerosol composition used in these studies, we would expect different results from these instruments if used in the same space.

VOCs

VOCs are a broad class of chemicals ubiquitous in the indoor environment. Concentrations of VOCs have the potential to be elevated in retail spaces as VOCS are emitted by a large range of products and activities. VOCs can be emitted by the retail merchandise (e.g., textiles and furniture containing pressed wood), produced during typical building operational procedures, such as cooking or cleaning, and by building materials and displays present in the space. There is little evidence of harmful health effects caused by the majority of VOCs at concentrations typically found nonindustrial indoor environments (Molhave 2003). The average VOC concentrations found in retail stores, possible indoor sources, comparisons with standards and other environments, and implications of sampling approaches are discussed in the following section.

Measurements in retail stores

Indoor VOC concentrations in retail spaces have been reported in 12 journal articles, as shown in Table 1. The investigators found a total of 60 different VOCs in over 160 retail spaces using a variety of collection techniques. For the purpose of this article, VOCs are divided into eight categories. The VOC categories were developed by combining compounds that exhibit similar chemical behaviors and/or potential exposure characteristics. Table 3 lists the individual compounds in each category.

Eight of the papers in Table 1 (Kim et al. 2001; Tang et al. 2005; Hotchi et al. 2006; Lee and Hsu 2007; Bruno et al. 2008; Caselli et al. 2009; Wu et al. 2011; Chan et al. 2012) provided information that allowed for further analysis of the reported VOCs using this categorization. A summary of these results, converted to molar concentrations, is presented in Figure 4. Concentrations are weighted by the number of stores sampled when reported as an average of a store type.

Aromatic compounds. The concentration of aromatic compounds averaged 15 ± 41 ppb (mean ± standard deviation), with a maximum concentration of 195 ppb measured for toluene in photocopy centers (Lee and Hsu 2007). The BTEXS group (benzene, toluene, ethylbenzene, xylenes, and styrene) were found to have the highest concentrations in retail stores

Table 3. VOC categories and constituting compounds.

Name of category	*N**	Compounds
Aromatic compounds	11	Xylene and isomers, 1-ethyl-2-methylbenzene, 1-ethyl-3-methylbenzene, benzene, ethylbenzene, naphthalene, phenol, propylbenzene, styrene, toluene, benzothiazole, butylated hydroxytoluene
Halogenated compounds	8	Carbon tetrachloride, chloroform, freon 11, freon 113, methylene chloride, tetrachloroethylene, trichloroethylene, 1,4-dichlorobenzene
Terpenoids	6	Limonene, pinene, p-cymene
Alkanes	6	Cyclohexane, decane, dodecane, heptane, hexane, nonane, undecane
Alcohols	6	1-Butanol, 1-methanol-3-cyclohexene, 2-butoxyethanol, 2-ethyl-1-hexanol, ethanol, isopropyl alcohol, cyclohexanol
Carbonyls	6	2-Butanone, 4-methyl-2-pentanone, acetone, benzaldehyde, butyl ester acetic acid, decanal hexanal, nonanal, octanal, pentanal, acrolein
C_1-C_2 aldehydes	5	Acetaldehyde, formaldehyde
Remaining VOCs	9	1-(2-Methoxypropoxy)-2-propanol, decamethylcyclopentasiloxane, TMPD-MIB, TMPD-DIB, 1,3-butadiene, methyl tert-butyl ether, diethyl phthalate

*Number of studies investigating the category considered. Note that not all studies provided concentrations we could use for further analysis.

investigated in seven of the eight studies. Identified sources, particularly of toluene, include motor vehicle exhaust (Chao and Chan 2001; Kim et al. 2001), newspaper ink in printing shops (Caselli et al. 2009), photocopy centers (Lee and Hsu 2007), and building materials in pharmacies (Bruno et al. 2008) and shopping malls (Tang et al. 2005).

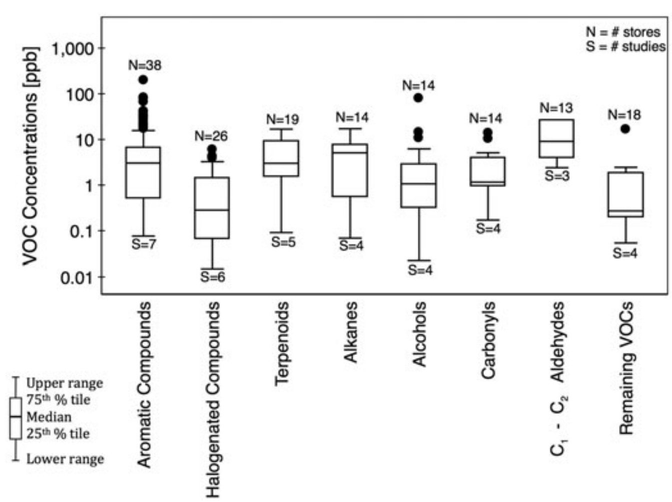

Fig. 4. Summary of categorized VOC concentrations. Data for aromatic compounds from Kim et al. (2001), Tang et al. (2005), Hotchi et al. (2006), Lee and Hsu (2007), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for halogenated compounds from Kim et al. (2001), Tang et al. (2005), Hotchi et al. (2006), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for terpenoids from Kim et al. (2001), Hotchi et al. (2006), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for alkanes from Hotchi et al. (2006), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for alcohols from Hotchi et al. (2006), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for carbonyls from Hotchi et al. (2006), Bruno et al. (2008), Caselli et al. (2009), and Wu et al. (2011). Data for C_1-C_2 aldehydes from Hotchi et al. (2006), Wu et al. (2011), and Chan et al. (2012). Data for remaining VOCs from Kim et al. (2001), Hotchi et al. (2006), Wu et al. (2011), and Chan et al. (2012).

Halogenated compounds. The concentrations for this category averaged 1 ± 1 ppb, with a maximum concentration of 6 ppb measured for trichloroethylene in a department store (Tang et al. 2005). Tang et al. (2005) identified halogenated compounds as contaminants of concern in a shopping mall in South China, mainly due to chlorinated cleaning agents, deodorizers, and domestic electrical appliances.

Terpenoids. The mean concentration of the terpenoids category was 5 ± 5 ppb, with a maximum of 17 ppb for limonene. Limonene, emitted by household cleaning products, was the primary pollutant in two supermarkets (Bruno et al. 2008).

C_1-C_2 aldehydes. Three studies reported acetaldehyde and formaldehyde concentrations across a variety of store types, and all suggested formaldehyde was the primary contaminant of concern. C_1-C_2 aldehydes concentrations averaged 13 ± 10 ppb, with formaldehyde reaching a maximum of 26 ppb, and acetaldehyde concentrations as high as 15 ppb. Identified formaldehyde sources included pressed wood products (Hotchi et al. 2006; Loh et al. 2006) and carpet (Wu et al. 2011). Acetaldehyde is typically emitted during baking processes and is naturally present in ripe fruits.

Carbonyls. The mean concentration of the carbonyls category was 3 ± 4 ppb. The highest concentration (14 ppb) was measured for acetone in the retail stores sampled by Wu et al. (2011), where it was likely emitted by medical and cosmetics products. Due to proximity to a nail salon, acetone was the primary contaminant of concern in the stores of a strip mall center (Eklund et al. 2008).

Alkanes, alcohols, and other VOCs. Compounds from the alkanes, alcohols, and remaining VOCs categories were not considered pollutants of concern by any study. They were found in retail spaces at mean concentrations of 5 ± 4 ppb, 5 ± 15 ppb and 1 ± 3 ppb, respectively. Specific sources were not identified. Four studies reported concentrations of non-halogenated C_6-C_{12} alkanes that are typically emitted by fuels, paints, sealants, and grease. Compounds from the alcohol category are typically generated by solvent-containing products and baking activities.

Overall individual VOC concentrations were low, with a mean under 10 ppb and a median under 2 ppb across all compounds and all studies. It remains unclear if the variability between store types explained the variation in VOC concentrations. Studies in which samples were collected in different store types can help to answer this question. Loh et al. (2006) reported higher toluene concentrations in multipurpose store, higher formaldehyde concentrations in housewares and furniture stores, and higher acetaldehyde concentrations in grocery stores. Chan et al. (2012) conducted measurement in two grocery stores and three furniture stores, and reported similar trends in formaldehyde and acetaldehyde concentrations.

In addition to individual VOC concentrations, three studies reported TVOC concentrations averaging 439 ± 313 $\mu g/m^3$. Tang et al. (2005) computed the TVOC by adding the concentrations as indicated by the peak area in total ion chromatography of all species together, while Bruno et al. (2008) and Caselli et al. (2009) summed all reported VOC concentrations. Bruno et al. (2008) observed the minimum TVOC concentration (188 $\mu g/m^3$) in a supermarket, and the maximum concentration (1393 $\mu g/m^3$) in a pharmacy.

Figure 5 contains a comparison of categorized VOC and TVOC concentrations by store type. Considering the limitations in sample size, number of compounds per category, and the presence of confounding factors across studies, there are insufficient data to draw definitive conclusions about differences between store type and VOC category concentrations.

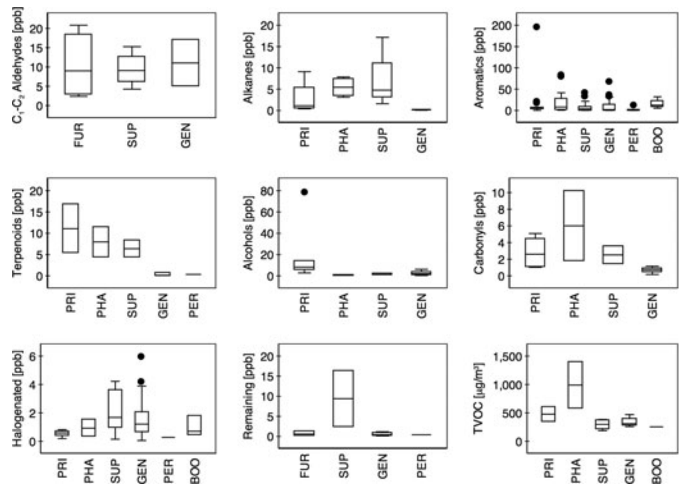

Fig. 5. Comparison of categorized VOC and TVOC concentrations by store type. FUR = furniture store (3 stores, data from Chan et al. 2012), SUP = supermarket/grocery (6 stores, data from Tang et al. 2005; Bruno et al. 2008; Chan et al. 2012), GEN = general merchandise/department store (7 stores, data from Kim et al. 2001; Tang et al. 2005; Hotchi et al. 2006), PRI = printing shop/photocopying center (14 stores, data from Lee and Hsu 2007; Caselli et al. 2009), PHA = pharmacy (2 stores, data from Bruno et al. 2008), PER = perfume shop (3 stores, data from Kim et al. 2001), and BOO = bookstore (1 store, data from Tang et al. 2005).

Comparison to exposure guidelines

Little is known regarding the health impacts from exposure to mixtures VOCs. For this reason, in this section we consider the health impacts of individual VOCs. Comparison of VOC concentrations to exposure guidelines is difficult as many organizations recommend different concentrations limits for specific compounds. We will consider here the most conservative reference limits published. Moreover, most chronic health guidelines assume either a continuous exposure, or an eight average period; while the duration of measurements conducted in the studies reviewed ranged from 30 min to 24 h. Given the assumption that the samples collected in these studies were representative of typical concentrations, a comparison to heath guidelines can be used in assessing exposure to VOCs. Six of the reviewed studies mentioned concerns about exposure of retail workers (Tang et al. 2005; Hotchi et al. 2006; Loh et al. 2006; Lee et al. 2007; Wu et al. 2011; Chan et al. 2012).

Across all studies that measured VOCs, four compounds were reported as exceeding the most conservative exposure guidelines published. Formaldehyde concentrations (average concentrations across all the studies 20 ± 8 ppb) exceeded the California Office for Environmental Health and Hazard Assessment chronic recommended exposure limit (CA OEHHA; chronic REL = 7 ppb; http://oehha.ca.gov/air/allrels.html) in most of the stores measured. In general merchandise stores (Hotchi et al. 2006; Chan et al. 2012), acetaldehyde concentrations were above the inhalation reference concentrations (RfC) set by the USEPA at 5 ppb (http://www.epa.gov/ttn/atw/hlthef/acetalde.html). It should also be noted that the RfC is defined as "an estimate with uncertainty spanning perhaps an order of magnitude," that assumes a continuous exposure over a lifetime. Tang et al. (2005) reported benzene concentrations above the Hong Kong Indoor Air Quality Objective (HKIAQO) objective of 5 ppb. Acrolein was only measured by Chan et al. (2012), and concentrations exceeded the US EPA RfC of 0.009 ppb.

Out of the 160 compounds detected across all studies that measured VOCs, several are considered potentially carcinogenic by the USEPA. For instance carbon tetrachloride, chloroform, and tetrachloroethylene were detected at several sites, but at concentrations lower than their USEPA RfCs. However, trichloroethylene concentrations averaged 1.1 ± 1.8 ppb, above its RfC of 0.4 ppb. This result is dominated by the concentrations found in a shopping mall in South China (Tang et al. 2005).

Comparison to non-retail environments

Two of the reviewed studies investigated multiple microenvironments. These studies allow for direct comparisons between VOC concentrations and eliminate potential confounding factors such as sampling techniques. Unfortunately, the findings are inconsistent, especially for VOCs generated outdoors, for which the location of the space is the decisive factor. For instance, Loh et al. (2006) reported higher average concentrations of aromatic compounds in retail stores than in transportation microenvironments, while Kim et al. (2001) reached the opposite conclusion. Residences and offices are two significant indoor environments, both in terms of occupancy and published investigations. The Relationship of Indoor, Outdoor, and Personal Air (RIOPA) Study was conducted in 100 residences from 1999 to 2001 in three U.S. cities (Weisel et al. 2005). Logue et al. (2011) reviewed 77 published studies that reported measurements of chemical pollutants in residences from 2001 to 2008 (newer homes than in the RIOPA Study) in the United States and in countries with similar lifestyles. The Building Assessment Survey and Evaluation (BASE) Study involved 100 office buildings across the United States (Apte and Erdmann 2002). The mean categorized VOC concentrations in retail stores, presented in Figure 4, were generally similar or slightly lower compared to the results reported in the BASE and the RIOPA studies. However, some of the contaminants found in retail stores were much lower than the mean concentration reported by Logue et al. (2011). For instance, formaldehyde averaged 20 ± 8 ppb in retail stores, 21 ± 11 ppb in residence (RIOPA; Weisel et al. 2005), 56 ± 25 ppb in residences (Logue et al. 2011), and 13 ± 7 ppb in offices. The concentrations in retail spaces are also in general agreement with averaged concentrations found in residences in North America in the 1990s, as reported by Hodgson and Levin (2003). Notable exceptions are acetone and toluene, which are on average 10 times higher in retail environments when compared to residences.

Implications of sampling approaches

While all samples of C_1-C_2 aldehydes were obtained using 2,4-dinitrophenylhydrazine (DNPH) cartridges, the sampling approach for all other VOCs differed amongst studies (cf. Table 1). VOCs were measured using stainless steel canisters (Summa canisters) in two studies, passive organic badges in three studies, and sorbent tubes in seven studies. The sorbents used in the latter seven studies also differed: four used tubes packed with Tenax TA, one with Tenax GR, and two with multiple sorbents.

Each sampling approach is associated with characteristic issues that can affect the identification and quantification of VOCs. For example, Summa canisters have been reported to show low recovery of alcohols (Ochiai et al. 2002), as well as aldehydes and terpenes (Batterman et al. 1998). Compounds with fewer than four carbon atoms and relatively high vapor pressures such as acetone, ethanol and isopropanol, are not readily sorbed by Tenax (Harper 2000). In addition to the use of different collection methods, variations in the duration of sampling from 30 min to 24 h might confound comparisons. Loh et al. (2006) also mentioned the potential differences in concentrations arising from mobile/personal versus stationary sampling, as the space might not be perfectly mixed.

Few field studies have investigated the differences in the concentrations obtained by various sampling techniques used simultaneously, and quantified these biases for the specific compounds collected. Depending on the compound sampled, organic vapor monitors have been reported to underestimate (Stock et al. 1999) or overestimate (Pratt et al. 2005) concentrations when compared to canisters. Dobos (2000) reported that styrene concentrations measured by organic vapor monitors were 31% higher than measurements from sorbent tubes.

Other pollutants

Ozone

Ozone is a contaminant that is typically generated though photochemical reactions between nitrogen oxides and VOCs in the troposphere. Many epidemiological studies have documented the adverse health effects of ozone on the respiratory and cardiovascular systems, particularly the association between short-term exposure to ozone and daily mortality (Bell et al. 2004; Gryparis 2004; Ito et al. 2005; Levy et al. 2005; Parodi et al. 2005; Zhang et al. 2006). Only two studies reported ozone concentrations in retail spaces. Lee and Hsu (2007) reported a maximum indoor ozone concentration of 70 ppb, measured when photocopying activities occurred, nearing the current USEPA NAAQS for ozone of 75 ppb. Indoor ozone concentrations before photocopying operations averaged about 4 ppb. Chan et al. (2012) presented the temporal profile of indoor and outdoor ozone concentrations for three stores over an afternoon. Average indoor concentrations ranged from 10 to 25 ppb, while average outdoor concentrations ranged from 29 to 37 ppb, both far below ozone health standards. The authors noted a positive relationship between ozone I/O ratios and AERs, moderated by potential losses to filters in mechanically ventilated spaces, further confirming the importance of outdoor air as a source of ozone.

SVOCs

SVOCs may be particularly important in the retail environment. Many stores have vinyl flooring, merchandise made of soft and hard plastics, foams, and fabrics, all of which may contain plasticizers and flame retardants. Also, cooking events, which occur in some retail environments, can release PAHs and pyrene (Weschler and Nazaroff 2008). Several SVOCs have been associated with adverse health effects and many SVOCs are endocrine-disrupting chemicals. Studies examining SVOC metabolites in blood and urine have provided direct evidence of widespread human exposure (Heudorf et al. 2007; Vonderheide et al. 2008; Weschler and Nazaroff 2008). Despite their health impact, SVOCs are understudied in indoor environments and there are relatively few standardized methods for their analysis. Only two studies have reported SVOC concentrations in retail environments (Hartmann et al. 2004; and Wu et al. 2011). Hartmann et al. (2004) used polyurethane foam (PUF) plugs to collect air samples and reported the concentrations of eight organophosphates in two furniture and three electronic stores in Zurich, Switzerland. Tributyl phosphate (TBP), tris(2-chloroethyl) phosphate (TCEP), and triphenyl phosphate (TPP) were found in all of sites. Tris(2-chloro-isopropyl)phosphate (TCPP), a flame retardant, was found in furniture stores, but not in electronics stores, and tris(1,3-dichloroisopropyl) phosphate (TDCP) was not found in any of the locations studied. Wu et al. (2011) used multi-bed sorbent tubes with a primary bed of Tenax-TA sorbent backed with a section of Carbosieve III to capture air samples and measure diethyl phthalate (DEP), as well as several VOC concentrations in 37 small- and medium-sized commercial buildings distributed across different sizes, ages, uses, and regions of California. DEP, a plasticizer commonly found in cosmetics and food packaging, was found in all 7 of the retail sites with mean concentration equal to 0.49 $\mu g/m^3$. This concentration is lower than the mean concentration found in residences (0.67 $\mu g/m^3$) by Rudel et al. (2003, 2010), Otake et al. (2004), and Fromme et al. (2004).

Fungi and bacteria

It is important to understand microbiological pollutants in the retail environment because of the high-person density and potentially favorable conditions for which these pollutants can proliferate. There is some evidence that highly occupied environments that have to bring in large amounts of fresh air can increase the levels of indoor microbiological pollutants due to outdoor sources (Wu et al. 2005). The impacts of biological aerosol exposure on human health are considerable (e.g., Monto 2002; D'Amato et al. 2005). Only two studies investigated the presence of bacteria in shopping malls (Li et al. 2001; Tringe et al. 2008). Li et al. (2001) collected airborne bacteria and used culturing to estimate the amount of colony forming bacteria per cubic meter of air in nine shopping malls. Generally, they found an increased amount of bacteria on weekends, with increased occupant density, as assessed by carbon dioxide measurements. Tringe et al. (2008) characterized bacteria present on HVAC filters in two malls in Singapore through genomic DNA sequencing and large scale cloning processes. Tringe et al. (2008) also compared bacteria found on HVAC filter dust with water from an adjacent river, floor dust samples (inside and outside), soil samples near the mall, and human nasal swabs. The microbiome captured on the HVAC filter dust was significantly less diverse compared to the soil and water samples. Each of the two malls shared some abundant microorganisms, but overall phylotypes were diverse, suggesting the malls have different microbiomes. The DNA functional analysis showed genes participating in cell mobility and secretion were over-represented, compared to previously reported genes in other soil and oceanic studies. Currently, there are no threshold values suggested for any microbiological measurement in the indoor environment.

Radon

Radon comes from the natural (radioactive) decay of geological materials (e.g., uranium in soil and rocks). Radon is responsible for many thousands of deaths each year in the United States (Turner et al. 2012). Thus, indoor radon is an important pollutant of concern, especially in underground stores or in locations with known high radon concentrations. Three studies have reported radon concentrations in retail spaces (Yu et al. 1997; Marley 2000; Wang et al. 2004). Yu et al. (1997) measured 10 underground shopping centers located in Hong Kong and found an average concentration of 29.2 Bq/m^3, comparable to the average of dwellings of 30.1 Bq/m^3 and lower than the concentration measured in underground railway stations of 41.6 Bq/m^3, sampled by the same author in Hong Kong. The average reported for the shopping malls is well below USEPA recommended action limit for radon of 148 Bq/m^3 (http://www.epa.gov/radon/aboutus.htmlusepa). Marley (2000) tested radon in a general merchandise store located in Northamptonshire (UK), an area classified as a radon-affected area. The affected area of the store was the basement. The average radon concentration reported before turning on the air conditioning was 326 Bq/m^3, and the radon average after 6 h from turning on the air conditioning was 22 Bq/m^3. The reported AER was 5 AERs per hour. The study indicated that high radon concentrations can be mitigated using an appropriate ventilation strategy. Wang et al. (2004) measured 8 underground supermarket and office structures in China and reported a total average of 33.7 Bq/m^3. The reported average in the supermarket/office was lower than the radon concentration found in the underground parking lot and in covered and uncovered tunnels measured by the same study.

CO

The USEPA considers CO as one of the criteria pollutants that can cause serious health effects, and reports that CO poisoning is responsible for 500 deaths annually in the United States (http://www.epa.gov/iaq/co.html). Some indoor activities, such as cooking with gas stoves, and outdoor activities, such as stock loading and nearby traffic, can elevate indoor CO levels inside retail buildings. Li et al. (2001) measured CO in 9 shopping malls and found an average between 890 and 5200 $\mu g/m^3$. According to the authors, heavy traffic near the shopping malls, cooking inside food courts, and in some malls the operation of the fuel-powered ice-resurfacing resulted in elevated indoor concentration of CO. Inside these malls, all the measured CO concentrations were below the Hong Kong Indoor Air Quality Objective (HKIAQO) and the NAAQS regulatoy limit of 10,000 $\mu g/m^3$ (8-h average).

Other inorganic pollutants (NOx, SOx)

The literature search did not reveal any studies that measured NOx, or SOx in retail environments.

Discussion

The following discussion focuses on the impact of ventilation on contaminants found in retail stores and the possible contaminants of concern for which control strategy should be prioritized.

Impact of ventilation rate on contaminant concentrations

Among all the reviewed studies, only four studies measured the impact of changing ventilation rates on pollutants concentrations or occupant's perception: VOCs: Hotchi et al. (2006) and Grimsrud et al. (2011); radon: Marley (2000); and occupant perception: Wargocki et al. (2004). In addition, Apte et al. (2011) modeled various ventilation scenarios (including scenarios that satisfy the ASHRAE 62.1 IAQ procedure

[ASHRAE 2010a]) in California big box retail stores and estimated VOC concentrations and energy consequences.

Hotchi et al. (2006) reduced the ventilation rate by 30% (0.83/h to 0.57/h) in a general merchandise store in the United States and observed subsequent increases in VOCs concentrations ranging from 15% to 170%. In three general merchandise stores, Grimsrud et al. (2011) suggested that the ventilation rates could be lowered and still maintain an acceptable IAQ in accordance with ASHRAE 62.1-2010 standard (ASHRAE 2010a) in regards to total volatile organic compound (TVOC) and formaldehyde. Marley (2000) suggested that an appropriate ventilation strategy is an effective solution to decrease radon concentrations in a general merchandise store located in a radon-affected area. Wargocki et al. (2004) found that the percent of panelists dissatisfied with IAQ increased from roughly 5% to 30% when the outdoor airflow rate decreased from 4 to 1 $L/s{\cdot}m^2_{floor}$ (0.8 to 0.2 $cfm/ft^2{}_{floor}$). To balance between energy consumption and air quality in retail stores, Apte et al. (2011) suggested alternative control strategies, such as source removal, air cleaning, and local ventilation, combined with moderate ventilation rates.

The grocery stores investigated by Chan et al. (2012) exceeded both the minimum ventilation rate specified by ASHRAE Standard 62.1-2010 (ASHRAE 2010a) and California Code of Regulations Title 24-2010 and had acetaldehyde (12.7 $\pm$ 3.3 ppb) and acrolein (9.4 $\pm$ 8 ppb) concentrations above exposure guidelines (5 ppb and 0.009 ppb, respectively). For acrolein, both indoor and outdoor concentration exceeded the reference exposure level, limiting the value of ventilation to reduce exposure. In addition, one of the retail stores investigated by Bennett et al. (2011) met both ASHRAE Standard 62.1-2010 (ASHRAE 2010a) and California Code of Regulations Title 24-2010 ventilation requirements and had formaldehyde (11.3 $\pm$ 4.7 ppb) above the most conservative exposure guidelines (7 ppb). In addition, two of the tested stores by Bennett et al. (2011) also exceeded ventilation requirements but the measured $PM_{2.5}$ (60.2 $\mu g/m^3$, 21.4 $\mu g/m^3$) were above the NAAQS outdoor regulatory limit (12 $\mu g/m^3$). For both stores, $PM_{2.5}$ outdoor concentration also exceeded the NAAQS regulatory limit, limiting the value of ventilation to reduce exposure. These findings suggest that comparing ventilation rates in the tested store to ventilation requirements does not necessarily correlate to the air quality in the store. Depending on the pollutant and its source, alternative control methods such as filtration might be more effective and possibly more economical than ventilation.

Contaminants of concern

From the contaminants found in retail stores reported in the literature, there is evidence that some pollutants in some retail types are present at concentrations higher than their established limits. The established limits of some pollutants vary widely between different organizations. Thus, to evaluate contaminants of concern it is necessary to compare exposure to pollutants through a common metric of harm, such as DALY (Murray and Lopez 1996). This will allow prioritizing mitigation strategies, including energy efficiency measures that affect indoor air quality.

Two different approaches were used to estimate DALYs lost from exposure to contaminants: (1) intake-incidence-DALY (IND) approach based on epidemiology-based concentration-response (C-R) functions following the work of Logue et al. (2012); and (2) intake-DALY (ID) approach based on animal toxicity literature following the work of Huijbregts et al. (2005). The IND approach is a preferred health impact model than the ID approach since it does not require interspecies extrapolations; however, only information on C-R functions in humans are available for $PM_{2.5}$ and ozone. For the rest of pollutants, animal toxicity data was available in the literature to apply the ID approach.

$PM_{2.5}$ DALYs lost were calculated separately for total mortality, chronic bronchitis, and nonfatal stroke outcomes. For the rest of pollutants, the DALYs lost were calculated separately for the cancer and noncancer outcomes taking into account the variations in susceptibilities of different age categories. For both methods, for each pollutant and each outcome, a Monte Carlo approach was used to quantify the central estimate and 95% confidence interval (CI) by sampling from uncertainty distributions of DALY factors.

Average concentrations for 30 pollutants (e.g., $PM_{2.5}$, acrolein, formaldehyde, acetaldehyde, trichloroethylene, toluene, benzene, xylene, styrene, carbon tetrachloride, chloroform, naphthalene, and ozone) were included in the analysis. $PM_{2.5}$ concentrations are taken from Grimsrud et al. (1999), Rea et al. (2001), Bennett et al. (2011), Brown et al. (2012), Chan et al. (2012), and Dong et al. (2013). VOCs concentrations are taken from Kim et al. (2001), Tang et al. (2005), Hotchi et al. (2006), Loh et al. (2006), Lee and Hsu (2007), Bruno et al. (2008), Caselli et al. (2009), Bennett et al. (2011), and Chan et al. (2012). Ozone concentrations were taken from Chan et al. (2012). These pollutants were chosen for their high potential health impacts at the concentrations found indoors, as well as the availability of damage factors to perform the calculations. Health impacts were determined using the damage per intake factors reported in Pope et al. (2003) and Huijbregts et al. (2005). For each pollutant, the average DALYs lost were estimated for customers and employees, assuming customers above the age of 15 years spend on average 0.48 hours of their daily time shopping, and employees work 8 h per weekday in the retail site.

The estimated average DALYs lost due to $PM_{2.5}$ exposure in retail stores in the United States contributed the largest to the annual health impacts, with an estimated 76 DALYs per 100,000 persons annually (95% CI: 7.9, 728.5). The average annual total DALYs from VOCs/ozone (29 pollutants) contributed an estimated 70 DALYs per 100,000 persons. Acrolein accounted for the vast majority of these losses, contributing an annual average of 60 DALYs lost per 100,000 persons (95% CI: 0.23, 15,609). It should be noted that the acrolein concentration used in the DALY analysis is largely based on two grocery stores from one study (Chan et al. 2012) and, thus, the results are highly uncertain and more testing is warranted to verify these concentrations. Both $PM_{2.5}$ and acrolein were mostly elevated in grocery stores with cooking activities, thus the DALYs lost presented herein may not apply to exposures in other store types. The total health burden was mainly attributed to the employees in retail stores. A figure showing the estimated number of DALYs lost due to indoor inhalation intake of $PM_{2.5}$, ozone, and selected VOCs and the corresponding pollutant concentrations is shown in the Supplemental Material.

Comparing the findings from this investigation to DALYs lost reported by Logue et al. (2012) in residences provides further evidence that $PM_{2.5}$ and acrolein are two common contaminants of concern. In addition to $PM_{2.5}$ and acrolein, Logue et al. (2012) identified formaldehyde as a pollutant that accounts for annual DALYs lost comparable to acrolein. In these residences, the average concentration reported for formaldehyde was 69 $\mu g/m^3$. In retail buildings, the average formaldehyde reported by the three studies (Hotchi et al. 2006; Wu et al. 2011; Chan et al. 2012) was 24.6 $\mu g/m^3$. It should be noted that these three studies took place in California, and therefore may not be representative of formaldehyde concentrations in retail stores in other states or countries. At this concentration formaldehyde accounts for 4 DALYs lost annually per 100,000 persons. DALYs lost from exposure to formaldehyde in retail buildings can be considered small even though the average concentration reported for formaldehyde in retail stores is 2.7 times the OEHHA chronic reference exposure for formaldehyde (9 $\mu g/m^3$).

Despite the large uncertainties associated with the toxicology data and the DALY approach, our analysis support the finding that mitigation strategies in retail stores, specifically those with cooking activities, should focus on decreasing exposure of employees to $PM_{2.5}$ and acrolein, with the caveat that more acrolein concentration data is needed to confirm this finding.

Conclusions

A review of ventilation measurements in retail stores found that half of the stores tested met/exceeded ASHRAE Standard 62.1-2010 (ASHRAE 2010a) or California Code of Regulations Title 24-2010; nonetheless, these ventilation rates were not sufficient to keep all pollutants below their most conservative limits, but this might not be true if we consider other authoritative limits. The work presented here reduced the number of pollutants found in retail environments (>70 pollutants) to a set of seven important pollutants that are found to exceed their established limits/reference exposures for a few of the stores tested ($PM_{2.5}$, acrolein, formaldehyde, acetaldehyde, trichloroethylene, benzene, and PM_{10}) and two priority pollutants ($PM_{2.5}$ and acrolein) that contributed the largest to DALYs lost. Only a limited number of studies measured acrolein in retail stores, which suggests that further attention on this pollutant is warranted. Because of the lack of health guidelines for ultrafine particles and SVOCs, the concentrations of these pollutant categories could not be judged whether it is safe or unsafe, but it would also be prudent to also generate additional measurements of these compounds. Few pollutants, such as $PM_{2.5}$ and acrolein, had elevated concentrations both indoors and outdoors above their established limits. Alternative ventilation strategies (i.e., nighttime flushes) for stores with high indoor concentrations and air cleaning approaches (i.e. particle filtration) might offer a more effective and less energy-intensive method to improve the air quality in retail stores. Generally, for the important pollutants identified, there remains a need to perform additional testing in retail stores in an effort to determine sources of pollutant and potentially link them to activities in the store, as well as determine the importance of outdoor sources.

Supplemental Material

Supplemental data for this article can be accessed on the publisher's website.

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