Indoor Environmental Quality in Social Housing: Review, Thermal Comfort and Odour Control

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

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Abstract

In this work, I explored the indoor environmental quality (IEQ) in social housing, and also discussed the indoor pollution associated with the operation of sources of scents that may be common in these units. I found that public housing residents may be disproportionately exposed to fine particulate matter (PM$_{2.5}$), nitrogen dioxide (NO$_2$), and pesticides. I also found that poor thermal comfort conditions are prevalent in social housing, mostly due to excess heat. Lastly, I found that incense and ultrasonic oil diffusers, which are commonly used to produce pleasant scents indoors, generate considerable amounts of PM$_{2.5}$. Considering the negative health effects associated with poor IEQ conditions, my results suggest that minimizing sources of pollution and improving comfort conditions should be prioritized in any retrofits planned in social housing developments, as similar improvements have been found to be effective in improving occupant health and reducing exposure to pollutants.
This thesis is dedicated to my parents, Ernesto and Maria Estela, the biggest role models I will ever have; to my grandpa, Eduardo, who will always be my hero; and to the memory of my 2 grandmothers, Georgina and Aurea, who were like second mothers to me and sadly passed away before I completed my education.

Dedico esta obra a mis padres, Ernesto y María Estela, los dos modelos a seguir más importantes de mi vida, a mi querido Abo quien siempre será mi héroe, y a mis adoradas Aba y Abue, que nunca voy a dejar de extrañar.
Acknowledgments

Completing this two-year master’s journey would not have been possible without the guidance and supervision of Dr. Jeffrey Siegel, an extraordinary researcher and excellent teacher, to whom I will always be grateful for for taking me in as a student and patiently mentoring me throughout my journey. Thank you, Professor, for always answering my questions, providing advice, and being actively involved in my research. I also would like to thank Prof. Marianne Touchie who was my thesis second reader, and a great mentor and advisor. Thank you for your patience and helpfulness.

To Prof. Kim Pressnail, Prof. Brenda McCabe, Prof. Doug Reeve, and Prof. Vanderburg: thank you for having been important figures in my graduate school journey, by supporting me in several activities outside of my research, and also acting as mentors. I have learned a lot from you.

To all my colleagues in the Building Science research group: thanks for being great friends and teammates. You create a supportive and friendly environment in the group that was conducive of great work, and a lot of my success was thanks to your support. I learned a lot from you and enjoyed working with you.

To my family: dad, mom, thanks for supporting me in all the possible ways a parent can support a son throughout my life; Adriana, thank you for being a fantastic sister, who always cheers me up and who is making me proud every day; and Tatiana, thanks for being my companion and my partner- I could not have done this without you.

I would also like to express my gratitude to the Alfred P. Sloan Foundation, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the Mexican National Council for Science and Technology (CONACyT) who provided funding that supported this research.
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Chapter 1
Motivation

1 Motivation

Canadians and Americans are indoor creatures, spending over 90% of their time indoors (Leech et al. 2002). In European countries, similar trends can be observed, with people spending most of their time indoors (Schweizer et al. 2007). This time activity pattern highlights the role that the indoor environment plays in exposure to airborne pollutants: given that exposure is a function of time, longer time spent indoors often results in higher exposure to airborne contaminants. Therefore, maintaining healthy indoor environments is an important element of public health. Further, the fact that social housing inhabitants may be more vulnerable due to age or socioeconomic status highlights the need to maintain healthy and comfortable indoor environments for these residents.

1.1 Common indoor air pollutants

The indoor environment is very complex and there are numerous pollutants of concern. Further, epidemiological data for many compounds present in the air does not exist or is limited. However, there is a wide range of literature documenting the emission mechanisms and health effects of certain common air pollutants. Fine particulate matter (PM$_{2.5}$) is perhaps the main air pollutant of concern indoors. Firstly, there are several sources: cooking (He et al. 2004), vacuuming (He et al. 2004), incense burning (Lee and Wang 2004), candle burning (Derudi et al. 2014), smoking (Charles et al. 2008), among others. Secondly, it has documented chronical health effects which can shorten people’s lifespan (Logue et al. 2012). This is mainly because fine particles are able to deposit deep into people’s lungs, often carrying with them additional harmful pollutants, such as semi-volatile organic compounds (SVOCs).

Another very common pollutant of concern is mould, and more generally, dampness. While a mechanistic association between mould and poor negative health effects has not yet been established (Mendell et al. 2011; Mendell and Kumagai 2017), dampness and mould have been associated with allergic reactions and adverse respiratory effects, including: asthma development and exacerbation, respiratory infections, bronchitis, wheezing, coughing, allergic rhinitis, and eczema (Mendell et al. 2011). Of public health concern is the prevalence of dampness issues in
buildings: a review study in 2007 estimated a weighted average mould and dampness prevalence of 47% in US and Canadian cities, based on the results from 8 different studies (Mudarri and Fisk 2007).

In addition to PM$_{2.5}$ and dampness, volatile and semi-volatile organic compounds (VOCs and SVOCs, respectively) are also of concern indoors. Since these categories encompass thousands of compounds, it is practical to focus on certain specific ones which are known to be harmful. In the VOC category, formaldehyde (HCHO) is one of the main indoor pollutants of concern. HCHO is classified as a carcinogen by the International Agency for Research on Cancer (IRC) (IARC 2012), and is also a strong irritant (Salthammer et al. 2010). Its prevalence in the indoor environment is high due to the high number of sources that are common in buildings, such as engineered wood products (particle board, oriented strand board), certain paints, mineral wool (Salthammer et al. 2010). In addition to formaldehyde, another VOC commonly studied in the indoor environment and with potentially worse chronic health effects is acrolein (Logue et al. 2012). Acrolein is known to be a pulmonary toxicant, further, it is also known to contribute to the development of lung cancer when acting in combination with other carcinogens (Seaman et al. 2007). It is emitted indoors by several sources, including: smoking, incomplete combustion (incense, candle burning), heating cooking oil, or oxidation of VOCs emitted by furnishings and building materials (Seaman et al. 2007). Similar to VOCs, SVOCs (which are compounds with a higher boiling point than VOCs) are also very varied, so focusing on a few pollutants of concern is also a common approach. Some of the most commonly studied SVOC categories in the indoor environment are pesticide compounds (e.g. certain organophosphates such as diazinon, or some pyrethroids such as permethrin), phthalates (commonly found in plasticizers), polycyclic aromatic hydrocarbons (PAHs, combustion by-products), and poly-brominated diphenyl ethers (PBDEs, found in several commercial flame retardants). All of these compounds have been associated with adverse health outcomes. Diazinon has been banned as a pesticide in the US, given its neurological effects (US EPA 2003). Exposure to phthalates has been associated with altered semen quality and other adverse reproductive outcomes, as well as increased risk of asthma and allergies (Hauser 2005; Jurewicz and Hanke 2011). PAHs have been found to cause a variety of cancers, and have also been associated with genetic mutations (Kim et al. 2013). PBDE’s are known endocrine disruptors, as well as potential developmental neurotoxicants (affecting infants and toddlers who may have higher exposure through maternal milk and house dust) (Costa et al.
In summary, VOCs and SVOCs encompass thousands of compounds commonly present in the indoor environment. While most VOCs are harmless, there are a few that have serious negative health effects. SVOCs, on the other hand, have been understudied and toxicological data for many of these compounds does not exist yet.

In addition to organic gas phase compounds, there are also certain inorganic compounds of concern present in indoor air. Perhaps the three most commonly discussed ones in the literature are nitrogen dioxide (NO\textsubscript{2}) and ozone (O\textsubscript{3}), both of which have negative chronic health effects (Logue et al. 2012). NO\textsubscript{2}, a byproduct of combustion, is prevalent in houses with combustion appliances which are not vented properly. It is known to have adverse respiratory effects, such as shortness of breath and frequency of cough even at levels which may not be considered harmful (van Strien et al. 2004). O\textsubscript{3}, a pollutant which mostly comes from outdoors, can also be generated indoors through the operation of devices such as photocopies, laser printers or ion generators. It is a pollutant of concern because it is a respiratory irritant, with increased mortality risks even at low concentrations (Bell et al. 2006).

Overall, this summary of common indoor air pollutants highlights some of the complexity of the indoor environment and exemplifies that there are multiple contaminants of concern with various degrees of harmfulness to occupants. Therefore, the design and evaluation of environments where vulnerable populations spend considerable amounts of time must be performed with IEQ considerations in mind.

1.2 Thermal comfort

In addition to considering indoor air pollutants, the quality of indoor environments is also highly affected by the thermal comfort of occupants. Firstly, there exists evidence that poor thermal comfort can negatively influence occupants’ health. As early as 1968, a report by the World Health Organization (WHO) recognized that discomfort conditions could lead to pathological issues, including colds, pharyngitis and neuralgia if they affected the body’s ability to thermoregulate. This report identified a “zone of indifferent metabolism”, which ranges from 15°C to 22°C, and asserted that within this zone, the body’s energy expenditure to thermoregulate was minimal (Goromosov 1968). Later in 2012, Ormandy and Ezratty investigated more recent WHO guidelines for thermal comfort. They found that since the 1968 report a revised range of 18°C to 24°C was suggested in 1982, although no evidence was
provided to support this range. Subsequent reports adopted this range, but also noted that, for vulnerable populations (such as elders and children) it was recommended to keep the temperature above 20°C, and that temperatures below 12°C had been identified as a health risks for these populations (Ormandy and Ezratty 2012).

Additional to the evidence linking poor thermal comfort in residences and adverse health effects, thermal comfort has also been linked to reports of Sick Building Syndrome (SBS) symptoms in office spaces. SBS is defined by the United States Environmental Protection Agency (US EPA) as “situations in which building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified” (US EPA 1991). Jaakkola et al. (1989) studied the association between dryness, thermal comfort and reports of SBS. They found that SBS symptoms increased when the temperature was perceived as too cold or too hot by the occupants. They also found that, above 22°C, increases in temperature where correlated linearly with increases in SBS scores. This not only shows that poor thermal comfort may lead to perceived symptoms in occupants, but also demonstrates the importance of adequate comfort conditions for occupants' perception of the indoor environmental quality (IEQ) of their space. In fact, a recent study showed that thermal comfort was the most important IEQ parameter as perceived by the occupants (Lai and Yik 2009).

1.3 Exposure disparities

Given that indoor air quality (IAQ) and thermal comfort have a documented effect on occupant health and perception of IEQ, it becomes important to evaluate whether there are documented exposure disparities between units of different socioeconomic levels. A recent work by Jacobs (2011) explored the associations between housing disparities and adverse health effects. This article found that higher percentages of ethnical and racial minorities live in substandard housing in the US, and that there has been only a small reduction in the percentage of houses with severe or moderate problems in the past three decades. Additionally, reported data from the WHO included in the study also showed that problems such as mould, bad air quality and cold temperatures are also more prevalent in low income households in several surveyed European cities. Jacobs also highlighted that there are numerous studies that have shown that increased housing segregation and crowdedness (which are more prevalent in low income neighbourhoods) is correlated with increased mortality rates.
1.4 Social housing IEQ

Considering the evidence that there are housing quality disparities between individuals of different socioeconomic levels, and that these disparities have been associated with negative health effects, it becomes important to further explore the relationship between housing and health. Since 1999, a few review studies have explored the evidence linking dwelling conditions and occupant health. Wilkinson (1999) concluded that several studies had identified positive statistical correlations between poor housing conditions and adverse health effects. Saegert et al. (2003) found that home improvements had been associated with health improvements with statistical significance, but that most of the reviewed studies had only focused on a single health condition. Rauh et al. (2008) concluded that poor housing conditions (which are likely to be more common in communities with a low socioeconomic status) may be harmful for their occupants. Together, these studies evidence that there is a relationship between dwelling conditions and occupant health. Therefore, contexts such as social housing, where housing conditions may be substandard due to building age or deferred maintenance, should be studied to understand if the IEQ conditions in these settings is worse than in non-social housing ones, and to evaluate whether there is evidence that social housing occupants have a higher prevalence of certain diseases due to their living conditions.
Chapter 2
Objectives and Organization of Thesis

2 Objectives and Organization of Thesis

This thesis encompasses the results of three investigations, all related to indoor environmental quality (IEQ) in social housing: a literature review summarizing the state of the knowledge in the field, a monitoring project exploring indoor environmental quality (IEQ) conditions in seven social housing buildings in Toronto, and a laboratory investigation into particulate matter emissions from sources of scents used to overcome odour concerns in social housing.

The literature review was motivated by a need to understand if there is evidence that poor IEQ conditions are more prevalent in social housing than in non-social housing. It is also partially motivated by the results of Adamkiewicz et al. (2011) who discussed that future research should examine more in detail the pollutants that drive disparities in indoor exposures due to socioeconomic status. The fieldwork was motivated by the need to characterize the seasonal variation in thermal comfort in the monitored buildings, and to develop a comprehensive understanding of comfort conditions before the buildings underwent energy retrofits (which will serve as a baseline for comparison with post retrofit results in future investigations). The laboratory work was motivated by the need to quantify PM emissions of novel scent sources to assess their polluting potential in social housing.

2.1.1 Objectives and research questions

The central objective of this thesis is to develop a better understanding of IEQ conditions in social housing units, through a combination of bibliographical, experimental and laboratory research. Firstly, through a literature review, I aim to answer the following research questions:

1) What indoor air pollutants have been studied in social housing buildings?

2) Are social housing inhabitants disproportionally exposed to these pollutants when compared to non-social housing residents?

3) Are occupants thermally comfortable in social housing?
4) Are there associations between living in social housing and negative health effects?

5) Can green retrofits improve IEQ in social housing?

From the results of the literature review, I found that poor thermal comfort is a prevalent issue in multi-unit social housing. This finding motivated the following questions to be answered by field research:

1) Is there seasonal variation in the thermal comfort conditions in the monitored multi-unit social housing units in Toronto?

2) What are the likely drivers of discomfort in the buildings?

3) Is there evidence of poor ventilation in the units?

Lastly, during the fieldwork research, I found that unpleasant odours were common in social housing units, and that several residents used scenting sources (commonly incense and scented candles) to mask these odours. Knowing that these sources of scents are also sources of indoor pollution, and that there are new sources of scents becoming popular which have not been thoroughly studied (in particular essential oil diffusers and wax warmers), I set the following questions to guide the laboratory investigation, with the goal of gaining a better understanding of the pollution that can be generated through the operation of these sources of scents in social housing units:

1) What are the PM$_{2.5}$ emission rates for incense, essential oil diffusers and wax warmers?

2) In what settings does the use of these sources result in considerable PM$_{2.5}$ concentrations?

2.1.2 Organization

The present chapter summarizes the objectives and organization of this work. Chapter 2 elaborates on the motivation behind this work. Chapter 3 presents the theoretical background for each of the three investigations described in this thesis. Chapter 4 describes the methodologies followed. Chapter 5 summarizes the results in each investigation and Chapter 6 discusses their implications. The journal and conference articles that were prepared for each investigation, as well as supplemental information, are presented in the appendices.
Chapter 3
Introduction

3 Introduction

One of the main characteristics of the 20th century is the unprecedented migration to urban centers. According to the United Nations, more than half of the world’s inhabitants lived in urban centers as of 2014 (United Nations, Department of Economic and Social Affairs 2015). This has often led to a reduction in housing affordability in cities, due to the increased demand for housing. In response to this, local governments have devised several strategies to provide affordable and adequate housing to low income urban dwellers, one of them is the creation of subsidized public housing dwellings. In the past decade, populations in these housing developments across the world have grown to be quite substantial. In Canada, the census results from 2011 by Statistics Canada reported over half a million subsidized housing dwellers (Statistics Canada 2011). In Europe, a report by the Dutch Ministry of Kingdom Relationships, reported over 1.3 million social housing households as of 2008 (Dol and Haffner 2010). In the United States, the US Census Bureau reported that there were over 1 million public housing homes as of 2015 (US Census Bureau 2015). These figures, while quite substantial on their own, are probably an underestimate of social housing populations, given that there is no standardized definition of what constitutes social or public housing, and that many rental assistance programs as well as low income houses may not be captured in the numbers. One example is the US: the 1 million social housing units only constitute 22% of the total households receiving some rental assistance (other programs include, for example, Section 8). Similar cases are also likely true in other countries.

Given the high populations of social housing in the world, and that residents in these units are generally more vulnerable due to socioeconomic status and age, it becomes important to understand if the indoor environment in these units is disproportionately worse than in non-social housing. In order to explore this, I conducted a literature review to explore the state of the knowledge regarding IEQ in social housing, focusing on air pollutant concentrations, thermal comfort, health effects associated with living in social housing and the effectiveness of green retrofits in improving IEQ.
To complement the review, I participated in a field investigation, to address the lack of large scale cross-sectional and longitudinal studies focused on monitoring IEQ in social housing. This experimental work was part of a larger project which began in 2015 and is designed to monitor the impact of energy upgrades on the indoor environment. In this work, I focused on thermal comfort, since I found in the literature review that poor thermal comfort is a prevalent issue in social housing. Further, preliminary investigations into the data have found that overheating during the summer resulted was a major issue in several of the units (Haaland et al. 2016; Touchie et al. 2016). My goal for the current investigation is to evaluate thermal comfort over a full year of data (April 2015 to April 2016) to understand the seasonal effect on comfort, and better characterize the sources of discomfort.

Additionally, in the literature review I also found evidence to believe that social housing residents may be exposed to higher levels of fine particles (PM$_{2.5}$) than non-social housing residents, with smoking being the most evident driver of PM$_{2.5}$ concentrations. PM$_{2.5}$ is a harmful air pollutant, because small particles deposit deep into people’s lungs. During the field work, in addition to noting smoking prevalence in the units, I noticed that usage of scent sources (in particular incense and candles) was common. Considering that these sources are known emitters of PM$_{2.5}$ (Manoukian et al. 2013), it is important to characterize them as sources of pollution in social housing to understand their relative contribution to PM$_{2.5}$. Further, it is important to consider the drivers of the usage of these sources. One very common use of scents sources is to mask existing bad odours. While incense and candles have been commonly studied previously (Derudi et al. 2014; Fine et al. 1999; Lee and Wang 2004; Manoukian et al. 2013), newer sources such as ultrasonic oil diffusers and wax warmers have seldom been tested. It is likely that as these sources become more accessible to customers, they may make their way into social housing units. These sources are likely PM emitters: the mechanism of the diffuser resembles the mechanism of ultrasonic humidifiers, which have been known to emit PM (Highsmith et al. 1988; Tyndall et al. 1995; Umezawa et al. 2013); and the operation of wax warmer involves warming of a surface, which may result in PM emissions since warm surfaces are known to emit PM if dust comes into contact with them (Afshari et al. 2005).
Chapter 4
Methodology

4 Methodology

The first component of this investigation was the literature review of social housing IEQ. To conduct the review, I queried two popular academic databases, Google Scholar and Web of Science, with different combinations of these keywords: social housing, indoor air quality (IAQ), indoor environmental quality (IEQ), energy efficiency, thermal comfort, health and public housing. This process yielded approximately 40 papers which I selected for further review. I categorized these papers based on their relevance to the subject of the review. I reviewed in more detail those which I deemed most relevant (which included measurements of pollutants or IEQ parameters) and highly relevant (which included useful information about the life quality in social housing units), and I also scanned through their references and keywords. In total, I selected 49 papers for inclusion in the review. The majority of the papers were published in peer reviewed archival journals, with the exception of a few conference papers and a federal report.

I then extracted data regarding the buildings studied, study format, pollutant concentrations, health effects, green retrofits effectiveness, from all the papers using a standardized format for further analysis and comparison. Further, in addition to selecting these papers, my investigation also involved selecting studies conducted in non-social housing settings to provide a basis of comparison. I selected these non-social housing studies so that they would be as similar as possible to the social housing studies: conducted in the same or similar city, the population consisting mostly of multi-unit buildings (most social housing is multi-unit), and also more than one comparison study was used to increase the sample size. The lack of appropriate studies for comparison was one of the main limitations of the literature review.

Further to the literature review, the second component of this investigation was the experimental field work conducted in three social housing developments in Toronto to monitor various IEQ parameters before, during, and after energy upgrades were undertaken in the buildings. Some of the upgrades included: low flush toilets, lighting retrofits, installation of thermostats, and replacement of boilers and air handling units. The monitoring consisted of two distinct components. The first one was a long-term monitoring package deployed in all suites for the
entirety of the study. This package contained a data logger, a CO₂ sensor, and a temperature probe encapsulate within a half black sphere. The data logger was set to record air temperature, relative humidity, CO₂ concentrations (from the CO₂ sensor) and an estimate of mean radiant temperature (from the temperature probe) every 15 minutes. The second component consisted of short term monitoring packages. These were deployed for a week on each suite on four occasions: late spring and late fall before retrofits were implemented, and spring and fall after retrofits were undertaken. The short-term packages included: an optical particle counter (to measure PM concentrations), a formaldehyde sensor, a portable air cleaner (to collect particle-bound contaminants in the air cleaner filter), and a polydimethylsiloxane (PDMS) sampler to collect SVOCs.

While a lot of data was collected during this study, this work presents results from the long-term packages for the period covering April 1, 2015 to April 1, 2016. I utilized this data to evaluate thermal comfort using two approaches. First, I applied the ASHRAE Graphical Comfort Method, outlined in section 5.3.1 of ANSI/ASHRAE Standard 55-2013 (ANSI/ASHRAE 2013), to determine (for each 15 minutes) if the occupants were within the comfort zone or not. This model is only valid if the air speed is less than 0.2 m/s and the occupants’ activity level results in a metabolic rate between 1.0 and 1.3 mets. I used this method to create two models: a variable clothing model (in which occupants were assumed to switch between light clothing and heavier clothing if they were uncomfortable), and a fixed clothing model, in which occupants were assumed to have a fixed clothing level appropriate for the season. For the second approach, I applied the ASHRAE Analytical Comfort Method, outlined in section 5.3.2 of ANSI/ASHRAE Standard 55-2013 (ANSI/ASHRAE 2013). This approach is valid if the air speed is less than 0.2 m/s, and the occupants’ activity level results in a metabolic rate between 1.0 and 2.0 mets. With this method, I calculated the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). I then used the PMV, which is based on a scale from -3 PMV (cold) to +3 PMV (hot), to assess whether the conditions in the space were within the comfort zone of ±0.5 PMV.

The last portion of this investigation, which consisted on measuring the PM₂.₅ emission rates of incense, essential oil diffusers and wax warmers was conducted in the laboratory. I tested all the three sources of scents in a sealed 1.3m³ acrylic test chamber with a minimal air exchange rate. The source was allowed to operate in the presence of four different optical particle counters. After an operation time (different for each source), the source was turned off and emissions
ceased. The chamber remained closed for an hour after emissions ceased in order to allow for particles to deposit. To calculate the emission rate, I estimated a mass balance model based on the measured concentrations, using a combination of linear and non-linear regression.
Chapter 5
Results

Note: The results presented in this section have been published or submitted for publication on the following articles:


This section summarizes the results from three investigations: a literature review, field work and laboratory experimental work. The literature review analyzed a total of 49 papers, most of which were articles published in peer review archival journals. Most studies were cross-sectional in design, and also the majority of them are recent, with 75% having been published after 2008. Further, most papers were written in North America (in particular, in the United States). This altogether suggests that long-term longitudinal research in social housing is limited, that most of the published results are based on the context of North American social housing (which may not be representative of other parts of the world given the lack of standardized definitions of what constitutes social housing), and that this is a relatively new area of research. The field work monitored hygrothermal conditions inside 70 units across 3 social housing developments in Toronto for a full calendar year; in this section I present the monitoring results for the period of April 2015 to April 2016. The laboratory experimental work consisted on tests designed to measure the PM\(_{2.5}\) emission rates of common scent sources, that may be used in social housing to mask poor odours; in this section I present the measured PM\(_{2.5}\) emission rates for incense, an ultrasonic oil diffuser and a wax warmer.
5.1 Indoor air quality

In the first component of the review I evaluated reported pollutant concentrations in social housing. I included pollutants on the review based on 2 considerations: firstly, that they had been reported in social housing in the literature, and secondly, that they had harmful chronic health effects, based on the results of Logue et al. (2012). As a result, I included the following pollutants: PM$_{2.5}$, NO$_2$, formaldehyde, mould and dampness, allergens, and pesticides. Figure 1 summarizes the PM$_{2.5}$ concentrations reported in the review papers. This figure highlights the wide variation, between and across studies, that PM$_{2.5}$ concentrations have in the context of social housing indoor environments (note the logarithmic y scale). Additionally, this figure highlights that the relationship between indoor and outdoor PM$_{2.5}$ is not consistent: while several of the reported outdoor concentrations are close to the central tendency measure of the indoor concentrations, some units reported by Brugge et al. (2003) and Noris et al. (2013) show very large differences (up to an order of magnitude) between indoor and outdoor concentrations.

There are some important insights regarding PM$_{2.5}$ pollution in social housing that can be drawn from Figure 1. Firstly, the variation in sample sizes and context from studies is an important factor that should be considered when making comparisons across studies. One example of this is Burgos et al. (2013), who measured PM$_{2.5}$ concentrations inside public housing units and in (homes) in slums (the higher means are the slum measurements). Arguably, slums exist in a very different context than most public housing and therefore those results are not representative of social housing units in the city where the study was conducted. In this study, it is also important to note that the outdoor concentrations in the slums are higher than those for the social housing units. Further, the variation in sample sizes is very considerable between studies: there is almost a factor of 20 difference between the smallest and largest sample sizes. In addition to these contextual differences, the figure suggests the significance of smoking as a driver of PM$_{2.5}$ concentrations, even though only two studies distinguished units or buildings with smokers from those without. The most relevant study for this is Russo et al. (2015): the units with smoking occupants located in a building without a smoking ban (light blue bar) had the highest PM$_{2.5}$, whereas units without smoking occupants located in a building with a smoking ban (dark green bar) had the lowest concentrations. This also highlights the importance of building-wide effects: the dark blue bar (suites without smoking occupants located in buildings without smoking ban) showed higher average concentrations than the dark green bar, suggesting that PM$_{2.5}$ from
smokers in other suites was transferring between units. These results are consistent with another study which found that smoking is an important driver of PM$_{2.5}$ concentrations in social housing (Mahdavi et al. 2016). Smoking is of particular concern in social housing since there is evidence that individuals of low socioeconomic status are more likely to be smokers, at least in the United States (Flint and Novotny 1997).

![Figure 1 PM2.5 concentrations reported in the literature.](image)

**Figure 1 PM2.5 concentrations reported in the literature.** Each bar represents the central tendency (mean, median, geometric mean) of the concentrations in a group of units. Green bars indicate that concentrations were measured after green retrofits or renovations were implemented, blue bars indicate that there were no renovations prior to sampling. Caps indicate ranges: dashed lines minimum-maximum, short dashed one geometric standard deviation, continuous lines one standard deviation, and long dashed interquartile range. Light colour indicates that smoking was reported in the units. Gray dots represent outdoor concentrations (if reported). This figure was published as Figure 1 in *Building and Environment* (Diaz Lozano Patino and Siegel, 2018).

I compared the results of PM$_{2.5}$ concentrations in social housing to studies conducted in non-social housing, to evaluate exposure disparities. A study by King et al. (2010), focusing on second hand smoke (SHS) transfer between apartments in multi-unit housing, reported a median
of 10.2 μgm$^{-3}$ for units without smoking occupants and a median of 29.4 μgm$^{-3}$ for units with a smoking occupant (their measurements were stratified by time of day, and these corresponded to the evening). Further, the Relationship of Indoor, Outdoor and Personal Air (RIOPA) study (which was conducted in several US cities; and had a sample population which consisted of 40% multi-unit buildings) reported a mean indoor PM$_{2.5}$ of 17.6 μgm$^{-3}$ (SD = 12.6 μgm$^{-3}$) (Meng et al. 2005; Weisel et al. 2005). Based on these results, it seems to appear that concentrations of PM$_{2.5}$ in social housing may be higher than in non-social housing, suggesting possible disproportionate exposures.

The next contaminant I studied in the review was NO$_2$, a combustion by-product. Six of the reviewed studies reported central tendency metrics for NO$_2$ concentrations, which ranged from 11.4 μgm$^{-3}$ to 95.6 μgm$^{-3}$ (Baxter et al. 2007; Broderick et al. 2017; Brugge et al. 2003; Colton et al. 2014; Noris et al. 2013; Zota et al. 2005). In comparison, a study by Hansel et al. (2008) found mean indoor NO$_2$ concentrations of 57.3 μgm$^{-3}$ (SD = 64.5 μgm$^{-3}$), in the homes of 150 asthmatic children from Baltimore (40% of which were considered low income and could potentially live in public housing). This simple comparison suggests that the reported NO$_2$ concentrations in social housing may be comparable to those in non-social housing, possibly suggesting that exposure disparities are not prevalent. However, it is important to understand the sources of NO$_2$ and their prevalence in social housing. Since NO$_2$ is a by-product of combustion, it usually comes to the indoor environment through the operation of combustion appliances or from outside. In the case of the six reviewed papers, all authors found that units with high NO$_2$ concentrations were those with either gas stoves/ovens or older gas furnaces. Social housing units with gas stoves/ovens may be at increased risk of having higher NO$_2$ concentrations considering that some studies have shown that social housing residents may use their ovens for supplemental heating due to poor thermal comfort conditions (Brugge et al. 2001, 2006). In these circumstances, the poor thermal performance of the social housing unit could also become a driver of higher NO$_2$ concentrations.

While I found evidence of disproportionate exposure to PM$_{2.5}$ and NO$_2$, I found no evidence of disproportionate exposure to HCHO, or mould and dampness. With regards to HCHO, studies reported concentrations in social housing (reporting either means or medians) in the range of 10.2 μgm$^{-3}$ to 28 μgm$^{-3}$ (Broderick et al. 2017; Colton et al. 2014; Coombs et al. 2016; Jacobs et al. 2015; Noris et al. 2013). This range is comparable to results of large scale studies that
evaluated HCHO in non-social housing buildings, such as the results from the RIOPA study who reported mean HCHO concentrations of 21 µgm⁻³ (Hun et al. 2010), or the range of 20 µgm⁻³ to 40 µgm⁻³ reported by Health Canada based on measurements in several Canadian cities (Health Canada 2007). With regards to mould, nine of the reviewed studies reported mould sightings. The percentage of units with visible mould ranged from 0.3% to 75% (Adamkiewicz et al. 2014; Bradman et al. 2005; Brugge et al. 2001, 2006; Colton et al. 2014, 2015; Howden-Chapman et al. 2007; Northridge et al. 2010; Takaro et al. 2004), with an average across all studies of 36%. This percentage falls below the reported weighted average percentage of 47% units in Canada and the US with moisture problems, presented in Mudarri and Fisk (2007).

In addition to serve as an indicator of dampness, mould may also release spores that may trigger allergic reactions. From the reviewed studies, one study discussed mould spores as allergens (Brugge et al. 2003). However, other studies evaluated other allergens commonly present in the indoor environment. The most commonly reported allergens were *bla g1* and *bla g2* (both cockroach allergens), which were found in higher concentrations in houses with evidence of pest infestation (Bradman et al. 2005), and also higher concentrations in the kitchen than in the bedrooms (Peters et al. 2007a; Peters, et al. 2007b). The allergen concentrations highlight the presence of pests, which in addition to triggering allergic reactions, are also drivers of pesticide usage (Chew et al. 2006). One particularly concerning example of harmful pesticide usage is shown in the results of Julien et al. (2007), who found high prevalence of cypermethrin and diazinon, both of which are organophosphates that have been retired from market since 2001 and 2002 (respectively) due to their harmful health effects. A more recent study by Lu et al. (2013) further reported that cypermethrin and permethrin were the most commonly found pesticides in a public housing development in Boston. These studies show that pesticide usage in public housing may lead to the presence of harmful semi volatile organic compounds, which is particularly concerning in settings where vulnerable populations (e.g. children) may come into direct contact with them. Overall, the results from the IAQ literature in social housing suggest that there is evidence of potential disproportionate exposure to PM$_{2.5}$ (mostly driven due to smoking in social housing buildings), to NO$_2$ (in the cases of units that have gas stoves and use them for supplementary heating), and pesticides (driven by the presence of pests).
5.2 Thermal comfort

Following an evaluation of pollutant concentrations in public housing, I analyzed evidence of poor thermal comfort, to obtain a broader picture of the IEQ conditions reported in the literature. The reported thermal conditions in social housing are summarized in Table 1. In general, the results in the table show that poor thermal comfort is prevalent across several studies, with the most prevalent issues being overheating or undercooling, which cause temperatures to be too high inside the units. Comparisons across different studies of thermal comfort is challenging, given that there are multiple approaches to assess this (interview of occupants, comfort modelling based on ambient parameters measurements). A study by Földváry et al. (2017), which evaluated comfort conditions in non-social housing multi-unit buildings in Slovakia, reported that underheating was prevalent in 18% of the apartments, while overheating occurred in 7% of the suites. This limited comparison suggests that thermal comfort issues may be more prevalent in social housing, which could be explained due to factors more likely to be prevalent in public housing such as older envelopes, undersized or inefficient heating systems, undersized (or lack of) cooling systems, deferred maintenance, poor window conditions, low air movement.

Table 1 Thermal comfort conditions reported in social housing. This table was published in Building and Environment by Diaz Lozano Patino and Siegel (2018)

<table>
<thead>
<tr>
<th>Study</th>
<th>Season</th>
<th>Units</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noris et al. (2013)</td>
<td>COOL</td>
<td>B1 PR</td>
<td>25% time above, 1% below ASHRAE 55(^a)</td>
</tr>
<tr>
<td></td>
<td>COOL</td>
<td>B1 AR</td>
<td>18% time above, 4% below ASHRAE 55(^a)</td>
</tr>
<tr>
<td></td>
<td>HEAT</td>
<td>B2 PR</td>
<td>20% time below, 17% above of ASHRAE 55(^a)</td>
</tr>
<tr>
<td></td>
<td>HEAT</td>
<td>B2 AR</td>
<td>28% time below, 13% above ASHRAE 55(^a)</td>
</tr>
<tr>
<td></td>
<td>HEAT</td>
<td>B3 PR</td>
<td>41% time below, 4.3% above ASHRAE 55(^a)</td>
</tr>
<tr>
<td></td>
<td>HEAT</td>
<td>B3 AR</td>
<td>12% time below, 9.4% above ASHRAE 55(^a)</td>
</tr>
<tr>
<td>Brugge et al. (2001)</td>
<td>HEAT</td>
<td>All</td>
<td>73% units with overheating 38% used oven at least once to heat</td>
</tr>
<tr>
<td>Brugge et al. (2003)</td>
<td>HEAT</td>
<td>All</td>
<td>MIT between 23°C to 28°C</td>
</tr>
<tr>
<td>Brugge et al. (2006)</td>
<td>HEAT</td>
<td>All</td>
<td>59% units too cold and 58% units too hot at least once(^b)</td>
</tr>
<tr>
<td>Giancola et al. (2014)</td>
<td>COOL</td>
<td>All</td>
<td>Retrofits increased thermal inertia</td>
</tr>
<tr>
<td>Santamouris et al. (2014)</td>
<td>HEAT</td>
<td>MSG(^c)</td>
<td>MIT = 12.5°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LSG(^c)</td>
<td>MIT = 18.4°C</td>
</tr>
<tr>
<td>Peretti et al. (2015)</td>
<td>HEAT</td>
<td>All</td>
<td>MIT = 21°C; no discomfort in surveys</td>
</tr>
<tr>
<td>Sakka et al. (2012)</td>
<td>COOL</td>
<td>All</td>
<td>MMIT above 29°C; 80% of time above 30°C</td>
</tr>
<tr>
<td>Haaland et al. (2016)</td>
<td>BOTH</td>
<td>PR</td>
<td>Uncomfortable 50% of time; excess heat main issue</td>
</tr>
<tr>
<td>Touchie et al. (2016)</td>
<td>COOL</td>
<td>PR</td>
<td>Survey: &gt;50% reported discomfort</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Monitoring: 50% of the time above 26°C</td>
</tr>
<tr>
<td>McGill et al. (2014)</td>
<td>BOTH</td>
<td>All</td>
<td>Indoor temperatures within 18°C to 24°C</td>
</tr>
<tr>
<td>Howden-Chapman et al.</td>
<td>HEAT</td>
<td>PR</td>
<td>MIT = 13°C</td>
</tr>
</tbody>
</table>
To further explore thermal comfort in social housing, I analyzed the monitoring data collected through the field work in three social housing developments in Toronto, to evaluate comfort conditions inside these units during an entire year before the buildings underwent energy retrofits. Seven buildings across three social housing developments were monitored since February 2015, and the following results correspond to the period from April 1, 2015 to April 1, 2016. Figure 2 summarizes the indoor and outdoor temperatures for the entire monitoring period. It can be seen that, during the summer months, the indoor temperature was very close to, or exceeded, the outdoor temperature, suggesting that cooling mechanism in most units (if any is present, as some units have none) is ineffective. The implications of this finding are profound: during the summer, the indoor temperatures in several units is close to the outdoor temperature. In the case of an extreme heat event, it is clear that these buildings will not provide a cool and safe environment for occupants to shelter during the event.

Further, this figure suggests that the main source of discomfort throughout the entire year in most units is due to excess heat, with several units spending considerable amounts of time with indoor air temperatures above 27°C. Additionally, this figure also suggests that buildings do not have the same thermal performance: Building A has the highest prevalence of high temperatures, whereas buildings C, D, E and F seem to have high temperatures only during the summer months. This is indicative of different problems: high temperatures in the summer are due to lack of

<table>
<thead>
<tr>
<th>Year</th>
<th>Building</th>
<th>Season</th>
<th>Pre-Retrofit</th>
<th>After Retrofit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Mavrogianni et al.</td>
<td>COOL</td>
<td>All</td>
<td>Indoor T = 16°C</td>
</tr>
<tr>
<td>2015</td>
<td>Richardson et al.</td>
<td>HEAT</td>
<td>PR</td>
<td>Indoor bedroom T = 18°C</td>
</tr>
<tr>
<td>2017</td>
<td>Broderick et al.</td>
<td>HEAT</td>
<td>PR</td>
<td>&gt; 70% of the occupants not comfortable</td>
</tr>
</tbody>
</table>

Footnotes:

a The authors chose the temperature boundaries of the comfort zone based on typical levels of indoor humidity, and noted that these boundaries are only applicable if the windspeed is less than 0.2 m s⁻¹
b Too hot and too cold were indexes (identified by authors using Exploratory Factor Analysis) that encompassed several questions regarding thermal comfort, including questions related to: operation of heating system by housing authority, stuffiness of air in the apartment, usage of oven to heat apartment, etc.
c Units were classified in terms of the severity of the thermal discomfort. MSG represents the “most severe group”, LSG represents the “least severe group”
cooling/undercooling, whereas high temperatures during the winter are generally attributable to overheating.

**Figure 2** Indoor and outdoor temperatures for all monitored suites during between April 1, 2015 and April 2, 2016. This figure was submitted for publication to Building and Environment by Diaz Lozano et al. (2018a)

Given that air temperature is just one of the many parameters that affects thermal comfort, I conducted two further models using the provisions specified in ANSI/ASHRAE Standard 55-2013 (ANSI/ASHRAE 2013). Figure 3 shows the predicted percent time comfortable calculated using the Graphical Comfort Zone Model from the ANSI/ASHRAE Standard 55-2013, and assuming a seasonally appropriate fixed clothing value, while Figure 4 shows the predicted percent time comfortable calculated using the same method but assuming that occupants will switch clothing to maximize their comfort. In the figures, it can be observed that the results of these two figures are consistent with those of Figure 2: discomfort is more prevalent in the summer months, and Building A shows the highest percentage discomfort throughout the year. Further, the comparison between Figure 3 and Figure 4 showcases the importance that the clothing value has on the predicted comfort: assuming that occupants will reduce their clothing value makes a very noticeable difference, especially in the winter and in the fall.
Figure 3 Fixed clothing model predicted occupant comfort, using the Graphical Thermal Comfort Method. Data included is from April 1, 2015 to April 1, 2016. This figure was submitted for publication to Building and Environment by Diaz Lozano et al. (2018a)
In addition to modelling comfort using the Graphical Comfort Zone Model from the ANSI/ASHRAE Standard 55-2013, I calculated the Predicted Mean Vote using the Analytical Comfort Zone Model also from the ANSI/ASHRAE Standard 55-2013. Figure 5 summarizes the calculated PMV values for all suites. The PMV is a metric used to evaluate comfort, values below -0.5 indicates increasing discomfort due to cold, and values above +0.5 indicates increasing discomfort due to hot. This figure shows that there seems to be no correlation between discomfort and floor height, but the distribution of PMV values in building A shows that it has higher instances of discomfort due to heat than other buildings. Overall, the majority of the suites, according to this model, should be within the comfort zone most of the time. This is an important finding as it seems contrasting to the results of the Graphical Comfort Zone Method, highlighting that thermal comfort modelling results may be model dependent.

**Figure 4** Variable clothing model predicted occupant comfort, using the Graphical Thermal Comfort Method. Data included is from April 1, 2015 to April 1, 2016 This figure was submitted for publication to Building and Environment by Diaz Lozano et al. (2018a)
Figure 5 Box plot of the calculated PMV calculated for the period from April 1 2015 to April 1, 2016. Blue lines indicate ±0.5, which represents the comfort range. Gray bars indicate floor for each suite, black boxes represent building height. This figure was submitted for publication to Building and Environment by Diaz Lozano et al. (2018a)

The last data analyzed from the field work was the CO\(_2\) concentrations, to evaluate whether there was evidence that the monitored units were under ventilated, which would have indoor air quality and occupant comfort implications. Figure 6 plots the indoor CO\(_2\) concentration elevation over outdoors. It shows that the majority of the suites had elevations below the recommended 700 ppm in ANSI/ASHRAE Standard 62.1 (ANSI/ASHRAE 2016) suggesting that there were adequate air exchange rates. The figure also shows that there is no correlation of increasing or decreasing CO\(_2\) elevation with floor number or building. Further, the few suites that have extreme values are probably attributable to increased occupancy, as there was no evidence that it was attributable to sensor errors.
Figure 6 Box plot of indoor CO$_2$ concentration elevation over outdoors. Horizontal line represents 700ppm, the recommended concentration in ANSI/ASHRAE Standard 62.1 to create an indoor environment where the majority of the occupants will be satisfied (ANSI/ASHRAE 2016). Gray bars indicate floor for each suite, black boxes represent building height. Graph covers the period from April 1, 2016 to April 1, 2016. This figure was submitted for publication to Building and Environment by Diaz Lozano et al. (2018a)

5.3 Odour control

During the field collection of data for the thermal comfort modelling, I observed that using incense was common, and that unpleasant odours were prevalent in the buildings. Current research suggest that odour transmission is a common problem in multi unit buildings, for example, residents often report smelling tobacco smoke from neighbouring units (Hewett et al. 2002). Because of this, it is likely that occupants may take action to mitigate potentially unpleasant odours coming from other units. However, there is reason to believe that some of the mechanisms occupants use to mask bad odours may result in further indoor air pollution. Combustion sources of scents will likely emit particles through the combustion process, and newer technologies such as ultrasonic oil diffuser or wax warmers also may generate PM$_{2.5}$
through other mechanisms (as described in Chapter 3). Therefore, I decided to investigate the PM$_{2.5}$ emission rates of three common scent sources: incense, ultrasonic oil diffusers and wax warmers. The resulting emission rates are summarized in Figure 7. This figure shows that there is very high variation between the different sources: the emission rates of incense are about an order of magnitude greater than those of the diffuser, and two orders of magnitude greater than those of the wax warmer. There was also variation across different tests within the same sources, with the results of the wax warmer showing the largest amount of variation, which could be attributable to variations in temperature of the surface, or variations in the wax used (even though it was from the same package).

![Figure 7](image)

**Figure 7** PM$_{2.5}$ emission rates for incense, wax warmer, and ultrasonic oil diffuser. Each bar represents the results from one test. Caps indicate± 1 standard deviation. This figure was accepted for publication at the ASHRAE for the 2018 Annual Conference in Houston (Diaz Lozano et al., 2018b)

The results of in Figure 7 highlight the potential of some of these sources to be significant contributors of PM$_{2.5}$ in social housing settings. At the top of the list of concern would be incense, with an averaged measured emission rates of 42.9 mg h$^{-1}$, followed by the ultrasonic oil diffuser with an average PM$_{2.5}$ emission rate of 1.7 mg h$^{-1}$. For comparison, cigarette smoking has been reported to have a PM$_{2.5}$ emission rate of 1.9-2.7 mg h$^{-1}$ (Charles et al. 2008), assuming
a burning time of 10 minutes. Given that cigarette smoking has been identified as driver of PM$_{2.5}$ concentrations in social housing units (Mahdavi et al. 2016), the use of incense and oil diffusers could also have a strong influence on PM$_{2.5}$ concentrations.

The results from this section highlight three important findings. Firstly, indoor air pollution in social housing is mostly due to elevated PM$_{2.5}$ concentrations, pesticide usage, and NO$_2$ (in cases with combustion appliances). Secondly, poor thermal comfort conditions are prevalent, with exposure to high temperature being the most common issue. In the case our field investigation, this was mostly due to insufficient cooling. Lastly, sources to produce pleasant scents are also emitters of PM$_{2.5}$ and could increase significantly the existing concentrations.
6 Discussion

Note: The results presented in this section have been published or submitted for publication on the following articles:


- Diaz Lozano Patino, E., A. Mahdavi, and J.A. Siegel. Particulate Matter Emission Rates from Common Scent Sources. 2018. Accepted for presentation at the 2018 Houston ASHRAE Conference.

6.1 Implications

The main implication of poor IEQ in social housing is that it may lead to the development of negative health effects. Therefore, studies that have evaluated the health effects associated with living in social housing provide valuable information to assess the prevalence of certain illnesses in social housing residents. As part of the literature review, I investigated the published evidence that associated residing in social housing with the development of adverse health effects. Table 2 summarizes the findings from this investigation. Overall, there is a high prevalence of respiratory issues in social housing residents, with elevated prevalence of asthma and asthmatic symptoms being reported by several investigations (Brugge et al. 2001, 2006; Howden-Chapman et al. 2007; Popkin 2002). The negative health effects summarized Table 2 are a result of several factors that are present in social housing. First, household factors such as high allergen concentrations have been associated with greater odds of having asthmatic residents (Chew et al. 2006). Second, neighbourhood level effects may lead to increase exposure to pollutants, both outdoors (due to polluting land uses near social housing developments, as reported by Corburn et al. (2006)) and indoors (due to increased time spent indoors as a result of unsafe neighbourhoods, also noted by Corburn et al. (2006)). In addition to respiratory health, poor mental health also appears to be common in social housing. This may be attributable to increased
psychological distress associated with living in units and neighborhoods of poor quality, as described by Evans (2003). The results of Popkin (2002) also highlight two important points. First, that these health issues are not isolated to a single housing development but are widespread (at least at a national level in the US). Second, that in the context of the US, incidence of asthma is higher in social housing than at a national level. In their report, Popkin (2002) notes that 13% of their sample reported an asthma attack in the past year, contrasted to the national average of 4% for the same year.
### Table 2 Reported health effects associated with living in social housing.
This table was published in Building and Environment by Diaz Lozano Patino and Siegel (2018).

<table>
<thead>
<tr>
<th>Health issue</th>
<th>Study</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General health</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>(Adamkiewicz et al. 2014)</td>
<td>SHS associated with poor health</td>
</tr>
<tr>
<td></td>
<td>(Jacobs et al. 2015)</td>
<td>Children mean score of 2.1&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>Self-reported</td>
<td>(Popkin 2002)</td>
<td>38% indicated very good/excellent</td>
</tr>
<tr>
<td>Quality of life</td>
<td>(Howden-Chapman et al. 2007)</td>
<td>24% reported fair or poor health</td>
</tr>
<tr>
<td></td>
<td>(Colton et al. 2015)</td>
<td>Mean score of 3.2&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>(Krieger et al. 2005)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Mean score of 4.2&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Physical health</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chronic illness</td>
<td>(Jacobs et al. 2015)</td>
<td>39% adults reported chronic illness</td>
</tr>
<tr>
<td></td>
<td>(Krieger et al. 2005)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>50% reported symptoms within last day</td>
</tr>
<tr>
<td>Asthma</td>
<td>(Chew et al. 2006)</td>
<td>7.9 days with symptoms in past 2 weeks</td>
</tr>
<tr>
<td></td>
<td>(Krieg et al. 2005,&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1 or more asthmatic resident in 36% of units</td>
</tr>
<tr>
<td></td>
<td>(Northridge et al. 2010)</td>
<td>21.8% diagnosed with asthma</td>
</tr>
<tr>
<td>Adult asthma</td>
<td>(Popkin 2002)</td>
<td>22% of respondents diagnosed</td>
</tr>
<tr>
<td></td>
<td>(Brugge et al. 2001)</td>
<td>40% reported prevalence</td>
</tr>
<tr>
<td>Children asthma</td>
<td>(Jacobs et al. 2015)</td>
<td>17% of children with reported asthma</td>
</tr>
<tr>
<td></td>
<td>(Colton et al. 2015)</td>
<td>40 children&lt;sup&gt;e&lt;/sup&gt; with asthma</td>
</tr>
<tr>
<td></td>
<td>(Brugge et al. 2001)</td>
<td>56% reported prevalence</td>
</tr>
<tr>
<td></td>
<td>(Brugge et al. 2001)</td>
<td>21.8% diagnosed with asthma</td>
</tr>
<tr>
<td>Wheezing</td>
<td>(Howden-Chapman et al. 2007)</td>
<td>42% reported symptom in past 3 months</td>
</tr>
<tr>
<td></td>
<td>(Brugge et al. 2001)</td>
<td>40% reported symptom in last month</td>
</tr>
<tr>
<td>Coughing</td>
<td>(Brugge et al. 2001)</td>
<td>48% reported symptom in last month</td>
</tr>
<tr>
<td>Sneezing</td>
<td>(Brugge et al. 2001)</td>
<td>48% reported symptom in last month</td>
</tr>
<tr>
<td>Obesity</td>
<td>(Levy et al. 2004)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Present in 56% of respondents</td>
</tr>
<tr>
<td>Cockroach allergy</td>
<td>(Levy et al. 2004)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Present in 59% of respondents</td>
</tr>
<tr>
<td>Dust mite allergy</td>
<td>(Levy et al. 2004)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Present in 59% of respondents</td>
</tr>
<tr>
<td>SBS symptoms&lt;sup&gt;f&lt;/sup&gt;</td>
<td>(Colton et al. 2015)</td>
<td>Mean score of 4.1&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Mental health</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>(Jacobs et al. 2015)</td>
<td>Adult mean score 2.1 for sadness&lt;sup&gt;h,h&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>(Popkin 2002)</td>
<td>29% indicated poor mental health</td>
</tr>
<tr>
<td>Depression</td>
<td>(Santamouris et al. 2014)</td>
<td>8.2% of population suffers from it</td>
</tr>
<tr>
<td></td>
<td>(Popkin 2002)</td>
<td>10% had 1 major episode in last year</td>
</tr>
<tr>
<td>Self-efficacy</td>
<td>(Popkin 2002)</td>
<td>Low scores in general&lt;sup&gt;i&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory index&lt;sup&gt;j&lt;/sup&gt;</td>
<td>(Brugge et al. 2006)</td>
<td>Associated with 7 risk factors&lt;sup&gt;k&lt;/sup&gt;</td>
</tr>
<tr>
<td>Building index&lt;sup&gt;k&lt;/sup&gt;</td>
<td>(Brugge et al. 2006)</td>
<td>Associated with 4 risk factors&lt;sup&gt;m&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Acronyms:**
SHS: Second Hand Smoke, SBS: Sick building syndrome

**Footnotes:**
<sup>a</sup>Includes respiratory, cardiovascular and neurological health
<sup>b</sup>Scale: 1= excellent, 5 = poor
<sup>c</sup>Population consisted of asthmatic children
<sup>d</sup>Based on Pediatric Asthma Caregiver Quality of Life Scale (1 to 7, higher score indicates better quality of life)
<sup>e</sup>Children total population not reported
<sup>f</sup>Symptoms include: dizziness, headaches, nausea, coughing, tiredness, nosebleeds, breathing problems, blurred vision, wheezing, sneezing, ear infection, rashes, burning/itchy eyes, sore/dry throat.
<sup>g</sup>Score represents number of symptoms reported
<sup>h</sup>Includes depression, anxiety and nervousness
<sup>i</sup>Self-efficacy was assessed using 4 standard measures from the Pearlin Mastery Scale.
<sup>j</sup>Includes: coughing, breathing problems, wheezing, sneezing attacks, skin rash, sore or dry throat
<sup>k</sup>Cockroaches, rodents, mould, water leaks, apartment too hot, apartment too cold, chemical use, insecticide use. Statistically significant only in univariate analysis (only apartment was also significant in multivariate analysis).
<sup>l</sup>Includes: dizziness, headache, nausea, blurred vision, burning/itching eyes
<sup>m</sup>Cockroaches, rodents, mould, water leaks, apartment too hot. Statistically significant only in univariate analysis.
The second major implication of the findings of this paper is that poor thermal comfort, in the monitored suites, varies seasonally, which implies that distinct factors are causing the discomfort. According to the indoor temperatures monitored, as well as the results from the Graphical Comfort Zone model, it seemed that almost no discomfort occurred due to cold temperatures, while extensive discomfort occurred due to hot temperatures. As discussed previously, there are potential health implications of this as exposure to high temperatures could lead to issues such as heat strokes, especially in vulnerable populations. The underlying causes of the high temperatures are distinct for each season. During the heating season, the discomfort is likely due to overheating. In this season, there is considerable difference between the fixed clothes model and the variable clothes model. While this indicates that occupants can potentially avoid discomfort by switching into lighter garments, it is questionable whether it is appropriate to expect residents, especially seniors with potential mobility problems, to need to switch into summertime clothing every time they walk into their suites to be comfortable, instead of being able to maintain a reasonable clothing level for winter (e.g., a long sleeve shirt, trousers and a sweater). The most appropriate measures to reduce wintertime overheating would be to provide occupants control of the heating system in their units and replace the boilers with appropriately sized units. These two measures were implemented on the buildings after the monitoring period, and future studies will be able to evaluate their effectiveness in reducing overheating occurrences.

In contrast, during the cooling season, the discomfort is clearly driven by lack of cooling/undercooling. The units are maintaining temperatures very close to the outside temperatures, which coupled with radiant energy coming through the windows, is resulting in very uncomfortable indoor environments. In these circumstances, it does not seem like occupants can improve their comfort conditions by switching into lighter garments, as our model assumed that occupants would wear the lowest allowable clothing level, and this still resulted in discomfort most of the time. These findings are not surprising: none of the buildings are equipped with central air conditioning, and those units that have window units may not have enough capacity the cooling loads. The need to reduce summertime discomfort is critical, given that extreme heat events are likely to become more frequent due to climate change (Coumou and Rahmstorf 2012). In the short term, exposure to hot temperatures could be mitigated by reducing air exchange rates, retrofitting windows (some units have considerably high window to wall ratios)
and also implementing cooling centers in the building for occupants to have a place to go to during hot days. In the long term, it seems evident that these buildings will need to be equipped with a central cooling system appropriately sized to manage the loads associated with extreme heat events.

The third major implication of the findings of this work is that sources to produce pleasant scents indoors may become significant contributors to PM$_{2.5}$ concentrations in social housing. In order to estimate the concentrations associated with the operation of these sources in a typical social housing environment, I created a mass balance model for two typical social housing units, a 50 m$^3$ bachelor apartment and a 125 m$^3$ two-bedroom apartment. I used the following parameters for the model: a deposition loss rate of 0.42 h$^{-1}$ (Williams et al. 2003), a portable air cleaner (PAC) with a clean air delivery rate (CADR) of 70 m$^3$h$^{-1}$, and varying air exchange rates (AERs): a low range of 0.2-1.2 h$^{-1}$ (Figure 8), and a high range of 2.2-4.4 h$^{-1}$ (Figure 9). One important limitation about this model is that I assumed that there was no outdoor PM$_{2.5}$, which results in the model underpredicting indoor PM$_{2.5}$ concentrations. In both Figure 8 and Figure 9, it can be appreciated how the operation of these sources, particularly the incense and the oil diffuser, can result in very large PM$_{2.5}$ concentrations. Figure 8 shows that at low air exchange rates (common for several indoor environments, even those in leaky buildings) the incense could be slightly more polluting in a larger space with no air cleaning than in a small space with air cleaning, albeit still resulting in very large concentrations in both spaces. Figure 9 shows how adding substantial mechanical ventilation is not sufficient to properly mitigate very strong sources such as the incense; even in the case of the two-bedroom apartment with PAC, the high ventilation scenario still shows considerable concentrations at high AERs. These figures also show that an increasing AER has a smaller effect in scenarios with PAC operation, further highlighting the limits of ventilation as a control for sources with strong emissions. One consideration, however, is that many of these sources are episodic in nature. The results presented in Figure 8 and Figure 9, which assumed steady state concentrations, are likely an overestimate given that some of these sources may not operate long enough to achieve steady state. In this case, a time-dependent model would be best suited to estimate the concentrations.
Figure 8 Low ventilation mass balance model, predicting the concentrations associated with the operation of the three different sources in varying conditions, with varying AERs. INC represents incense, OD represents oil diffuser, WW represents wax warmer, Bach indicates that it is a bachelor's apartment and two bed indicates that it is a two-bedroom apartment. A similar figure was accepted for publication to ASHRAE for the 2018 Annual Conference in Houston (Diaz Lozano et al., 2018b)

Figure 9 High ventilation mass balance model, predicting the concentrations associated with the operation of the three different sources in varying conditions, with varying AERs. INC represents incense, OD represents oil diffuser, WW represents wax warmer, Bach indicates that it is a bachelor's apartment and two bed indicates that it is a two-bedroom apartment. A similar figure was accepted for publication to ASHRAE for the 2018 Annual Conference in Houston (Diaz Lozano et al., 2018b)
6.2 Limitations

To provide more context to each investigation presented in this work, it is important to discuss the limitations that may have affected the results. For the literature review, the main limitations were the lack of a standardized definition of social housing (for the search terms used in the review process, see Chapter 4 Methodology), and the difficulty of finding comparable non-social housing studies to discuss relative prevalence of poor IEQ conditions in social housing. The first limitation was mitigated by ensuring that the reviewed papers studied either buildings in developments considered public or social housing, or low-income housing, and including this classification in the results (see Appendix). The second limitation was mitigated by selecting buildings with similar context to the social housing buildings when possible (multi unit, located in cities with comparable outdoor pollution), and also attributing the drivers of poor IEQ conditions to specific building factors (such as smoking presence or sources of combustion). The thermal comfort monitoring work had three main limitations. First, the fact that residents were being observed could have altered their behavior (similar to the Hawthorne Effect). This could have led, for example, different window operation or AC usage. Further, the presence of research team members every 3 months to download the data could have increased the chances of the Hawthorne Effect taking place. Unfortunately, it is not possible to test from our data whether this effect affected our results, nor to estimate its magnitude if it did. Second, the measurement of mean radiant temperature (MRT) was done using a very approximate approach, and the data analysis suggested that the results were almost identical to the air temperature. Lack of an appropriate measure of MRT could result in inaccurate modelling of the comfort conditions. Third, errors on the underlying parameters for the comfort calculations (air velocity and metabolic rate) could have affected our results. This limitation is an inherent limitation to the models used, since they were developed for a range of metabolic rates and an assumed air speed. To analyze comfort at higher air speeds or different metabolic rates it would be necessary to use an alternative model. Fourth, since the carbon dioxide sensors had an independent power connection, there were several periods of data that were lost due to power loss to the sensors. We overcame this limitation by only including suites that were not missing more than 2 weeks of data or 3 consecutive days of data. The scents emission testing also had a few limitations. First, tests were conducted in chambers that had a small air exchange rate, however, it was determined (by comparing the loss rates of different experiments) that this played a minimal role and had
very little effect on our results. Second, the testing was done without a fan which could have led to poor air mixing in the chamber, however I decided to follow this protocol to avoid resuspension of particles due to excess air movement which would have introduced more error. Third, these sources may not be used equally by different populations. The frequency of usage, as well as the operating time for each usage, was not considered in the mass balance models estimating concentrations. Lastly, I failed to clean the oil diffuser by running it with distilled water between tests, but given the small variation in the tests results, I do not believe this affected the outcome significantly.

6.3 Retrofits to improve IEQ in social housing

In this work, I have discussed the evidence that poor IEQ in social housing, manifested as increased air pollutant concentrations, pest presence, pesticide usage, and prevalent poor thermal comfort conditions, have lead to unhealthy indoor environments. I have also presented evidence that living in social housing has been associated with poor health, and that novel sources of pleasant scents may contribute to further pollution as they become more widely used and make their way into social housing units. In order to mitigate these exposures, social housing authorities may decide to implement retrofits to improve the housing quality. Therefore, I also investigated the existing evidence regarding the impact of renovations and interventions on IEQ and occupants’ health. Table 3 summarizes the results of thirteen investigations which evaluated the effect of green retrofits on select IEQ parameters and occupants’ health. In general, investigations found that targeted retrofits were able to improve health and reduce pollution (with statistically significant improvements), however, some authors found increased PM$_{2.5}$ and HCHO concentrations after retrofits (Broderick et al. 2017; Jacobs et al. 2015; Richardson et al. 2006). This could be due to lower ventilation rates post-retrofit and the use of HCHO emitting materials during construction. In general, the retrofit results present an opportunity to reduce exposure if they are designed with IEQ considerations.
Table 3 Summary of effects of “green” retrofits on select IEQ parameters. This table was published in Building and Environment by Diaz Lozano Patino and Siegel (2018).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Study</th>
<th>Change in metric</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Adult Health</strong></td>
<td><em>(Breysse et al. 2011)</em></td>
<td>Improved overall health, reduced asthma and non-asthma respiratory problems*</td>
</tr>
<tr>
<td></td>
<td><em>(Colton et al. 2014)</em></td>
<td>Improved self-reported health*</td>
</tr>
<tr>
<td></td>
<td><em>(Colton et al. 2015)</em></td>
<td>Reported fewer SBS symptoms*</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Variesb</td>
</tr>
<tr>
<td><strong>Children Health</strong></td>
<td><em>(Breysse et al. 2011)</em></td>
<td>Reduced reported non-asthma respiratory problems*</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Improved general physical health*</td>
</tr>
<tr>
<td><strong>PM$_{2.5}$</strong></td>
<td><em>(Colton et al. 2014)</em></td>
<td>Reduction of 57%*</td>
</tr>
<tr>
<td></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Average decrease of 47.5%c</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Higher GM in green units</td>
</tr>
<tr>
<td></td>
<td><em>(Coombs et al. 2016)</em></td>
<td>No significant difference</td>
</tr>
<tr>
<td></td>
<td><em>(Richardson et al. 2006)</em></td>
<td>Fine particles increased by 15%</td>
</tr>
<tr>
<td></td>
<td><em>(Broderick et al. 2017)</em></td>
<td>Average concentration increase of 70%*</td>
</tr>
<tr>
<td><strong>CO$_2$</strong></td>
<td><em>(Colton et al. 2014)</em></td>
<td>No significant change</td>
</tr>
<tr>
<td></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Average decrease of 30% of indoor minus outdoor concentrations</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Higher GM in green units</td>
</tr>
<tr>
<td></td>
<td><em>(Broderick et al. 2017)</em></td>
<td>Average concentration increase of 20%</td>
</tr>
<tr>
<td><strong>Ventilation</strong></td>
<td><em>(Breysse et al. 2011)</em></td>
<td>Supplied at 70% of ASHRAE standard 62.2</td>
</tr>
<tr>
<td></td>
<td><em>(Colton et al. 2014)</em></td>
<td>Reduced, but not statistically significant</td>
</tr>
<tr>
<td></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Increased*, by more in suites with ERV</td>
</tr>
<tr>
<td><strong>HCHO</strong></td>
<td><em>(Colton et al. 2014)</em></td>
<td>Increased, not significantlyd</td>
</tr>
<tr>
<td></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Variese</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Higher GM in green units</td>
</tr>
<tr>
<td></td>
<td><em>(Coombs et al. 2016)</em></td>
<td>No significant difference</td>
</tr>
<tr>
<td></td>
<td><em>(Broderick et al. 2017)</em></td>
<td>Average concentration increase of 43%*</td>
</tr>
<tr>
<td><strong>NO$_2$</strong></td>
<td><em>(Colton et al. 2014)</em></td>
<td>Reduction of 65%</td>
</tr>
<tr>
<td></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Average decrease of 58% of indoor concentrationf</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Less time outside of ASHRAE comfort zone</td>
</tr>
<tr>
<td></td>
<td><em>(Peretti et al. 2015)</em></td>
<td>No change linked to improvements</td>
</tr>
<tr>
<td></td>
<td><em>(Giancola et al. 2014)</em></td>
<td>Reduced fluctuations in temperature, better comfort during cooling season</td>
</tr>
<tr>
<td></td>
<td><em>(Howden-Chapman et al. 2007)</em></td>
<td>Average 30% reduction of time below 10°C*</td>
</tr>
<tr>
<td></td>
<td><em>(Richardson et al. 2006)</em></td>
<td>No significant change</td>
</tr>
<tr>
<td><strong>RH</strong></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Reduced time with bathroom RH &gt;75%</td>
</tr>
<tr>
<td></td>
<td><em>(Peretti et al. 2015)</em></td>
<td>Lower RH due to mechanical ventilation</td>
</tr>
<tr>
<td></td>
<td><em>(Howden-Chapman et al. 2007)</em></td>
<td>Average 33% reduction of time above 75%*</td>
</tr>
<tr>
<td></td>
<td><em>(Richardson et al. 2006)</em></td>
<td>Reduction in bedrooms and living areas</td>
</tr>
<tr>
<td><strong>Mould</strong></td>
<td><em>(Colton et al. 2015)</em></td>
<td>Reduced sightings in green units by 90%.*</td>
</tr>
<tr>
<td></td>
<td><em>(Howden-Chapman et al. 2007)</em></td>
<td>47% decrease in sightings after interventions*</td>
</tr>
<tr>
<td><strong>VOCs</strong></td>
<td><em>(Noris et al. 2013)</em></td>
<td>Variesg</td>
</tr>
<tr>
<td></td>
<td><em>(Jacobs et al. 2015)</em></td>
<td>Higher GM in green units</td>
</tr>
</tbody>
</table>
The results in Table 3 do not fully capture all the aspects about retrofits discussed in the literature. Firstly, many of the retrofits (envelope improvement, ventilation and HVAC upgrades, glazing replacement) also provide an opportunity to reduce energy consumption, which would serve as an incentive for housing authorities to invest in retrofits. This is particularly important considering that doing retrofits with the sole purpose of improving occupant’s health may not be cost-effective for many social housing authorities, considering that the costs of poor health do not directly accrue to them (even if the provincial/state government funds both housing and health, the costs of poor health are not necessarily perceived by the social housing authorities who manage most of the day to day operations). This is contrasting to, for example, energy retrofits which have a direct benefit to the social housing authorities who are responsible for paying the energy bills. Secondly, the use of integrated pest management (IPM) is not fully represented by the results of the table. As presented before, pests and pesticide usage associated with pest presence is a common problem in social housing. IPM consists of a collection of strategies devised with the goal of eliminating pests and preventing further reoccurrences with long term measures. The results of Peters et al. (2007a) and Peters et al. (2007b) show that IPM is effective in controlling pests and reduce exposure to pest allergens, and highlight that occupant engagement is key for successful IPM implementations. Lastly, the role of compartmentalization of units is not discussed in Table 3. While there is evidence that compartmentalization of units is not enough to prevent transfer of pollutants, such as environmental tobacco smoke (ETS) (Bohac
et al. 2011), it is still a valuable strategy for two reasons: it can help prevent transfer of pests, and it can serve as a fail-safe mechanism in case occupants decide to ignore building wide smoking bans. In the context of legislative initiatives that may increase smoking inside buildings, such as marijuana legalization in Canada, it becomes particularly important to consider effective measures to control smoking related pollution.

In this discussion, I have shown that there is evidence that living in social housing is associated with poor health. Further, I have evaluated how sources of pleasant scents commonly used indoors can become important drivers of PM$_{2.5}$, a harmful indoor air pollutant, which already appears to exist in higher concentrations in social housing when compared to non-social housing. Lastly, I have shown that green retrofits, which also have potential to reduce energy consumption of buildings, can be leveraged to improve the IEQ and health of occupants as long as they are designed with IEQ considerations from the onset.
Chapter 7
Conclusion

7 Conclusion

In this work, I explored the IEQ conditions in social housing as well as the PM$_{2.5}$ generation of common sources scents indoors, which may be used in social housing to mask unpleasant odours. I found that residents in social housing may be disproportionately exposed to higher levels of PM$_{2.5}$, mainly due to cigarette smoking in the buildings, and that sources of pleasant scents (such as incense and oil diffusers) may exacerbate this exposure. I also found that poor thermal comfort was prevalent in public housing, with high temperatures being the most common source of discomfort. Through a field investigation, I corroborated that this discomfort mainly occurred during the summer due to lack of proper cooling. This is of particular concern considering that climate change is likely going to result in more frequent extreme heat events, placing social housing residents at increased risk of developing heat related illnesses. I also found that residing in social housing has been associated with higher chances of developing respiratory diseases. Lastly, I found that poor IEQ conditions can be alleviated through building retrofits, if these are conducted with IEQ considerations from the onset.

As the populations in urban centers continue to grow, and more subsidized housing needs to be constructed, it is imperative that policy makers and social housing authorities increase their awareness of the poor IEQ conditions prevalent in the existing social housing stock. It is also important that they become familiar with the strategies that can be undertaken to improve the conditions in the existing buildings and also design new buildings with preventive approaches in mind.
Contributions

- Literature review- Appendix A: I conducted the search for papers, developed the figures, and wrote the paper. Professor Siegel provided feedback, as well as content and editorial revisions.

- Thermal comfort paper- Appendix B- I assisted with the equipment preparation and execution of 2 rounds of site visits (which were focused on downloading data as well as installing indoor air quality monitoring equipment), and developed the figures and wrote the paper. The other authors had been involved in starting the project, and provided feedback, as well as content and editorial revisions.

- Emissions from Scents Sources- Appendix C – I designed the experimental protocol and assisted in the execution of the experiments. Alireza Mahdavi conducted the simulation for the modelling of PM concentrations presented in the discussion. The other authors had been involved in starting the project, and provided feedback, as well as content and editorial revisions.
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IARC. 2012. Formaldehyde. IARC monographs on the evaluation of carcinogenic risks to humans.


Statistics Canada. 2011. Table 3 Shelter cost and housing affordability by housing tenure for non-farm, non-reserve dwellings, Canada, 2011.


Copyright Acknowledgments

- Literature review- Appendix A: This paper has been published in Building and Environment by Elsevier (https://doi.org/10.1016/j.buildenv.2018.01.013). According to Elsevier’s Copyright policies valid as of the submission date of this work, authors are allowed to include Published Journal Articles as part of their thesis.

- Thermal comfort paper- Appendix B- This paper will be submitted for publication been to Building and Environment shortly after the submission of this thesis. According to Elsevier’s Copyright policies valid as of the submission date of this work, authors are allowed to include pre-print version of their articles. Further, according to Elsevier’s article on “Clarification of our policy on prior publication”, published by Gemma Hersh on 27 January 2016 (https://www.elsevier.com/editors-update/story/publishing-ethics/clarification-of-our-policy-on-prior-publication), the publication of this work does not count as a prior publication.

- Emissions from Scents Sources- Appendix C – This paper has been accepted for presentation at the 2018 Houston ASHRAE Conference. According to ASHRAE’s Author’s Manual valid as of the submission date of this work, authors are allowed to include their articles as part of their thesis.
Indoor environmental quality in social housing: A literature review

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ARTICLE INFO

Keywords: Public housing, Low income housing, Indoor air quality, Thermal comfort, Green retrofits, Health impacts

ABSTRACT

The unprecedented levels of urbanization in the last century have led to significant social housing populations in cities across the world. Housing conditions in social housing units are usually substandard, which often correlates with higher exposure to indoor pollutants, and ultimately negative health effects. We reviewed 49 articles in the literature documenting indoor environmental quality (IEQ) conditions in social housing which were focused on air pollutant concentrations, thermal comfort, or health effects associated with living in these units. We found evidence that social housing residents may be disproportionately exposed to higher levels of PM$_{2.5}$, which is heavily influenced by the presence of cigarette smoking in the building. However, we found no evidence that they are disproportionately exposed to higher levels of other pollutants such as formaldehyde and dampness. Poor thermal comfort was also found to be a prevalent issue in social housing, but there are not enough data on comparable non-social housing to make a definitive statement about relative prevalence. We also found that there are strong indicators that residing in social housing is associated with negative health effects, with high prevalence of respiratory problems. Lastly, we found that green retrofits have the potential to improve the IEQ conditions, but these retrofits must be tailored to the specific context of each building. Given the increasing importance of social housing to most urban areas, and the potential vulnerability of social housing inhabitants, it is imperative that we maintain healthy environments for these occupants.

1. Introduction

The last century has seen unprecedented levels of urbanization in human history. As of 2014, about 54% of the global population lives in urban areas [1]. This growth has increased the demand for dwellings in or near urban centers, often reducing housing affordability. To cope with this, governments have invested in social housing, which consists of subsidized rental units available for low-income inhabitants. This has led to large social housing populations across the world. According to the 2010 Housing Statistics in Europe prepared by the Dutch Ministry of Interior and Kingdom Relations, there were over 1.3 million social housing households in Europe in 2008 [2]. In Canada, Statistics Canada reported over half a million subsidized housing tenants as of 2011 [3]. Lastly, the United States Census Bureau reported over 1 million public housing units in the US in 2015 [4]. These numbers are only a fraction of the total number of low income households, as buildings which are part of other rental assistance programs (such as Section 8 housing in the US) are often excluded from these figures. In the case of the US, for example, the reported social housing stock only accounts for 22% of all units receiving some form of rental assistance [5]. Considering that social housing populations are generally more vulnerable due to age (seniors account for 12%–49% of the populations in some investigations [6–11]) and/or socioeconomic status, it becomes increasingly important to study the indoor environmental quality (IEQ) in these environments. This is partially to evaluate whether these occupants are disproportionately exposed to environmental factors that may lead to negative, and/or exacerbate existing, health effects.

One reason to believe that poor IEQ conditions in social housing may have negative health consequences stems from the existing knowledge about the relationship between dwelling conditions and health. Factors such as building age and poor maintenance may lead to worsened overall housing conditions within social housing units. There have been numerous review papers exploring the correlation between these conditions and negative health outcomes [12–16]. Wilkinson et al. found that statistical correlations between poor housing conditions and negative health outcomes had been identified by several authors [15]. Thomson et al. [12] later concluded that the evidence linking housing improvements and positive health outcomes was not conclusive, but noted that this lack of evidence may be due to practical difficulties with housing studies as well as political factors. In 2003, Saegart et al. [13] found that there were indeed statistically significant correlations in studies documenting home improvements and positive
health outcomes, but most studies only focused on one health condition. More recently, in 2008, Rauh et al. [14] developed a comprehensive framework that can be used to evaluate the relationship between neighborhood and housing conditions, socioeconomic and minority status, and health conditions. They found strong indications that poor housing conditions, which are more prevalent in populations with low socioeconomic status, may be harmful for the health of occupants. While these studies help us understand that poor housing conditions are associated with negative health effects, there is no comprehensive literature review documenting the IEQ in social housing units, and exploring how these IEQ conditions may lead to negative health outcomes.

The central objective of this paper is to evaluate whether there is evidence that social housing IEQ is worse than its non-social housing counterpart, and if this has been correlated with negative health outcomes. This objective is partially motivated by the results of an investigation by Adamkiewicz et al. [17] who reviewed empirical evidence of disparities in indoor exposures due to socioeconomic status. They found that there was evidence of higher indoor pollutant concentrations in low income households, and suggested that future research should further examine these pollutants, emphasizing comparisons between different populations. To achieve this objective, this paper first analyzes the following two components of IEQ: air quality and thermal comfort. Indoor concentrations of pollutants, including particulate matter, formaldehyde, mold, and nitrogen dioxide, are discussed as exposure to these contaminants has been associated with a variety of acute and chronic health impacts [18]. Thermal comfort is discussed second; while not as critical as pollutant concentrations in low income households, and suggested that future research should further examine these pollutants, emphasizing comparisons between different populations. To achieve this objective, this paper first analyzes the following two components of IEQ: air quality and thermal comfort. Indoor concentrations of pollutants, including particulate matter, formaldehyde, mold, and nitrogen dioxide, are discussed as exposure to these contaminants has been associated with a variety of acute and chronic health impacts [18]. Thermal comfort is discussed second; while not as critical as pollutant concentrations from a health perspective, it is still regarded as the most influential parameter for occupant perceptions of IEQ in their units [19]. Further, temperature and humidity (which are key underlying parameters of thermal comfort) also serve as indicators of hygrothermal conditions. Poor hygrothermal conditions could lead to more severe issues, such as dampness, which has documented negative health effects [20]. These IEQ assessments are considered in the context of investigations of the health of social housing occupants. Lastly, the review explores the role of green retrofits in improving the IEQ and mitigating negative health effects. Retrofits are particularly important given the large investment in existing social housing units around the world. The overall goal of this paper is to provide both the context of current conditions and explore approaches to improve IEQ-related health outcomes in social housing.

2. Methodology

The review was conducted using the following two online databases: Web of Science and Google Scholar. Both databases were queried using various combinations of the following keywords: indoor air quality, social housing, indoor environmental quality (IEQ), energy efficiency, thermal comfort, health, and public housing. Approximately 40 papers were identified as relevant to the subject of this review paper and were flagged for further review. A system for categorization was then developed to evaluate these papers. Category 4 papers were considered the most relevant and included measurements of pollutants or indoor environmental quality parameters. Category 3 papers were considered highly relevant with insightful information about the quality of life of social housing residents. Category 2 papers were considered somewhat relevant with potentially useful information about related topics (for example, modeling of environmental tobacco smoke in multi-unit buildings, or presence of pesticides on urban and farmworker households). Category 1 papers were slightly relevant or not relevant to social housing. Examples in this category include research on air quality in slums or effects on indoor air quality of using solid fuels for cooking.

Following the categorization, the references and keywords of the Category 4 papers were also searched. Some of the keywords identified in this step were: community-based participatory research, retrofits, asthma, built environment, and green construction. This resulted in a total of 55 papers being identified as either Category 4 or Category 3, and selected for further in-depth analysis. Some of the papers identified in this step had previously been classified as Category 2, but upon further review were reclassified to Category 3. Moreover, the following six papers were added to the review based on the authors knowledge of them, even though they were not found in the databases: Broderick et al. [21], Chan et al. [22], Garland et al. [23], Haaland et al. [24], Mahdavi et al. [25], and Touchie et al. [26]. The Broderick and Chan articles were very recent at the time the review was conducted. The Garland article did not have social housing/public housing keywords, and used very generic keywords that made it difficult to find. The Haaland, Touchie and Mahdavi articles were conference papers, and thus were not found by the search engines. This suggests that either very recent papers, papers that do not use specific keywords, or conference papers that the authors did not have knowledge of, may have been omitted from this analysis.

After compiling a comprehensive list of papers, a detailed review of each of them was conducted. The review consisted of extracting information in a standardized format, to make it easier to analyze the papers. Data regarding the buildings studied, location of the study, IEQ parameters analyzed, and health data was compiled. Examination of the references in this process resulted in four additional articles being identified and added to the review: Chew et al. [27], Corburn et al. [28] 28, Bashir [16] and Russo et al. [29] Through this review process, papers were once more evaluated with regards to their relevance to the topic of this paper. Some papers were identified as containing useful information but not very applicable to the purpose of this paper, so they were excluded from the main review. In total, 49 papers were deemed to be relevant and included in the main analysis of the review. With the exception of Popkin et al. [7] (which is a federal report), all of the included articles are either papers published in peer reviewed archival journals or conference papers.

In addition to selecting and reviewing papers that directly explore IEQ in social housing, or related topics (such as health outcomes associated with living in social housing), we also selected studies performed in non-social housing locations to contextualize our results. While the ideal comparison would be between identical social housing and non-social housing buildings occupied with individuals of similar demographics, no such comparison has ever been reported in the literature to our knowledge. Therefore, in order to identify suitable investigations in non-social housing to be used for comparison, we prioritized the following criteria: firstly, we ensured it was in a similar context, by using studies from the same or similar cities. Secondly, we ensured the compared studies were performed in multiunit buildings, similar to most social housing units. Thirdly, we attempted to utilize at least two or more non-social housing investigations to increase our comparison sample size. In general, the lack of available data for comparison is perhaps the largest limitation of our analysis; however, we believe the existing data is sufficient to achieve the goal of this paper, which is to explore the context of current conditions in social housing units. The comparison, while not as controlled as we wish it could be, adds valuable information about relative exposure risks between social housing and non-social housing. Further, since the data for comparison were not homogenous enough to support a robust statistical significance comparison, we completed descriptive comparisons relating them whenever possible to physical explanations.

3. Results

The final 49 papers selected for inclusion in the review are presented in Table 1. The study design was classified as cross-sectional, modeling or longitudinal. The majority of studies were cross-sectional, indicating that there is limited amount of data on long term monitoring of IEQ in social housing. Most of the studies are quite recent, the oldest
being from 2001, and over 75% of them were published in the last decade. This may reflect increased probability of inclusion in search engines. Another important consideration for inclusion is that the paper must address social housing. However, there is no universally accepted definition of social housing, which is an important limitation for our study. Therefore, papers were classified based on the following two categories: subsidized public (SP) were those cases where the authors clearly indicated that the units belonged to government-subsidized buildings, whereas low income (LI) were those where the authors did not mention public subsidies but noted that the population of the units had a low income. This lack of international standardization of social housing terminology introduces some unwanted variation to the

<table>
<thead>
<tr>
<th>Study</th>
<th>Design†</th>
<th>Year</th>
<th>Type‡</th>
<th>Building*</th>
<th>Location</th>
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<td>LI</td>
<td>M, 8D</td>
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<td>SP</td>
<td>(several) M(3)</td>
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<td>SP</td>
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<td>2015</td>
<td>SP</td>
<td>2M(3)</td>
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<td>Coombs et al. [61]</td>
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<td>SP</td>
<td>M, 14D</td>
<td>Cincinnati, USA</td>
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<tr>
<td>Fabian et al. [62]</td>
<td>MOD</td>
<td>2016</td>
<td>LI</td>
<td>19M/T(4)*</td>
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<td>SP</td>
<td>7M(4–19)</td>
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<td>2016</td>
<td>SP</td>
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<td>2016</td>
<td>SP</td>
<td>7M(4–19)</td>
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<td>LO &amp; CR</td>
<td>2017</td>
<td>SP</td>
<td>15SD</td>
<td>Dublin, Ireland</td>
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<td>Chan et al. [22]</td>
<td>CR</td>
<td>2017</td>
<td>SP</td>
<td>3M</td>
<td>California, USA</td>
<td>18</td>
</tr>
</tbody>
</table>

† LO = Longitudinal, CR = Cross-sectional, MOD = Modeling.
‡ SP = Subsidized public, LI = Low income.
§ # = number of buildings (if none, then study did not indicate number). M = Multi-unit, T = Townhouse, SD = Semi-detached, D = detached. (#) = no. of stories.
Atlantic City, NJ; Chicago, Il; Durham, NC; Richmond, CA; Washington, D.C.
Does not indicate.
Project used data from several homes with different characteristics
Neighborhood based study.
Survey done through parent-report questionnaires in 26 New York schools.
Also included a literature review.
Project used data from a variety of homes through the American Housing Survey.
Obtained data from several studies.
13 units in apartment buildings, 12 units in 2-3 story buildings.
Melrose Commons project is an affordable housing project.
Measured hallway concentrations, not inside units
Postal survey.
Multi-unit townhouses.

Categories: subsidized public (SP) were those cases where the authors clearly indicated that the units belonged to government-subsidized buildings, whereas low income (LI) were those where the authors did not mention public subsidies but noted that the population of the units had a low income. This lack of international standardization of social housing terminology introduces some unwanted variation to the

Table 1 Overview of studies included in the literature review.
review. Further, most of the studies are from North America, particularly the United States, with very few from Europe, and only one from Latin America. This introduces some bias into our paper and reduces the variability between type of social housing across studies, especially considering that seven of these papers come from one single large scale project, the Healthy Public Housing Initiative (HPHI) [30–36]. Additionally, most of the buildings were multi-unit, with a few town houses in some developments. Therefore, strategies aimed at improving social housing IEQ must be adapted to the context of multi-unit buildings, which is often quite different from detached single-family homes. Lastly, there were also few double-blind case controlled studies, potentially introducing further bias into the reported results.

The first major component of the analysis evaluates pollutant concentrations reported in the literature. The pollutants selected for review were particulate matter (PM), formaldehyde (HCHO), mold, allergens and antigens, pesticides, and nitrogen dioxide (NO2). Two factors were considered when selecting which pollutants to include in the review: availability of reported pollutant concentrations in social housing and harmfulness of the pollutant based on the results from Logue et al. [18].

The most commonly reported pollutant was PM$_{2.5}$. The reported concentrations are summarized in Fig. 1. PM$_{2.5}$ is a harmful air contaminant since small particles can deposit deep into the lungs of occupants, and carry with them other pollutants, such as metals or semi volatile organic compounds. Logue et al. [18] reported that PM$_{2.5}$ has the biggest chronic health impact among common residential indoor pollutants, measured in disability-adjusted life years (DALYs). Three important observations can be drawn from Fig. 1. Firstly, there is a wide variation in the reported indoor concentrations of PM$_{2.5}$, both across different studies and within the same study. For example, the pre-retrofit results of Noris et al. [54] are an order of magnitude larger than those reported by Russo et al. [29] (with the exception of the pre-retrofit smoking units). Within Noris et al. [54], the variation in one of the groups is also almost an order of magnitude. Secondly, the relationship between indoor and outdoor concentrations is also very different across groups. In the cases where indoor and outdoor concentrations are very close to each other, it is reasonable to assume that indoor sources are either minimized or properly mitigated (with high air exchange rates or air cleaning). On the other hand, the groups that show much larger indoor concentrations highlight the significance of indoor sources. Lastly, the impact of green renovations on indoor PM$_{2.5}$ varies in both magnitude and sign and this will be discussed further in section 4 (discussion).

There are several factors that must be considered when reading this figure. Firstly, the sample sizes of the summarized studies are very different, ranging from 3 to 98 units (note that Jacobs et al. [58] did not specify the size of each group in their study, but their total sample size is 325 units). Secondly, the context of certain papers may be significantly different from the others. For example, the Burgos et al. [52] paper compared the PM$_{2.5}$ concentrations inside slum households and public housing units. Their largest mean value of 77.8 μg m$^{-3}$ corresponds to the slum measurement, which does not constitute an indicator of PM concentrations in social housing in general. Thirdly, some papers made a distinction between smoking and non-smoking suites, while others did not. This is an important distinction since evidence suggests smoking is one of the main drivers of indoor PM concentration in multi-unit social housing [25]. Reported smoking suites are indicated in the figure with light blue and light green bars. In Russo et al. [29], a comparison of smoking and non-smoking suites is presented both in buildings with smoke free policies (green bars) and those without them (blue bars), showing that smoke free policies help to reduce PM$_{2.5}$ concentrations. Richardson et al. [42] also measured particulate matter concentrations but was not included in the figure since they did not report PM$_{2.5}$. They found a significantly higher concentration of fine particles (with diameter between 0.3 and 3 μm) in units where there was a smoker present, whereas the concentrations in houses with no smokers were similar to the outdoor concentration.

To contextualize the results presented in Fig. 1, it is prudent to compare them with existing studies that focused on PM$_{2.5}$ in non-social housing residential units. One study conducted by King et al. [63] evaluated secondhand smoke (SHS) transmission between units in multi-unit housing. In order to do so, they measured PM$_{2.5}$ concentrations in units where smoking was allowed and in those where it was not. They stratified their data by time of day, and found the highest concentrations in the evening: a median of 10.2 μg m$^{-3}$ in units without smoking tenants and a median of 29.4 μg m$^{-3}$ in units with smoking tenants. Another good basis for comparison is the Relationship of Indoor, Outdoor and Personal Air (RIOPA) study, conducted between 1999 and 2001, which sampled over 300 houses without smoking occupants across three cities (Elizabeth, NJ; Houston, TX; and Los Angeles, CA). Although this study did not solely focus on multi-unit housing, around 40% of buildings in each city were 5 units or more [64]. They found a mean indoor PM$_{2.5}$ concentration of 17.6 μg m$^{-3}$ (SD = 12.6 μg m$^{-3}$) [65]. The results from these two studies suggest that social housing residents may be exposed to higher PM concentrations than the average resident in non-social housing multi-unit residences.

After PM$_{2.5}$, the second most commonly reported pollutant was HCHO, which is also one of the indoor air contaminants with the highest chronic health effects according to Logue et al. [18] HCHO is a known respiratory irritant and a probable carcinogen [66]. While most investigations report HCHO concentrations in social housing from 22.6 μg m$^{-3}$ to 28 μg m$^{-3}$ (reported as either medians or means, depending on the investigation) [21,54,58,61], Colton et al. [8] found a geometric mean (GM) HCHO concentration of 17.6 μg m$^{-3}$. The authors attributed these lower values to differences in air exchange rates in the control units across the studies and the use of low volatile organic compounds (VOC) emitting materials [8]; but differences in the number of smokers in the units, age of buildings and types of furniture could also play a role.

The HCHO values reported in the social housing literature are consistent with, but on the lower end of, concentrations that have been found in residences of several Canadian cities. Measurements done by Health Canada [67] in homes in Charlottetown, Ottawa, Regina and

Fig. 1. Reported indoor and outdoor PM$_{2.5}$ concentrations by different authors. Each bar represents a group of units, the height of the bar represents the measure of central tendency reported (mean, median or geometric mean). Green bars indicate that the units underwent a “green” renovation or intervention before being sampled. Blue bars indicate that no renovation took place. Light green and light blue indicate that smoking was reported in the units. Dashed lines represent minimum-maximum range (if available), continuous lines represent one standard deviation, short dashed lines represent one geometric standard deviation and long dashed lines represent the interquartile range (IQR). The gray dots represent the outdoor concentration, if reported. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Quebec City yielded average indoor HCHO concentrations between 20 and 40 μg m⁻³. Another study by Gilbert et al. [68] focused on residences in Prince Edward Island and found mean HCHO concentration of 39 μg m⁻³. In the US, a study done by Hun et al. [66] looked at HCHO data from the RIOPA study and found a mean indoor HCHO concentration of 21 μg m⁻³. These comparisons suggest that there is no evidence of higher exposure to HCHO in social housing. Some factors that could explain this are higher air exchange rates (due to window operation or leaky enclosures) or less prevalence of HCHO emitting materials (such as pressed wood products). On the other hand, smoking is a known source of HCHO emissions [69], so the concentrations in units with smokers could be higher. This last hypothesis cannot be verified with the existing papers since none of the authors who reported HCHO concentrations differentiated smoking from non-smoking suites.

In addition to HCHO and PM₂.₅, a commonly studied pollutant category was mold. Although this contaminant was not discussed by Logue et al. [18] (who focused exclusively on non-biological pollutants), there is evidence that mold and dampness are known to cause negative health effects [20], even though the mechanistic association between fungal growth and health has not been fully established [20,70]. One possibility is that spores or other biological agents associated with fungal activity may trigger allergic reactions in occupants. From the reviewed papers, only Brugge et al. [38] discussed this relationship, and argued that limitations in measurements of viable spores probably underestimate allergen exposure. However, in general, mold is a problem because its growth rate is an indicator of dampness, which has been associated with several illnesses [20,70]. In the reviewed literature, investigators followed one of three approaches to characterize mold presence and dampness: measuring fungal activity, measuring building material dampness, and reporting mold growth observations. Brugge et al. [38] measured total viable fungi in dust samples, and calculated the colony forming units per gram of dust (cfu g⁻¹). They found a median concentration of 14,400 cfu g⁻¹ for bedrooms and living rooms, which is higher than what other studies have found in non-social housing bedrooms [71]. Richardson et al. [42] measured the wall dampness before and after the study houses underwent renovations, and found a pre-renovation average wall surface wood moisture equivalent (WME%) of 9.5, and a 1 year post-renovation average wall surface WME% of 6.5. They also found that the WME% went back to the pre-renovation levels 2 years after completion of the renovations. Bradman et al. [41] also measured the wall moisture in 130 homes, and found that 34 of them had a moisture index greater than 17%. It is difficult to contextualize the moisture content and WME% values present in the literature given that there is high variation in the critical values (a value below which no fungal activity will occur) for moisture content reported in the literature [72]. There is also an additional complication when comparing moisture content values that the relationship between material dampness and mold growth is dependent on the material properties [72]. However, these three studies tell an important story together: the high fungal activity documented by Brugge et al. [38] and the high WME% values reported by Bradman et al. [41] are both indicators of dampness problems. The findings by Richardson et al. [42] highlight that retrofits may appear to solve dampness issues in the short term but may not actually resolve them in the long term, an important consideration for practitioners.

Another approach taken by authors was to report mold sightings, instead of attempting to quantify dampness through moisture content measurements or fungal activity through colony cultivations or spore counts. A recent study by Mendell and Kumagai [70] suggested that these types of observation-based metrics have potential to be used to define thresholds for unhealthy levels of indoor dampness. The reported mold sightings are summarized in Fig. 2. This plot indicates that there is wide variation in instances of mold growth in conventional pre-renovation units (blue bars) ranging from 2 to 75%, with most studies reporting percentages equal or greater than 40%. This seems to be comparable to results from other investigations which reviewed mold reports in residences. Mudarri and Fisk [73] reviewed 8 studies reporting mold or dampness in houses in several US and Canadian cities, and estimated a mold and dampness prevalence weighted average of 47%. These results seem to suggest that dampness and mold growth issues are not necessarily more prevalent in social housing than in non-social housing.

Even though only one study discussed mold spores as allergens [38], other studies looked at other common allergens and antigens in the indoor environment. The most commonly measured allergen was cockroach (bla g1), which was reported in four papers. Bradman et al. [41] found significantly higher bla g1 concentrations in homes with evidence of pest infestation than in those without evidence. Both Peters et al. [32,35] studies, conducted in the same social housing developments in Boston, found significantly higher bla g1 concentrations in the kitchen areas than in the bedroom areas. Similarly, Chew et al. [27] found higher concentrations of bla g2 (another cockroach allergen) in kitchens than in beds. The importance of reducing allergen concentrations is increased in homes with higher asthma prevalence. Levy et al. [34] found high allergen prevalence among asthmatic children in public housing (in particular, allergies to cockroach and dust mites were the most prevalent), and concluded that interventions focused on reducing allergen concentrations would improve children’s health.

These results also indicate that pests, particularly cockroaches, are a persistent problem in social housing units. In addition to increasing allergen concentrations that may exacerbate existing respiratory conditions, presence of pests may lead to occupants using pesticides [27], which are also indoor pollutants of concern. Julien et al. [30] studied organophosphate and pyrethroid pesticide loadings in public housing developments in Boston in 2007, and detected permethrin and chlorpyrifos in all units, and also found a high prevalence of cypermethrin (90% of units) and diazinon (98%). Both chlorpyrifos and diazinon are organophosphates that had been retired from the market since 2001 and 2002 respectively, due to their negative health effects. Later, in 2013, Lu et al. [53] also studied pesticide loadings in public housing developments in Boston, and found that pyrethroids (mostly permethrin and cypermethrin) were the most commonly found pesticides, while the most commonly found organophosphates were fenthion (24% of units) followed by chlorpyrifos (7%). The presence of these compounds, which have been known to have negative health effects [39], is a concern, especially in settings where children or other vulnerable residents may come into direct contact with them.
concentration of 57.3 μg m⁻³ long term residential maximum exposure limit for nitrogen dioxide suggested by Health Canada [75], indicating that NO₂ still may be an issue in some residences. However, this comparison is limited because it does not account for the difference in prevalence of combustion sources not properly ventilated, regardless of it being social housing or not. Since there is no large-scale investigation documenting gas stove prevalence in social housing across several cities, a statement of relative prevalence of high NO₂ concentrations is difficult to make. There is some evidence in the literature of a higher prevalence of the use of ovens for heating in low income housing [33,37], this is a particularly extreme example of how increased exposure to NO₂ can occur in social housing.

In the analysis of exposure to these pollutants, it is important to understand the influence of regional factors in the data reported in the literature. Wherever possible, we have related the presence of pollutants to indoor sources to ultimately link it to building characteristics, in order to separate these from regional factors. From the pollutants reviewed, PM₂.₅, NO₂ and pesticides seem to have the clearest links to indoor sources prevalent in social housing: evidence suggests that smoking is the main driver of PM₂.₅, that combustion is the main source of NO₂ and that presence of pests is likely a driver of pesticide usage.

The second major component of the analysis was to evaluate the data regarding thermal comfort in social housing. Recent research suggests that thermal comfort is the most important IEQ parameter as perceived by the occupants [19]. It is also a complicated parameter, since it is a function of many underlying variables: dry and wet bulb temperature, mean radiant temperature, occupant metabolic level, clothing level, and air speed. Table 2 summarizes the findings from all reviewed studies that incorporated thermal comfort into their scope. From this table, it seems that there is strong evidence that thermal comfort is an issue in social housing across the world. High temperatures due to overheating or undercooling appear to be the most common problems, followed by underheating.

In order to contextualize the results in Table 2, a useful reference is a study prepared by Foldáry et al. [76], who studied the effect of renovations on IEQ in multi-unit housing in Slovakia. They defined the acceptable temperature range as 20–24 °C, and reported underheating and overheating in 18% and 7% of the units pre-renovation respectively. These values were reduced to 2% and increased to 12%, respectively, after renovations [76]. This shows that underheating and overheating are problems that may appear in non-social housing multi-unit buildings, possibly with less prevalence given that these percentages seem smaller than those in Table 2. A further complication underlying the results in Table 2 is the relationship between thermal comfort, control of the conditioning system, and payment of energy/fuel costs of heating and cooling. These factors vary great in both social housing and non-social housing units.

When analyzing both thermal comfort and pollutant exposure in social housing, it is important to note that, to our knowledge, there is no existing study that directly compares the IEQ in social housing with the IEQ in other residences in a controlled manner. Thus, our comparisons are limited given that the variability across building types and locations. However, our results indicate that residents in social housing seem to have increased probabilities to be exposed to harmful indoor air and poor thermal comfort than those of other residences.

4. Discussion

One of the main implications of the results of this paper is that the increased likelihood of exposure to poor IEQ conditions in social housing units constitutes a health concern for its residents, especially considering that social housing populations are generally more vulnerable due to age or socioeconomic status. There is strong evidence in the literature that illustrates the well-established association between housing disparities and negative health outcomes (e.g., Jacobs [49]). For example, there are clear disparities in morbidity between non-residents and residents of social housing in New York [49]. Jacobs [49] also pointed out that, at a national level, housing problems are more prevalent in low income homes, as well as in homes of minorities, and that this has largely remained unchanged in the past three decades.
There have been numerous studies documenting health problems in social and low-income housing, which are summarized in Table 3. General health was ranked closer to poor overall than to good/excellent. On a larger scale, we see that the results from Popkin et al. [7] indicate that less than 40% of their population reported very good/excellent health. The physical health results were dominated by respiratory issues, with asthma being the most commonly studied issue. In general, studies found elevated prevalence of asthma in children of public housing developments in New York City, and attributed this to both household level and neighborhood level effects. Allergen presence and pesticide usage are key household level driving factors, as reported by Chew et al. [27]. These factors may cluster with other building issues, and exacerbate their negative effects, as reported by Adamkiewicz et al. [6] Further, neighborhood level effects may increase harmful exposures both outdoors and indoors. Corburn et al. [28] found that polluting land uses may lead to higher outdoor pollutant exposures in neighborhoods where social housing developments exist. They also argued that unsafe conditions in these communities may lead to occupants spending more time indoors, increasing their exposure to the pollutants described previously in this work. In addition to physiological health, mental health issues appear to be exacerbated in social housing. Links between housing conditions and mental health are explored by Evans [77]. In the case of social housing, there are several stressors associated with housing conditions that may cause or exacerbate mental health issues such as depression or anxiety. These issues seem to also be widespread, at least at a national level (in the United States). Popkin et al. [7], who reported on the HOPE VI program, a large-scale project aimed at restoring distressed social housing developments in the United States, established several indicators that health problems, including asthma prevalence and mental health issues, are more prevalent in social housing than in conventional housing.

Another factor that plays an important role in the health of social housing residents is occupant behavior. Firstly, occupants play an important role in the maintenance and upkeep of their units. This is particularly important in issues such as pest control or moisture management. Sharpe et al. [11] found that fuel poverty behaviors resulted in increased probabilities of mold contamination. Secondly, occupant behavior plays an important role in the medical treatment for any existing conditions, which is a relevant consideration when analyzing studies that document the relationship between housing conditions and health. One example of this is highlighted by Lambertino et al. [46], who studied asthma in Chicago public housing. They found three key categories for predictors of asthma hospitalizations: housing conditions, clinical severity, and asthma management. The last category (which was evaluated based on medication use and planning for asthma) was associated with emergency department visits and hospitalizations, and highlights the role occupants have in taking care of their health. Given that occupant behavior is challenging to alter, one possible strategy to reduce exposure to asthma triggers and to improve the health conditions could utilize community health worker interventions, which are demonstrated to have potential to reduce asthma symptoms [40].

Given the evidence that poor IEQ conditions in social housing is an issue that warrants attention, several authors have explored what role maintenance and retrofits play in improving and maintaining good IEQ. With regards to maintenance, increased request for repairs, as well as issues associated with deferred repairs (such as water leaks) are associated with negative health outcomes [33,37]. With regards to retrofits,
breathing problems, blurred vision, wheezing, sneezing, ear infection, rashes, burning/or dry throat.

only in univariate analysis.

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Table 3
Prevalence of health issues in social or low-income housing, baseline data (before retrofits targeted to address these effects have been carried out).

<table>
<thead>
<tr>
<th>Health issue</th>
<th>Study</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>General health</td>
<td>Overall</td>
<td>Adamkiewicz et al. [6]</td>
</tr>
</tbody>
</table>
| | Self-reported | Popkin et al. [7] | Children mean score of 2.113%
| | | Howden-Chapman et al. [44] | 24% reported fair or poor health |
| | Quality of life | Krieger et al. [40], | Mean score of 4.24%
| Physical health | Chronic illness | Popkin et al. [7] | 39% adults reported chronic illness |
| Asthma | Garland et al. [23] | 50% reported symptoms within last day |
| | | Krieger et al. [40], | 7.9 days with symptoms in past 2 weeks |
| | | Chew et al. [27] | 1 or more asthmatic resident in 36% of units |
| Adult asthma | Colton et al. [9] | 21% reported having asthma |
| | Popkin et al. [7] | 22% of respondents diagnosed |
| | Brugge et al. [37] | 40% reported prevalence |
| Children asthma | Jacobs et al. [58] | 17% of children with reported asthma |
| | Colton et al. [9] | 40 children2 with asthma |
| | Brugge et al. [37] | 56% reported prevalence |
| | Northridge et al. [47] | 21.8% diagnosed with asthma |
| Wheezing | Howden-Chapman et al. [44] | 42% reported symptom in past 3 months |
| | Brugge et al. [37] | 40% reported symptom in last month |
| Coughing | Brugge et al. [37] | 48% reported symptom in last month |
| Sneezing | Brugge et al. [37] | 48% reported symptom in last month |
| Obesity | Levy et al. [34], | Present in 56% of respondents |
| | Levy et al. [34], | Present in 59% of respondents |
| | Dust mite allergy | Levy et al. [34], | Present in 59% of respondents |
| | Colton et al. [9] | Mean score of 4.18 |
| SBS symptoms | | Jacobs et al. [58] | Adult mean score 2.1 for sadness3,4 |
| Mental health | Depression | Santamour et al. [10] | 8.2% of population suffer from it |
| | | Popkin et al. [7] | 10% had 1 major episode in last year |
| Self-efficacy | | Popkin et al. [7] | Low scores in general3 |
| Other | Respiratory index | Brugge et al. [33] | Associated with 7 risk factors5 |
| | Building index | Brugge et al. [33] | Associated with 4 risk factors6 |


3 Includes respiratory, cardiovascular and neurological health.

5 Scale: 1 = excellent, 5 = poor.

6 Population consisted of asthmatic children.

7 Based on Pediatric Asthma Caregiver Quality of Life Scale (1–7, higher score indicates better quality of life).

8 Children total population not reported.

9 Symptoms include: dizziness, headaches, nausea, coughing, tiredness, nosebleeds, breathing problems, blurred vision, wheezing, sneezing, ear infection, rashes, burns, itching eyes, sore/dry throat.

4 Score represents number of symptoms reported.

8 Includes depression, anxiety and nervousness.

1 Self-efficacy was assessed using 4 standard measures from Pearlin Mastery Scale.

2 Included: coughing, breathing problems, wheezing, sneezing attacks, skin rash, sore or dry throat.

3 Cockroaches, rodents, mold, water leaks, apartment too hot, apartment too cold, chemical use, insecticide use. Statistically significant only in univariate analysis (only apartment was also significant in multivariate analysis).

4 Included: dizziness, headache, nausea, blurred vision, burning/itching eyes.

5 Cockroaches, rodents, mold, water leaks, apartment too hot. Statistically significant only in univariate analysis.

several studies as well as some government initiatives, such as the HOPEIV program (described in detail by Popkin et al. [7]), have also been planned to investigate how the IEQ of these units can be improved at a large scale. These retrofits not only provide a potential opportunity to reduce the negative health exposure of the occupants, but also may provide social housing authorities an opportunity to reduce the energy consumption of their units. In our review, we identified thirteen papers which studied the impact of retrofits on select IEQ parameters which are summarized in Table 4. A description of the retrofits performed is presented in Table S1 in the supplemental information, and a record of the baseline buildings used for comparison and the significance levels for the statistically significant results is presented in Table S2 in the supplemental information. In general, retrofits statistically improved child and adult health measures for several different health outcomes in four investigations that explored them. Reductions in concentrations of PM2.5, HCHO, and NO2 generally decreased, but several studies [21,42,58] saw increases with green buildings suggesting that renovations may not always reduce pollutant concentrations. Mold prevalence decreased in both studies where it was investigated. Ventilation changes reported by Noris et al. [54] were very different than those reported by Colton et al. [8], even though both investigations increased air tightness and provided mechanical ventilation. The disparities are probably attributable to building specific factors (initial air tightness, window operation, specifics of the mechanical ventilation system). A similar analysis is appropriate for the CO2 concentrations, the mixed results are probably attributable to mixed ventilation rates. In the case of Noris et al. [54] and Colton et al. [8], the CO2 results are consistent with the ventilation results: Noris et al. [54] reported a decrease in CO2 and an increase in ventilation, Colton et al. [8] reported no significant changes in both.

There are three important aspects of retrofits that are not fully captured by the results in Table 4: the opportunity for energy reductions, the use of integrated pest management to combat pests, and the use of compartmentalization to reduce pollutant transfer between suites. Energy usage reductions were examined by two papers: Breyssse et al. [48] and Howden-Chapman et al. [44], who found reductions of 45% and 5% respectively. However, retrofits that were common in the reviewed papers, such as improved envelope, glazing upgrades, mechanical systems retrofit, and lighting replacement, are likely to result in reduced energy consumption. Energy retrofits and IEQ improvements are interconnected and interrelated goals, and retrofits should be designed with both considerations in mind. Failing to do so could lead to worsened IEQ conditions, an example of this is increased pollutant concentrations observed in buildings with lower air exchange rates (e.g. reduced natural ventilation in low energy social housing reported by Ward et al. [45], increased PM2.5 and HCHO in Broderick et al. [21], and increased PM2.5 in Jacobs et al. [58]).

In addition to ensuring energy-oriented retrofits do not worsen IEQ, a second important consideration is reducing exposure to pests without increasing pesticide usage. Integrated pest management (IPM, which is a collection of strategies aimed at preventing pests in the long term) has been proven to be an effective way to control and reduce pests and associated allergens, as shown by Peters et al. [35] and Peters et al. [32]. These studies showed that IPM can achieve significant reductions in pest related allergen concentrations, and that engaging the occupants (so they maintain their units clean and inhospitable to pests) is key.

Further, retrofits involving compartmentalization are important strategies to reduce transfer of pollutants between units. A pollutant of particular concern in this regard is environmental tobacco smoke (ETS), which has been shown to be a major source of PM2.5 in social housing [25,29], and it is known to affect neighboring units even if they do not have smokers [36]. Fabian et al. [62] used a CONTAM model to show that ventilation upgrades and compartmentalization helped reduced environmental tobacco smoke (ETS) infiltration, although they argued that their results may not be applicable to all buildings and suggested smoke free policies as the best strategy to manage ETS. Other authors
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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2018.01.013.


THERMAL COMFORT IN MULTI-UNIT SOCIAL HOUSING BUILDINGS

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Keywords: Public Housing, Low Income Housing, Over-heating, Indoor Environmental Quality, Temperature, Relative Humidity, CO₂.

ABSTRACT
Thermal comfort influences occupant health and perceptions of the indoor environment. It is particularly important for vulnerable populations because they may be more sensitive and prone to illness when exposed to high or low temperatures. One context where populations may be vulnerable due to socioeconomic status is social housing. In this study, we evaluated hygrothermal conditions inside 70 social housing units in Toronto across seven buildings for a year. We found that all the buildings had a high prevalence of discomfort due to high heat in the summer, with some units spending most of the time above 28°C. This was indicative that there is insufficient cooling in the units. Further, we found that some units were over-heated during the winter season. Additionally, by analyzing CO₂ concentrations, we found that there was no evidence that the units were under-ventilated. Our results were compared to occupant surveys administered in the beginning of the study, and we found that there were discrepancies between the monitoring results and what occupants reported. In particular, there were several reports of under-heating in the winter while the monitored data did not show evidence of under-heating. In conclusion, we noted that older buildings may not be fit to withstand extreme heat events that some cities are experiencing and may be placing some of their occupants at risk of heat stresses. Planned energy retrofits are an opportunity to address thermal comfort concerns.

HIGHLIGHTS
- Monitored hygrothermal conditions inside 70 social housing units for a year.
- Exposure to high temperatures is common, especially in the summer due to inexistent or inadequate cooling.
- The monitored year did not show evidence of under-heating, suggesting that the units are not too cold during the winter.
- The indoor CO₂ concentration data indicated that the units appeared to receive adequate levels of fresh outdoor air.
INTRODUCTION

Thermal comfort has the highest influence on occupant perception of the Indoor Environmental Quality (IEQ)\(^1\) in their homes. Further, there are established links between exposure to low or high indoor temperatures and health. A 1968 report by the World Health Organization (WHO) noted that thermal conditions which interfered with the human body’s ability to thermoregulate could lead to the development of certain conditions such as colds, pharyngitis, or neuralgia\(^2\). This report also recommended a range of 15°C to 22°C, within which the metabolic energy expenditure to maintain a body’s internal temperature was minimal. A more recent investigation in 2012 noted that the WHO later revised this range in 1982 to be 18°C to 22°C, although the authors did not find the scientific basis to justify this change\(^3\). Harm due to exposure to cold temperatures can lead to lower resistance to respiratory infections and increased blood pressure (with associated circulatory problems) in vulnerable populations (Collins et al\(^4\)). Exposure to high temperatures such as during heat waves can lead to heat fatigue, heat exhaustion and heat strokes\(^5\); in the case of elderly people, the risk is higher due to their lower overall fitness as well as increased likelihood of having additional illnesses which could raise their heat related morbidity and mortality\(^5\). Therefore, in buildings where there are high percentages of vulnerable populations, it is critical to provide an adequate hygrothermal environment.

One particular context where residents may have higher vulnerability due to age and socioeconomic status is social housing. The expansion of urban centers across the world in the past century\(^6\) (which has often reduced housing affordability) has resulted in large populations in social housing developments in several countries\(^7–9\). Inhabitants of these developments are generally of low income, and there may also be considerable senior populations in some buildings. There is substantial evidence that poor thermal comfort and exposure to very low or very high temperatures are consistent problems in social housing. According to a recent literature review on IEQ in social housing, there are at least 15 recent investigations reporting comfort conditions in social housing, and overall discomfort due to high temperatures is more common than due to low temperatures\(^10\). However, this paper also identified that there are very few large, long-term studies which monitored hygrothermal conditions inside social housing units and also incorporated occupant surveys into their studies.

Since February 2015, we have monitored a variety of indoor environmental parameters in over 70 suites across seven multi unit social housing buildings in Toronto. This paper is motivated by results from our previous investigations, which evaluated data for the beginning of the study and suggested that over-heating during the summer is a major problem in the units\(^11,12\). In the present investigation, we analyzed a full year of data (April 2015 to April 2016) to better understand the seasonal effect on thermal comfort, as well as to fully characterize the comfort conditions in all the buildings before they underwent energy retrofits during 2016-2017. This paper presents an analysis of the expected comfort conditions based on the indoor environmental parameters we monitored (temperature, mean radiant temperature, relative humidity and CO\(_2\) concentrations), and a discussion of the implications of these findings.

METHODOLOGY

Table 1 summarizes the characteristics of all the buildings in the study, which were located in three distinct sites in the City of Toronto. More details of the building mechanical systems,
construction and fenestration were reported by Touchie et al.\textsuperscript{11} Due to occupants moving, or opting in and out of the study, the sample size varied throughout our study, as shown in Table 1.

### Table 1 Building characteristics

<table>
<thead>
<tr>
<th>Site</th>
<th>Building</th>
<th>Year Built</th>
<th>No. floors</th>
<th>Floor area (m(^2))</th>
<th>Type of occupancy</th>
<th>No. monitored suites (Apr 1, 2015)</th>
<th>No. monitored suites (Apr 1, 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>1972</td>
<td>4</td>
<td>10,600</td>
<td>Seniors</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>1972</td>
<td>4</td>
<td>9,100</td>
<td>Seniors</td>
<td>9</td>
<td>8</td>
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<td>2</td>
<td>C</td>
<td>1965</td>
<td>7</td>
<td>11,800</td>
<td>Bachelor</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>1965</td>
<td>7</td>
<td>3,300</td>
<td>Seniors</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>1965</td>
<td>11</td>
<td>10,900</td>
<td>Bachelor</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>1974</td>
<td>19</td>
<td>13,800</td>
<td>Family</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>1974</td>
<td>18</td>
<td>19,200</td>
<td>Family</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

In each monitored suite, we deployed a sensor package to measure temperature, relative humidity, mean radiant temperature and carbon dioxide (CO\(_2\)). The monitoring packages were placed on metal rails installed on the wall (approx. 30 cm from the ceiling), and they were located in areas where there was minimal to no direct solar radiation throughout the day. Temperature and relative humidity were measured with an ONSET HOBO U12-13 data logger, which recorded data every 15 minutes. Mean radiant temperature (MRT) was estimated with an ONSET TMCx-HD temperature probe, which was located inside a plastic black half sphere attached to the monitoring packaged (pictures of the monitoring package were presented by Touchie et al.\textsuperscript{11}). CO\(_2\) was monitored with a SenseAir CO\(_2\) Engine K30 non-dispersive infrared carbon dioxide sensor. Details of the instruments deployed in the suites can be found in Table 2. One detail not captured by the table is the autocalibration functionality of the K30. This sensor has a built-in algorithm designed to reduce measurement error due to sensor drift. The K30 will record the lowest concentration reading over an interval of 7.5 days, and gradually adjusts readings so that the minimum value becomes 400 ppm. The adjustment is limited to a maximum change of 30 ppm/week.

### Table 2 Indoor monitoring equipment specifications

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Parameter</th>
<th>Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset HOBO U12-012</td>
<td>Temperature</td>
<td>0(^\circ)-50(^\circ)</td>
<td>±0.35(^\circ)</td>
</tr>
<tr>
<td>Onset HOBO U12-012</td>
<td>Relative Humidity</td>
<td>10%-90%</td>
<td>±2.5% RH</td>
</tr>
<tr>
<td>Onset TMCx-HD</td>
<td>MRT</td>
<td>0(^\circ)-50(^\circ)</td>
<td>±0.25(^\circ)</td>
</tr>
<tr>
<td>Sensair K30</td>
<td>CO(_2)</td>
<td>0-2000 ppm</td>
<td>±30 ppm</td>
</tr>
</tbody>
</table>

Further to monitoring indoor environmental conditions, occupants were surveyed at the beginning of the study to collect information regarding their perception of thermal comfort and air quality in their suites, and their behaviour (usage of air conditioning, fans, opening windows, etc). Details of the survey methodology were described by Touchie et al.\textsuperscript{11} In this paper, we will use some of the survey results in our analysis, while a future publication will focus entirely on exploring and analysing these results.

In addition to collecting data on the indoor conditions, meteorological and atmospheric conditions were also monitored at each site. Oregon Scientific WMR300 Weather Stations were installed in buildings A, C, and G to monitor temperature, relative humidity, wind speed, wind direction and rainfall. Further, an outdoor package containing an ONSET HOBO U12-
13 data logger and a CO₂ sensor (either a SenseAir CO₂ Engine K30 or a PP SYSTEMS SBA-5 CO₂ Analyzer) were installed in buildings A, C, D, and F.

Data analysis consisted of quality control checks as well as estimation of thermal comfort conditions based on the monitored parameters. All the data represented in this paper were subjected to the following quality control criteria. Firstly, the data were checked for sensor errors, which generally manifested in the CO₂ data or the mean radiant temperature (MRT) measurements. Indoor MRT measurements under 12°C or above 50°C were excluded, as values outside this range are unreasonable for the settings where the packages were located. For CO₂, data was excluded if the measurement was below 350 ppm (unreasonable for Toronto), or if the indoor concentration at a given time point was below the outdoor concentration at the same site (unrealistic). Secondly, data were checked for completeness: packages with more than 2 weeks of data missing (or a continuous gap of data greater than 3 days) were not included in Figures 3,4,5 and 6 (note that, since each of these figures covers a different time period, the number of units meeting the above mentioned thresholds varied across figures, for more details on the number of suites included in each figure see the Supplemental Information). Note that in the case of CO₂ data, the second check (completeness check) was performed before the sensor error test. This was because doing otherwise would have resulted in very few units with enough data to analyse. For the number of suites included in each figure of this paper, see Table 1 in the SI.

Following the data quality control, two distinct thermal comfort models were applied to evaluate comfort conditions in the suites. First, we used the ASHRAE Graphical Comfort Zone Method, described in detail in section 5.3.1 of ASHRAE Standard 55-2013, to estimate whether occupants were comfortable or uncomfortable at each timepoint during the monitored period. We then used these results to estimate the percentage of time that occupants spent outside of the comfort zone. This method is applicable if the average air speed is below 0.2 m/s, the occupants’ metabolic rates are between 1.0 met (eg. seated, quiet) and 1.3 met (0.1 met higher than standing, relaxed), and the occupants’ clothing levels are between 0.5 clo (eg. slightly below trousers and short-sleeve shirt) and 1 clo (eg. trousers, long-sleeve shirt, long-sleeve sweater and T-shirt). Using this method, we created two comfort scenarios, a fixed clothing scenario as well as a variable clothing model. The fixed clothing model represents a setting in which occupants maintain the following clothing levels based on the season: 1.0 clo in the winter, 0.75 clo in the fall/spring and 0.5 clo in the summer. Existing research suggests that clothing values are dependant on outdoor temperature and occupants adjustment of clothing level when they go indoors may be limited (for example if they have to go outdoors again, they may not be willing to go from pants to shorts). The variable clothing scenario assumed that occupants are willing to adjust their clothing (within the 0.5 – 1 clo range) if they are uncomfortable.

Second, we used the ASHRAE Analytical Comfort Zone Method, described in detail in section 5.3.2 of ASHRAE Standard 55-2013, to calculate the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) also at each time point during the monitored period (comfort compliance is achieved if -0.5<PMV<0.5). This method is applicable if the average air speed is below 0.2 m/s and the occupants’ metabolic rates are between 1.0 met (eg. seated, quiet) and 2.0 met (eg. cooking). For this method we also assumed a variable clothing model in which occupants would switch between 0.5 clo to 1.0 clo to maximize their comfort, as well as a constant 1.0 met activity level.
RESULTS
A summary of the meteorological conditions during the monitored period is presented in Table 3. The table contains the average from the stations at buildings A and C only, since the station at Building G contained erroneous data. Overall, the winter of 2015-2016 was a milder winter for Toronto standards, when compared to a 30 year historical summary.15.

Table 3 Summary of meteorological conditions

<table>
<thead>
<tr>
<th>Month</th>
<th>Avg. T (°C)</th>
<th>St. dev. T (°C)</th>
<th>Max. T (°C)</th>
<th>Min. T (°C)</th>
<th>Avg. RH. (%)</th>
<th>Avg. windspeed (ms(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr-15</td>
<td>8.7</td>
<td>5.5</td>
<td>21.9</td>
<td>-1.5</td>
<td>61.4</td>
<td>2.7</td>
</tr>
<tr>
<td>May-15</td>
<td>17.5</td>
<td>6.0</td>
<td>29.6</td>
<td>3.6</td>
<td>59.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Jun-15</td>
<td>18.7</td>
<td>4.0</td>
<td>28.7</td>
<td>7.8</td>
<td>71.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Jul-15</td>
<td>22.8</td>
<td>4.8</td>
<td>35.4</td>
<td>10.9</td>
<td>61.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Aug-15</td>
<td>21.4</td>
<td>4.0</td>
<td>34.4</td>
<td>12.1</td>
<td>69.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Sep-15</td>
<td>20.3</td>
<td>5.2</td>
<td>34.3</td>
<td>9.4</td>
<td>71.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Oct-15</td>
<td>10.5</td>
<td>4.6</td>
<td>24.5</td>
<td>-1.1</td>
<td>72.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Nov-15</td>
<td>7.4</td>
<td>5.4</td>
<td>22.7</td>
<td>-5.2</td>
<td>76.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Dec-15</td>
<td>4.8</td>
<td>4.0</td>
<td>15.8</td>
<td>-6.7</td>
<td>82.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Jan-16</td>
<td>-1.6</td>
<td>4.5</td>
<td>11.0</td>
<td>-14.8</td>
<td>73.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Feb-16</td>
<td>-1.6</td>
<td>7.1</td>
<td>16.4</td>
<td>-25.2</td>
<td>71.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Mar-16</td>
<td>3.3</td>
<td>6.0</td>
<td>19.5</td>
<td>-10.9</td>
<td>75.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

To evaluate the seasonal variation in indoor temperatures, a heat map showing the recorded temperatures in all monitored suites is presented in Figure 1. This plot suggests that indoor temperatures are highly dependant on outdoor temperatures during the cooling season, which is resulting in potentially uncomfortable conditions in the summer. Many units spend considerable amounts of time with average temperatures greater than 27°C, and in the summer several suites spend most of their time above 29°C. The average temperatures in Building A and some units in Buildings B and G are higher than 26°C throughout the entire monitored year, and above 28°C for the majority of the monitored period. These high temperatures are likely to be the source of the discomfort, and given that they occur throughout the year, this indicates that it is a dual problem of undercooling (in the summer) and over-heating (in the winter). Buildings C, D, E and F exhibit high temperatures mostly during the summer, therefore indicating no evidence that they are over-heated. The lowest average temperature was 19°C, and the occurrences of average temperatures under 21°C are minimal. This suggests that there is no evidence that the buildings are under-heated during the winter. However, the monitored year had a milder winter than usual for Toronto, thus the performance of the buildings under more extreme winter conditions is not captured by these data.
Figure 1 Heat map of weekly average indoor and outdoor air temperatures for the period April 1, 2015 to April 1, 2016. Note that the outdoor temperature for the first 2 weeks of April 2015 was estimated using data from Toronto Pearson International Airport, since the weather stations were not deployed on site until the week of April 19, 2015. The airport data was adjusted based on the weekly averages for the 2015 year.

The first comfort analysis we conducted was using the ASHRAE Graphical Comfort Zone, represented with the comfort maps shown in Figure 2. Each square in the plot represents a week worth of data, and gaps in the plots are due to missing data. The darker coloring represents increasing discomfort. Figure 2a shows the results from the fixed clothing model, and Figure 2b shows the results from the variable clothing model. The only difference between these two results is that, in Figure 2b, occupants were assumed to switch their clothing level between 0.5 clo and 1.0 clo to maximize their comfort, whereas in Figure 2a seasonal clothing values remained constant. All other parameters in the comfort modelling equations remained equal between the two models. While in both figures there seems to be more pronounced discomfort during the summer months (although some suites experience discomfort throughout the year), there is a clear difference between the models, highlighting the large effect that clothing levels have on occupant comfort. Further, since the highest discomfort occurs in the summer due to under-cooling, occupants cannot increase their comfort level by reducing the clothing level since they are already assumed to be dressed in light garments. In addition, both figures show variation between the comfort conditions across buildings. Building A seems to have the highest prevalence of discomfort in both models, followed by buildings B, G and F, while Building C seems to have the least prevalence of discomfort.
In order to further understand the distribution of discomfort throughout each building, we plotted the both model results from the ASHRAE Graphical Comfort Zone method for each suite, for the hottest and coldest month during the monitoring period (July 2015 and February 2016, respectively). Figure 3 and Figure 4 summarize the comfort ranges for both models for the months of July 2015 and February 2016, respectively. Both figures show that there is no evident correlation between increased discomfort and floor height, even though heat rising due to the stack effect would be a reason to believe that upper floors are more likely to experience discomfort due to heat than lower floors during the heating season. Further, in both figures, it is shown that building height is also not correlated with increased levels of discomfort, as both Building A (a 4-story building) and Building G (an 18-story building) have comparable levels of discomfort. Given that taller buildings have a stronger stack effect, our results suggest that even in the tallest building, this effect is not significant enough to cause a notable difference in comfort conditions between lower and upper floors.

From Figure 3 it can be seen that the percent time comfortable with regards to hot temperatures (i.e. percentage of time in which occupants are not too hot) is generally low in most suites, with the model suggesting some occupants would be comfortable only 10-20% of their time inside their units. This figure also reinforces the conclusion that buildings A, B and G have the lowest overall comfort conditions. In Building A in particular, there are four suites where comfortable conditions were predicted 0% of the time, which can be explained by the indoor temperatures staying above 28°C for the entirety of the monitoring period.

Figure 4 provides valuable information regarding the performance of the buildings during cold conditions. Firstly, the model suggests that discomfort due to cold is not prevalent, as only eight units exhibited a percent time comfortable with regards to cold temperatures (i.e. percentage of time in which occupants are not too cold) under 80%. Secondly, Figure 4 also shows that the percent time comfortable with regards to hot temperatures is much more varied during the cold winter months. In Building A, which had the most severe over-heating issues, the variable clothing model reaches levels up to 100% comfortable. This suggests that the over-heating in the winter results in indoor conditions that are more manageable by the occupants: a change of clothes into lighter garments could result in more comfort. This is an important distinction from the summer conditions where occupants could not achieve comfort by switching clothes in several units in Building A.
Figure 3 Percent comfortable for July 2015 estimated using the ASHRAE Graphical Comfort Zone method. Number on right axis indicates floor height, which increases from left to right in each building. Red squares indicate percent time comfortable with regards to hot temperatures (i.e. percentage of time in which occupants are not too hot). Grey bars indicate floor for each suite, grey boxes represent the height in floors of the building. Note that in the summer months the variable clothing and the fixed clothing model yield identical results for percent time comfortable with regards to hot temperatures because both use the minimum allowable clothing value of 0.5 clo.
Further to the analysis of the ASHRAE Graphical Comfort Zone Method, we also estimated the PMV according to the ASHRAE Analytical Comfort Zone Method to have an alternative estimate of the comfort conditions inside the units for comparison. The PMV uses a scale from -4 to +4, and it is assumed that occupants are cold if the PMV is less than -0.5 and are hot if it is greater than 0.5. Figure 5 and Figure 6 contain box plots for the calculated PMV values for July 2015 and February 2016, respectively. The PMV metric shows less variation between buildings, although buildings A, B and G still appear to be the most uncomfortable in the summer due to warm discomfort. It is noticeable that most of the PMV medians are above 0 in both July and February, reinforcing again the finding that discomfort due to heat is the main problem in the studied buildings. In the winter, the PMV analysis reinforces the finding that there is no evidence of widespread discomfort due to cold. Only 2 units have median PMV values below -0.5, and only 12 units have whiskers that go below -1 PMV. Further, the only 2 suites with whiskers that go below -2 in Building E are the same that have the lowest percent time comfortable with regards to cold temperatures in Figure 4, indicating that these 2 suites in particular show exceptionally cold conditions when compared to the rest of the units and also showing consistency between the Graphical and Analytical Comfort Zone Methods.
Figure 5 Box plot of the Predicted Mean Vote calculated using the ASHRAE Analytical Comfort Zone Method for July 2015. Red lines indicate ±0.5, which represents the comfort range. Grey bars indicate floor for each suite, black boxes represent the height in floors of the building.

Figure 6 Box plot of the Predicted Mean Vote calculated using the ASHRAE Analytical Comfort Zone Method for July 2015. Red lines indicate ±0.5, which represents the comfort range. Grey bars indicate floor for each suite, black boxes represent the height in floors of the building.
In addition to analyzing the hygrothermal conditions inside the units, we also monitored CO₂ concentrations to evaluate ventilation and air infiltration. Elevated CO₂ concentrations with respect to atmospheric levels can be an indicator that the unit is not properly ventilated, relative to its occupancy. Figure 7 summarizes the calculated indoor minus outdoor CO₂ concentrations. Since all our outdoor CO₂ sensors showed comparable results, the outdoor concentrations used for this plot are the site average CO₂ concentrations. One important observation from Figure 1 is that the indoor CO₂ concentration does not seem to be correlated with building or floor height. Although the data shows a few points with very high indoor concentrations, overall there does not seem to be evidence to conclude that the units are under ventilated. Given the previous findings of Touchie et al.¹¹ who reported that the ventilation systems (both the central ventilation, which consists of a corridor pressurization system, as well as the spot ventilation systems for bathrooms and kitchens) performed below the ASHRAE 62.1 Standard, the CO₂ concentrations appear to suggest that the units may be receiving sufficient outdoor air through uncontrolled ventilation (in the form of infiltration) to maintain the suggested levels of CO₂ in ANSI/ASHRAE Standard 62.1. This comes with a few important implications. First, uncontrolled ventilation is not filtered and in certain contexts could increase indoor pollution by brining in outdoor pollutants. Second, infiltration can also lead to other problems such as mold due to unintended cooling of building surfaces that result in condensation of water vapour. Third, while the CO₂ concentrations may be below the recommended threshold in ANSI/ASHRAE Standard 62.1, it is necessary to highlight that CO₂ is just a proxy for ventilation and not an actual measurement of air exchange rates, and therefore is not directly indicating that ventilation levels are acceptable.
In order to explore the hypothesis that uncontrolled ventilation is making up for additional air exchange rate to maintain CO$_2$ elevation over outdoors below 700ppm in most units during most of the time, we performed a Spearman correlation test between median CO$_2$ elevation over outdoors, median temperature, and self reported window, hallway door and balcony door operation (data obtained from surveys), which is summarized in Table 4. From the results in this table, there seems to be no statistically significant (using a threshold of p < 0.0042 which accounts for a Bonferroni correction because of multiple tests on the same dataset) correlation between CO$_2$ elevation and self reported window and hallway door operation for either season. This suggests that increasing window and hallway door operation does not appear to be correlated with decreasing CO$_2$ elevation over outdoor concentrations. There is, however, a positive statistically significant correlation between decreased balcony operation and increased indoor temperature for the winter season, suggesting that units with less reported balcony door operation have higher indoor temperatures, which is expected.

Figure 7 Box plot of indoor minus outdoor CO2 concentrations for the period between April 1, 2015 and April 1, 2016. Horizontal line represents 700ppm, the recommended concentration as per ANSI/ASHRAE Standard 62.1 to create an indoor environment where the majority of the occupants will be satisfied, with regards to body odor perception$^{16}$. Grey bars indicate floor for each suite, black boxes represent the height in floors of the building.
### Table 4
Spearman correlation coefficients (p value) for CO₂ elevation, indoor temperature, window and door operation and median, classified by season. All monitoring data is from the period April 1 2015 to April 1 2016

<table>
<thead>
<tr>
<th>Variables</th>
<th>CO₂ elevation</th>
<th>Indoor temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window operation</td>
<td>0.13 (0.32)</td>
<td>-0.11 (0.38)</td>
</tr>
<tr>
<td>Hallway door operation</td>
<td>-0.05 (0.70)</td>
<td>-0.24 (0.06)</td>
</tr>
<tr>
<td>Balcony door operation</td>
<td>0.12 (0.34)</td>
<td>0.18 (0.16)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
<th>CO₂ elevation</th>
<th>Indoor temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window operation</td>
<td>0.25 (0.05)</td>
<td>-0.08 (0.56)</td>
</tr>
<tr>
<td>Hallway door operation</td>
<td>0.014 (0.92)</td>
<td>-0.03 (0.82)</td>
</tr>
<tr>
<td>Balcony door operation</td>
<td>0.26 (0.04)</td>
<td>0.45 (0.0002)</td>
</tr>
</tbody>
</table>

### DISCUSSION

Our results show that the monitored suites experienced high indoor air temperatures during the summer, and that this led to our model predicting long periods of discomfort due to heat. While there did not seem to be any correlation between the floor height of the unit and discomfort within the unit, there is a clear variation of discomfort prevalence across buildings, which is likely attributable to the differences in indoor temperatures observed in Figure 1, where it is shown that buildings A and G maintain higher indoor temperatures throughout the year. While in the summer the temperatures in these buildings are comparable to those of others, in the winter they appear to be a few degrees higher on average, suggesting more severe over-heating in these buildings. Given that during the monitoring period the occupants did not have any control over the set point of the heating system in their units, the only means available to mitigate over-heating was the operation of windows. The survey results showed that for the winter months, buildings A and B had the highest self-reported wintertime window operation, while buildings E and C had the lowest. In the case of Building A, a high window operation rate during the winter is indicative that occupants feel the need to cool their units due to over-heating. This may also explain why Building A had statistically significant lower median CO₂ elevation over outdoors than all other buildings except Building D (K-sample equality of medians test, p<0.05) for the 2015-2016 winter months. The installation of smart thermostats (that will allow occupants to shut off the heating in their units) after the end of our monitoring period will provide us with the opportunity to investigate over-heating further.

Our findings have important implications for the social housing authority managing these buildings as well as other building managers of similar facilities. First, it is clear that discomfort is a problem throughout the entire monitored year. While our variable clothing model showed that in the winter occupants can reach comfort by switching into lighter garments, this is far from an ideal situation. Our model estimated comfort conditions every 15 minutes and assumed that occupants could change clothes at each interval to maximize comfort, which is not very realistic. Further, several of the residents are seniors, and many may have mobility issues. It is not appropriate to maintain an indoor environment in the winter (when heavy clothing is necessary for going outside) that requires occupants to fully change their clothes to be comfortable. Building operators should also consider that high heating set points may be detrimental from an energy perspective. Second, it is evident that inadequate cooling is provided to these units. This is of particular concern during extreme heat events, which are becoming increasingly common due to climate change. Our results showed that summertime indoor temperatures in most units are very close to outdoor temperatures. During heatwaves, this means that occupants will be exposed to high temperatures during prolonged periods of time. This is of high concern for elderly
populations, which are at elevated risk of developing heat-related illness and who also may have mobility issues which may make it harder for them to travel to cooler locations outside of their buildings. As such, it is important to evaluate strategies to mitigate high indoor summertime temperatures. Short term solutions to mitigate this problem include reducing air exchange rates (to reduce the amount of hot outside air that is coming into the units) and implementing cooling centers in the buildings for occupants to seek shelter without requiring them to travel far. In the long term, these buildings will need to be retrofitted to perform better during periods of high outdoor temperatures. These retrofits will likely involve measures to reduce solar gains (potentially by replacing the windows and improving the enclosure), and to provide some form of building-wide cooling (either through passive strategies or mechanical air conditioning systems).

To contextualize our analysis and discussion better, it is necessary discuss a few limitations of our study. First, there is a possibility that residents whose suites were monitored modified their behaviour due to being enrolled in the study (an example of the Hawthorne Effect). Changes of behavior such as different window operation and AC usage could result in data that is not fully representative of the conditions in these suites outside of the studied timeframe. Given the nature of this effect, unfortunately it is not possible to assess whether it affected our results based on our data, nor to estimate its magnitude. Second, there were some instrument limitations that affected our results. The design of the monitoring package required the CO$_2$ sensors to be connected to the power outlet to operate. Power interruptions (due to outages or disconnection) would result in no data being collected by the CO$_2$ sensors. Due to this, there were several periods where no CO$_2$ was collected. Our approach to measuring MRT was only an approximation, which resulted in MRT measurements being very close to air temperature (see Figure 1 in SI), possible underestimating radiant sources of energy that affect occupant comfort. However, if we underestimated MRT, this would imply that our results are also an underestimate of occupant’s discomfort level given that higher MRT would lead to higher discomfort due to heat. The instruments we used were limited by their accuracy and ranges described in Table 2. Our analysis showed that our results were not affected by this limitation: any fluctuations of temperature and humidity within these rages would have yielded almost identical results (see Figure 3 and Figure 4 in SI).

Third, the assumptions for the underlying parameters may not be representative of certain situations. Namely, the assumptions regarding air velocity and occupant’s activity level have very large impact on the comfort conditions, and the assumed values for these parameters limits our results. However, the values used were those allowable by the ASHRAE 55-2013 standard graphical and analytical comfort zone methodologies. In order to model comfort with different air velocities and activity levels, alternative methods should be used. Last, the variable comfort model did not have a “stepwise” correction to clothing value, meaning that if an occupant was deemed uncomfortable at the highest clothing value (1.0 clo), the model would switch instantly to the lowest clothing value (0.5 clo) and vice versa, instead of trying first an intermediate value of 0.75 clo. This limitation, however, affected very few data points in which discomfort due to hot temperatures became discomfort due to cold temperatures due to the abrupt switch.

Further to the limitations described above, there is an additional complication with analyzing thermal comfort. In addition to comfort being a function of many physical variables, there are physiological and psychological factors that also influence one’s level of comfort which are not considered in the thermal comfort models used in this study. A review by Brager and de Dear on thermal adaptation inside buildings found that psychological acclimatization and
psychological expectations have important effects on thermal comfort\textsuperscript{19}. Acclimatization occurs due to the body’s ability to adapt to new situations. Therefore, people from hot regions may develop higher tolerances to higher temperatures due to physiological adaptation. Psychologically, the lack of control over the hygrothermal conditions in a space may result in less tolerance for discomfort conditions. These two considerations are important when contextualizing the results presented in this investigation. Firstly, residents who have lived in these units for several years may have developed a higher tolerance for the high temperatures observed. Therefore, there may be a mismatch between occupant’s perception and the model results. Secondly, the design of the HVAC system of the buildings did not consider giving occupants control of their heating. Therefore, this lack of control may contribute negative to resident’s perception of their space, and reduce their tolerance for discomfort as described by Brager and de Dear\textsuperscript{19}. Considering that the energy retrofits that these buildings underwent included installing smart thermostats for occupants to control their heating systems, this presents an important point to evaluate when comparing the pre and post comfort conditions: the addition of the thermostat alone could introduce a placebo effect that improves the perceived comfort conditions without significantly changing the physical parameters that influence comfort.

The impact of these complications becomes evident when comparing the results from the thermal comfort modelling to those from the occupant surveys. While our monitoring and modelling results showed that buildings A, B and G appeared to be the most uncomfortable (due to high temperatures both in the summer and in the winter), the survey results suggest that F and G are the most uncomfortable (too hot in the summer and too cold in the winter). It was not surprising to have elevated reported discomfort due to heat in buildings F and G, since most buildings showed high prevalence of discomfort in our model. However, it was surprising to find that only about 50% of the surveyed occupants in Building A reported being too hot during the summer, when both our model as well as our monitoring results showed that this building has serious issues of under-cooling, with a vast majority of the summer time spent above 27°C in the monitored units. It was also striking to find that in buildings F and G more than 70% of survey respondents reported being too cold during the winter. Our results show clearly that average temperatures are over 23°C during the monitored period, which would make discomfort due to cold highly unlikely. Two possible explanations could explain these seemingly contrasting results. One is that the survey occurred before the monitoring period and occupants were recalling several years of experience living in those units, and when asked about wintertime comfort, it is likely that they thought about the winter prior to the beginning of our study which was much colder than the one captured in our monitoring results. Another possibility is that the position of the monitoring package (far away from windows) may not be representative of other areas of the units which may be colder (near windows and balcony doors). From the visits, we noted that many occupants had furniture near these locations and therefore may spend considerable amounts of time there.

Even though the surveys and the monitoring results disagreed in terms of which buildings had the highest prevalence of discomfort, there was agreement in both the survey results and the monitoring results that floor height appears to have no effect on the thermal comfort conditions. This is contrary to the conventional belief that the stack effect would result in higher temperatures (and thus more discomfort due to heat) in units in the top floors, compared to units in lower floors. In the case of our buildings, since there is no central air conditioning, the stack effect would have similar effects both in the winter (when heating is the driver of the effect) and in the summer (when indoor gains would become the driver of the effect). Since neither the results of the survey nor of the monitoring packages showed any
visible correlation between floor height and increased temperatures or discomfort, the stack effect may not be important to the thermal conditions in these buildings.

CONCLUSIONS
In this work, we presented the results of a long-term thermal comfort monitoring project in Toronto. We used the hygrothermal data collected to model thermal comfort, in accordance with the provisions outlined in the ASHRAE 55-2013 standard. We found that thermal comfort in the monitored buildings has considerable variation across different seasons, with discomfort due to high temperatures in the summer (an indicator of insufficient cooling) being the most prevalent issue in all monitored buildings. Considering that climate change is likely to result in more frequent extreme heat events, this will place thousands of social housing residents (especially elderly ones) at increased risk of developing heat related illness. Additionally, our results showed that some buildings had discomfort due to high temperatures in the wintertime, which is indicative of over-heating. However, we found that this discomfort can be mitigated by occupants if they wear lighter garments, as shown in our variable clothing model which assumes that clothing values are adjustable by the occupants. Lastly, we observed that the CO\textsubscript{2} concentration elevation over outdoors in most units is below the recommended threshold to maintain acceptable indoor air quality, although this threshold does not account for the presence of outdoor air pollutants, and also fails to recognize that CO\textsubscript{2} concentration elevation is not a true measurement of air exchange rate. Future studies should evaluate potential solutions to mitigate the summertime discomfort.

ACKNOWLEDGMENTS
The authors would like to thank the residents for their cooperation throughout the study, as well as the National Science and Engineering Research Council of Canada for providing funding.

REFERENCES


Appendix C: Diaz Lozano Patino, E., A. Mahdavi, and J.A. Siegel. Particulate Matter Emission Rates from Common Scent Sources. 2018. Accepted for presentation at the 2018 Houston ASHRAE Conference.
Particulate Matter Emission Rates from Common Scent Sources

Ernesto Diaz Lozano Patino
Student Member ASHRAE

Alireza Mahdavi
Student Member ASHRAE

Jeffrey Siegel, PhD
ASHRAE Fellow

ABSTRACT
The use of artificial scent generation products is a popular strategy to mitigate unpleasant odors indoors, as well as to generate pleasant scents. However, the operation of these products may result in the indoor emission of particulate matter (PM), a harmful pollutant with a variety of health impacts. In this paper, we studied three distinct types of scent generating products: incense (a combustion-based source), a wax warmer (a flameless heat-based source) and an ultrasonic oil diffuser (a device that uses ultrasonic vibrations to aerosolize an emulsion of water and essential oils). We measured the PM\(_1\) and PM\(_{2.5}\) emission rates of these sources in a sealed experimental chamber using concentration obtained from three particle monitoring devices (including one corrected with a gravimetric filter calibration). The results indicated that incense was the largest source of PM, with an estimated average PM\(_{2.5}\) emission rate of 42.9 mg h\(^{-1}\). The second largest source was the ultrasonic oil diffuser, with an estimated average PM\(_{2.5}\) emission rate of 1.7 mg h\(^{-1}\). The wax warmer resulted in the least amounts of emissions, with a PM\(_{2.5}\) emission rate of 0.17 mg h\(^{-1}\). We also compared the PM\(_1\) and PM\(_{2.5}\) emission rates obtained from the three instruments for the cases of wax warmer and oil diffusers. Although there were good agreements between the instruments for the particles generated by the wax warmer, with oil diffuser particles we saw less agreement for one instrument suggesting that some scenting sources may not be measured well with some particle counters. Finally, we performed a simulation of PM\(_{2.5}\) in two real indoor environments: a small room and an entire house and evaluated the effectiveness of air cleaning techniques in the reduction of PM\(_{2.5}\). In general, we found that ventilation and air cleaning may not be sufficient to effectively mitigate the PM\(_{2.5}\) of some of these sources in certain contexts. These three scenting approaches, especially incense, led to considerable indoor PM\(_{2.5}\), especially in a small room with limited ventilation or air cleaning. Overall, the results suggest caution in the use of scenting agents in indoor environments.

INTRODUCTION
As people spend most of their time indoors, the presence of particulate matter (PM) is a concern, given its negative health impacts (Logue et al. 2012). There is strong evidence in the literature that combustion-based sources of scents, such as candles and incense, generate considerable amounts of PM (Derudi et al. 2014; Fine et al. 1999; Lee and Wang 2004; Manoukian et al. 2013). These emissions are not only linked to the combustion process, but to the constitution of the sources themselves, as different candle compositions (e.g., different waxes and scenting agents) have been shown to result in different PM emission factors (Derudi et al. 2014). Recently, new technologies are emerging to provide scents indoors without combustion. These new technologies include electric warming of fragrance emitting materials (such as waxes or essential oils) and ultrasonic oil diffusers, which use ultrasonic vibrations to vaporize an emulsion of water and essential oils. However, the potential influence of these non-
combustion sources on increasing indoor PM is unknown. Although removing the combustion element may seemingly reduce the pollution associated with generating scents, there are several reasons to believe these emerging sources of scents may still emit significant quantities of PM. During the operation of electric wax warmers, it is likely that harmful compounds present on the wax (such as volatile organic compounds) may become airborne when heated (Derudi et al. 2012; Nazaroff and Weschler 2004). Furthermore, the heating process itself may result in PM emissions, as hot surfaces are known to emit particles when dust comes into contact with them (Afshari et al. 2005). However, there have been no earlier studies quantifying PM emissions from wax warmers. Ultrasonic diffusers, on the other hand, are potential sources of PM since their operation resembles the mechanism of ultrasonic humidifiers, which are known to generate PM (Highsmith et al. 1992; Sain et al. 2017; Sain and Dietrich 2015; Umezawa et al. 2013). Our recent preliminary investigation showed that ultrasonic oil diffusers indeed constitute a source of PM, with emission rates comparable to those of humidifiers (Diaz Lozano Patino et al. 2017). This study also found that the PM emission rate of ultrasonic oil diffusers varies widely depending on the quality of the source water and the oil type used.

The primary goal of the current paper is to measure the emission rates of PM from three sources of scents: incense, a wax warmer, and an ultrasonic essential oil diffuser. The secondary goal of this paper is to develop a mass balance model to estimate the PM concentrations resulting from the use of these sources in real residential indoor environments, and the mitigating impact of air cleaning strategies on PM concentrations. Our results will provide users of these scents sources with quantifiable information of PM generation, which is useful for further assessment of exposure to PM from these scenting approaches.

**METHODS**

We tested the sources of scents in a 1.3 m$^3$ (46 ft$^3$) sealed acrylic chamber with no air exchange rate (AER). The specifications of each source are summarized in Table 1. Oil diffuser tests were performed with two different oils (eucalyptus and lavender spearmint) resulting in 4 distinct sources: incense, eucalyptus oil diffuser, lavender oil diffuser, and wax warmer. With the incense, we completely burnt half of a typical incense stick in each PM generation test, which took around 15 minutes. With the oil diffuser, we added four droplets of eucalyptus or lavender oil to the 100-mL reservoir containing distilled water and let the system operate for 10 minutes. With the wax warmer, we placed approximately 30 g of wax inside the warming plate of the device and ran the warmer for 90 minutes. After this period, a fan was operated for 5 minutes to cool down the wax warmer (and stop particle generation). Each PM generation test (e.g., incense, eucalyptus oil diffuser, lavender oil diffuser, and wax warmer) was performed for a total of four replicates.

<table>
<thead>
<tr>
<th>Source</th>
<th>Specifications</th>
<th>Scent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incense</td>
<td>Stick incense, total burning time ~30 min</td>
<td>Vanilla</td>
</tr>
<tr>
<td>Wax warmer</td>
<td>Electric powered, $P_{diss} = 23.2$ W</td>
<td>Vanilla cinnamon</td>
</tr>
<tr>
<td>Oil diffuser</td>
<td>Electric powered, 100 mL reservoir, $P_{diss} = 8.6$ W</td>
<td>Eucalyptus, Lavender Spearmint</td>
</tr>
</tbody>
</table>

A very important consideration was cleaning of both the particle generating sources as well as the chamber, to avoid contamination from one test to affect the results of other tests. Between different sources, all the interior surfaces of the chamber were wiped with isopropanol-wetted laboratory wipes. For the wax warmer, the warming plate was thoroughly cleaned with soapy water. The oil diffuser was both rinsed and operated with distilled water alone between tests.

We used three different particle monitoring devices for recording PM concentrations, as described in Table 2. With the incense, we performed the tests with instrument 1 only, as the PM concentration was too high for the other two instruments. We used two different units of instrument 1 in all tests, one with a PM$_{2.5}$ inlet impactor and the other one with a PM$_{1}$ inlet impactor. Since instrument 1 only has one channel of particle counts, the impactor allowed us to
control the size of particles that the instrument would count. Instruments 2 and 3 also recorded a variety of PM concentrations including PM$_{1}$, PM$_{2.5}$, and PM$_{10}$. Air temperature and relative humidity (RH) inside the chamber were monitored with an ONSET HOBO U12-012 data logger in all the tests. For wax warmer tests the temperature of the wax was also monitored using an ONSET TMCx-HD temperature probe connected to an ONSET HOBO U12-012 data logger.

To estimate the emission rates, we employed a combination of linear and non-linear regression. Firstly, the loss term ($L$), which accounts for all loss mechanisms, was estimated using the data from the decay portion of each test, by estimating a linear regression model based on Equation 1:

$$\ln(C(t)) = \ln(C_{t_{gen}}) + \ln(e^{-Lt_{gen}})$$  

where $C(t)$ is the particle concentration as a function of time and $C_{t_{gen}}$ is the concentration at the end of the particle generation period and $t_{gen}$ is the particle generation time (10 minutes for oil diffusers, 15 minutes for incense, and 20-40 minutes for wax warmer). Afterwards, the source ($S$) was estimated using a non-linear regression model based on Equation 2:

$$C(t) = C_{0}e^{-Lt} + \frac{S}{L}(1 - e^{-Lt})$$  

where $C_{0}$ is the concentration at the start of the test, and $S$ is defined as $E$ (the emission rate) divided by $V_{c}$ (the chamber volume). In some tests, the loss rate during the decay portion of the experience was not comparable to the loss rate during the emission phase, due to the operation of an air cleaner. In these cases, we used the average loss rate from comparable tests without the air cleaner to estimate the emission rates using Equation (2).

To increase the accuracy of our results, we also performed a gravimetric calibration of the results for instrument 1. This device was equipped with a 37-mm polytetrafluoroethylene (PTFE) filter, which was conditioned and weighed before and after testing. Using the mass of the particles collected in the filter, as well as the recorded PM concentration, the measured flowrate through the instrument and the sampling time, the response factors summarized in Table 3 were calculated. These response factors were applied to the readings of both instrument 1 units to obtain the calibrated results. Our response factors are comparable but on the lower side of those reported by a previous study (Jenkins et al. 2004), who found that a DustTrack (an older Model 8520) overpredicted aerosol concentrations by factors between 2 and 4 when compared to gravimetric measurements.

Using the emission rate data, we also developed a mass balance model using Equation 3 to estimate PM$_{2.5}$ in two indoor environments: a 25 m$^3$ (883 ft$^3$) room, and a 250 m$^3$ (8830 ft$^3$) house. Another goal of this simulation was to evaluate if the use of air cleaning, such as a heating, ventilation, and air-conditioning (HVAC) system in a house or a portable air cleaner in a room provides sufficient effectiveness to reduce PM$_{2.5}$ in the indoor environment.

### Table 2. Particle counter specifications

<table>
<thead>
<tr>
<th>Code</th>
<th>Model</th>
<th>Manufacturer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument 1</td>
<td>DustTrack DT-II 8530</td>
<td>TSI</td>
<td>Optical particle counter with inlet impactor</td>
</tr>
<tr>
<td>Instrument 2</td>
<td>OPC N-2</td>
<td>Alphasense</td>
<td>Optical particle counter</td>
</tr>
<tr>
<td>Instrument 3</td>
<td>Mini-Wras 1371</td>
<td>Grimm</td>
<td>Optical and electrical particle counter</td>
</tr>
</tbody>
</table>

### Table 3. Instrument 1 response factors

<table>
<thead>
<tr>
<th>Source</th>
<th>PM$_{1}$</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0.153</td>
<td>0.159</td>
</tr>
<tr>
<td>Incense</td>
<td>0.148</td>
<td>0.157</td>
</tr>
<tr>
<td>Wax warmer and Oil diffuser</td>
<td>0.183</td>
<td>0.240</td>
</tr>
</tbody>
</table>

Using the emission rate data, we also developed a mass balance model using Equation 3 to estimate PM$_{2.5}$ in two indoor environments: a 25 m$^3$ (883 ft$^3$) room, and a 250 m$^3$ (8830 ft$^3$) house. Another goal of this simulation was to evaluate if the use of air cleaning, such as a heating, ventilation, and air-conditioning (HVAC) system in a house or a portable air cleaner in a room provides sufficient effectiveness to reduce PM$_{2.5}$ in the indoor environment.
In the above equation, $\beta$, $\lambda_r$ and $\eta_{HVAC}$ were considered as fixed parameters. $\beta$ is the deposition loss factor. We selected 0.42 h$^{-1}$ for deposition loss of PM$_{2.5}$ according to Williams et al. (2003). $\lambda_r$ and $\eta_{HVAC}$ indicate the recirculation AER and the HVAC filter efficiency in the house, respectively. We selected the value of 4.75 h$^{-1}$ for the recirculation AER according to Stephens et al. (2011), which was the median of the AERs reported in eight residential buildings. We also estimated 0.3 (30%) as $\eta_{HVAC}$ according to the data presented by Stephens and Siegel (2012) and Azimi et al. (2014) for a high performance HVAC filter. The simulation of PM$_{2.5}$ was performed as a function of infiltration AER varying from 0.2 to 1.3 h$^{-1}$ which was within the range reported for conventional houses in the United States by a previous study (Chan et al. 2005).

To evaluate the influence of different strategies on mitigating PM$_{2.5}$ in typical indoor environments (e.g., source mitigation or use of air cleaning technique), we performed the simulation for seven different case studies. Table 4 summarizes these case studies, which vary in terms of volume (e.g., room vs. volume), emission from different sources (E), and the presence or absence of air cleaning strategies. As the cleaning strategy, we considered portable air cleaner for the room and HVAC system for the house. We chose a value of 70 m$^3$·h$^{-1}$ (41 cfm) as a typical clean air delivery rate (CADR) of a small portable air cleaner (case #2). Also, to better understand the contribution of HVAC to the reduction of PM$_{2.5}$ in a house, we selected two runtime fractions: 20% (a typical case) and 100% (an ideal case when the system works continuously) (cases #4,5).

### Table 4. Simulation case studies and input parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Volume m$^3$ (ft$^3$)</th>
<th>Source</th>
<th>CADR m$^3$·h$^{-1}$ (cfm)</th>
<th>Runtime (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Room without portable air cleaner</td>
<td>25 (883)</td>
<td>Incense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Room with portable air cleaner</td>
<td>25 (883)</td>
<td>Incense</td>
<td>70 (41)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>House with HVAC (off)</td>
<td>250 (8830)</td>
<td>Incense</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>House with HVAC</td>
<td>250 (8830)</td>
<td>Incense</td>
<td>0</td>
<td>20%</td>
</tr>
<tr>
<td>5</td>
<td>House without portable air cleaner</td>
<td>250 (8830)</td>
<td>Incense</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>6</td>
<td>Room with portable air cleaner</td>
<td>25 (883)</td>
<td>Oil diffuser (lavender)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Room without portable air cleaner</td>
<td>25 (883)</td>
<td>Wax warmer</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### RESULTS

Figure 1 illustrates the PM$_{2.5}$ emission rates for the different sources tested. Incense emission rates are much higher than those from the oil diffuser and the wax warmer. Our results are comparable to previously reported stick incense PM$_{2.5}$ emission rates, which range between 9.8 mgh$^{-1}$ and 372.6 mgh$^{-1}$ (Lee and Wang 2004). Oil diffuser emission rates are consistent with those reported in our previous study which found higher emissions from lavender oil than from eucalyptus oil (Diaz Lozano Patino et al. 2017). Further, our results show that incense burning can result in higher PM emissions than cigarette smoking or candle burning. With regards to cigarettes, a previous study (Charles et al. 2008) reported cigarette PM emission rates ranging from 1.9-2.7 mgh$^{-1}$ (assuming a 10 min cigarette burning time). With regards to candles, the results of a previous investigation (Derudi et al. 2014) suggest an average PM$_{2.5}$ emission rate of 0.32 mgh$^{-1}$ (averaged across all candle types, and estimated using the reported burning rates), comparable to the emission rates for the wax warmer.
Figure 1  PM$_{2.5}$ emission rates for the different sources tested. Each bar represents one test. Error bars indicate ±1 standard error from the non-linear regression used to determine the emission.

From Figure 1, it is evident that there is notable variation between and within sources. Within sources, the wax warmer showed the most variation, whereas the lavender diffuser seems to be the most consistent. The within source variation is unexplained, but may be due to differences in the wax used in the warmer or small variations in temperature conditions. Across sources, incense emits over an order of magnitude more PM$_{2.5}$ than the diffuser, and more than two orders of magnitude more than the wax warmer. There are also two other important notes about the results in Figure 1 that are not evident in the plot. Firstly, we found from our results from other instruments that the PM$_{2.5}$ was mostly just PM$_{1}$, with PM$_{1}$ accounting for over 95% of the PM$_{2.5}$ emissions in most cases. Secondly, the PM$_{2.5}$ results presented in Figure 1 are those from instrument 1 after application of the response factors from the gravimetric colocation. Considering the response factors presented in Table 3, the raw readings from the instrument and resulting emission rates were 4 to 7 times higher than those presented in the Figure. This suggests that using this instrument without a gravimetric calibration will result in an overprediction of emission rates.

Another instrument-related finding was the variation between the different instruments used, as seen in Figure 2. On average, the other two instruments agree well with the calibrated instrument 1, however, there is considerable variation for most of the sources. In general instrument 3 (hollow symbols) showed more accurate results than instrument 2, this is both not surprising (instrument 2 is approximately 100 times cheaper than instrument 3) and potentially not relevant for other particles than those considered here. The variation across instruments can be potentially attributed to several factors: different calibration settings in the instruments (e.g., assumptions about the density and optical properties of the particles), poor mixing of air in the chamber, as well as different response times in the instruments. Similar to Figure 1, the results in Figure 2 for instrument 1 are those that have been calibrated with the response factors shown in Table 3. The raw results from instrument 1 would be considerably higher than any of the other results shown in the figures.
**DISCUSSION**

In addition to observing differences in the emission rates across the different sources, we observed that each source has unique emission profiles. The incense is characterized by a steep emission curve, with a constant slope. Emissions will continue to occur as long as the incense burns and will cease to occur very shortly after the incense stick is fully consumed. The wax warmer is characterized by having no emissions until the wax reaches a temperature of approximately 80°C (176°F), after which an emission curve is observed. In our results, we only considered the emissions data after the wax had reached this threshold temperature and the instruments recorded PM emissions. The oil diffuser has two distinct emission curves: one during the first few minutes of operation, which is followed by a short plateau, and then the second one with a different slope. Based on previous tests we determined that the first emission curve lasts around 10 minutes (this may vary by device and amount of oil used), so the results in this paper only consider this first emission period.

There were a few limitations that are important to consider when analyzing our data. We discovered that there were some minor leaks from the chamber, due to some small holes not being sealed properly. However, there was not wide variation in the loss terms of our data. If infiltration had played a significant role, it is likely that we would have seen more variation in the loss terms in our decay periods. Therefore, we believe that the leakage had a minor effect on our results. We also saw a lot of variation across our instruments, which could indicate poor mixing conditions within the chamber. However, we decided not to use a fan inside the chamber due to concerns that this could lead to resuspension of deposited particles from the chamber walls. Lastly, we had slightly inconsistent cleaning procedures for the oil diffuser. In the first couple of tests, we did not run the diffuser with distilled water between tests, which could lead to cross-contamination from residual oil between tests. Given the small amount of variation in the diffuser results, we do not think this factor had a major impact in our results.

In order to put these emissions results in context, we simulated the PM$_{2.5}$ concentrations that would result from the use of these products in a residence. Figure 3 illustrates the simulation of PM$_{2.5}$ vs. infiltration AER for the selected case studies (e.g., room without and with portable air cleaner, and house with HVAC system with 0 (off), 20,
and 100% runtime fractions) for incense and the worst-case scenario (room without portable air cleaner) for the essential oil diffuser and wax warmer. The first observation from Figure 3 is that burning incense in a room, even with the simulated portable air cleaner, results in very high PM$_{2.5}$ concentrations (e.g., much higher than polluted outdoor air). Even when considering the much larger volume of the house, particle concentrations can be quite high, even in the case with the continuously operating HVAC system. These results suggest that very high concentrations of PM$_{2.5}$ will result if incense is burned in typical residential environments. The model also considered no outdoor particles or particles from other indoor sources and thus is conservative about the particulate exposure that an occupant would receive. Although ventilation does reduce concentrations (particularly in cases with no or limited air cleaning), it does not change the fundamental findings above. It should be noted that the simulations consider time-averaged conditions and thus overestimate potential exposure if the scents are used episodically and not continuously. However, the high concentrations that the emissions from incense achieve are still of substantial concern from a particle exposure perspective.

The lavender essential oil diffuser and the wax warmer emit considerably less than the incense. Thus, only the worst-case scenario (room, no portable air cleaner) was considered. The essential oil diffuser still resulted in very high concentrations of PM$_{2.5}$ (again comparable to a polluted urban environment). This suggests that this type of device should not be used in small rooms and can result in high concentrations of indoor particles. The wax warmer emits considerably less than either of the two previous sources and the particle concentrations are generally below the USEPA National Ambient Air Quality Standards (NAAQS) for PM$_{2.5}$ of 12 µg/m$^3$ (annual average) suggesting that there are fewer concerns about the amount of particles emitted from this source.

One of the potentially surprising things about Figure 3 is that AER has a relatively small impact on the concentrations, particularly for any of the scenarios with air cleaning. This comes from the fact that the default assumption made about deposition rate and the removal rates of the air cleaning strategies result in ventilation providing less of the total removal rate. This highlights the limits of general ventilation for treating strong episodic sources like those associated with these scenting approaches.

![Figure 3](image)

**Figure 3** PM$_{2.5}$ vs. infiltration AER for various indoor environments and air cleaning techniques

In addition to primary PM emissions, these sources of scents are likely emitters of volatile organic compounds (VOCs); some of which could be harmful. These VOCs are also highly reactive gases which could generate more secondary particles through reactions with ozone, which is a common air pollutant in outdoor air.
Therefore, the operation of these sources of scents may be more contaminating in locations with elevated ozone concentrations or operated in the presence of an indoor ozone source. To estimate exposure to air pollution associated with these devices, it is important to consider the motivation to use these sources of scents and its prevalent use. Incense use is integrated with cultural practices, for example incense is commonly used in Asian residences as part of daily life. A previous study estimated that approximately fifty percent of the population in Southeast Asia use incense daily at home (Friborg et al. 2008). This large population may be exposed to high levels of indoor pollution associated with the use of incense, which could have negative health implications in the long term. Oil diffusers and wax warmers are most likely used to generate pleasant odors, and in some cases, to mask existent bad odors. These devices, however, are not removing the sources of bad odors, and their operation contributes to further indoor air pollution. Since oil diffusers and wax warmers are relatively new sources of scents, it is difficult to estimate the prevalence of their usage, but multifamily building occupants often report odor transport from neighboring units (Hewett et al. 2002) and utilize various strategies to control these odors.

CONCLUSION

We found that incense, a combustion-based scent source, results in considerably more PM$_{2.5}$ emissions that non-combustion based sources (an oil diffuser and a wax warmer). We also found that, while there was variation between the instruments we used to measure the PM concentrations, this variation was acceptable when considering the difference in sophistication between the instruments. The only exception to this statement was instrument 1, which needed to be adjusted (using gravimetric data) in order to show acceptable agreement with the other instruments and with the true emission rates. Lastly, our simulation of PM$_{2.5}$ concentrations suggests that ventilation and air cleaning may not be sufficient to mitigate the emissions from some of our tested sources in some of our modelled scenarios. These results suggest caution when using these sources of scents in most indoor environments.

ACKNOWLEDGMENTS

The Canada Foundation for Innovation and the Ontario Research Fund (Grant 32319) provided instrumentation for this research. Funding was also provided by NSERC (RGPIN-2014-06698) and by an ASHRAE Graduate Student Grant-in-aid to EDLP.

NOMENCLATURE

\[ \begin{align*}
L & = \text{Loss term for mass balance model (including all loss mechanisms), in h}^{-1} \\
C(t) & = \text{Concentration as a function of time, in mgm}^{-3} \text{ or mgft}^{-3} \\
t_{\text{gen}} & = \text{Time of particle generation, in minutes} \\
C_{\text{gen}} & = \text{Concentration at the end of } t_{\text{gen}, \text{, in mgm}^{-3} \text{ or mgft}^{-3}} \\
E & = \text{Emission rate, in mgh}^{-1} \\
S & = \text{Source term for mass balance model (in our experiments this corresponds to } E/V), \text{ in mgh}^{-1}\text{m}^{-3} \\
C_0 & = \text{Concentration at start of experiment, in mgm}^{-3} \text{ or mgft}^{-3} \\
V_c & = \text{Volume of chamber, in m}^3 \text{ or ft}^3 \\
\beta & = \text{Particle deposition loss, in h}^{-1} \\
\lambda_i & = \text{Air exchange rate, in h}^{-1} \\
\lambda_r & = \text{Recirculation rate, in h}^{-1} \\
\eta_{\text{HVAC}} & = \text{HVAC filtration efficiency} \\
f & = \text{HVAC runtime} \\
\text{CADR} & = \text{Portable air cleaner clean air delivery rate, in m}^3 \text{ h}^{-1} \text{ or cfm} \\
V & = \text{Room/house volume, in m}^3 \text{ or ft}^3
\end{align*} \]
REFERENCES


