Monitoring and Evaluation of Air Pollution in Residential and Commercial Buildings: Development and Implementation of Indoor Air Quality and Environmental Justice Frameworks for Communities and Energy Conservation Districts

by

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The over-arching theme of this work is to explore indoor air quality in two communities and two building types: an energy conservation district (ECD) focusing on commercial buildings and Environmental Justice (EJ) communities focusing on residential buildings. In the first part of this research, a framework was developed for monitoring and addressing indoor air pollution in the context of an ECD in Pittsburgh, Pennsylvania, comprised of 518 buildings. Indoor air quality (IAQ) assessments were performed in eight representative buildings, ranging from green certified to historic buildings, comparing exposure events at diurnal and seasonal time scales. Both the sampling data and feedback from building stakeholders, informed the development of an IAQ survey, which was used to establish a performance baseline and guide the future operation and maintenance (O&M) of buildings in the district. While several national and international organizations offer standards for pollution levels and techniques to measure ambient air, there are no consistent metrics or methods for assessing and monitoring IAQ for an entire community. The second part of this research uses a community-based approach and developed a framework to address environmental justice issues in underserved communities. Resident-led trainings and workshops, and citizen science campaigns were used to increase environmental consciousness at the grassroots. As distrust in outside institutions has limited the reach of environmental justice research in underserved communities, this research highlights the importance of bottom-up principles that involve residents in the process of goal-setting and execution of academic research. The third and final component of this research focuses on residential structures; seasonal IAQ assessments were conducted in thirteen homes situated in low-income neighborhoods in Pittsburgh, PA. Indoor and ambient air quality data, and quality of life (QOL) survey results were then combined with outcomes from a local citizen science initiative to explore the relationship between air pollution and QOL. Although the effects were less profound than expected, the analysis marks the beginning of needed research on IAQ and QOL that will serve as the basis of future work and supplement a larger field campaign led by the research team.

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Nomenclature

AADT	Annual Average Daily Traffic Count
ACH	Air Changes per Hour
AER	Air Exchange Rate
AHU	Air Handling Unit
ALA	American Lung Association
ALCOSAN	Allegheny County Sanitary Authority
ANOVA	Analysis of Variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS	Building Automation System
BC	Black Carbon
BPA	Bisphenol A
BRFSS	Behavioral Risk Factor Surveillance System Questionnaire
CATs	Community Action Teams
CB	Conventional Building
CBO	Community Based Organization
CBPR	Community Based Participatory Research
CDC	Center for Disease Control
CEE	Civil and Environmental Engineering
CFLs	Compact Fluorescent Lights
CFM	Cubic Feet per Minute
CHAD	Consolidated Human Activity Database

CO_2	Carbon Dioxide
ECD	Energy Conservation District
EJ	Environmental Justice
EJCAM	Environmental Justice Community Alert Matrix
ETS	Environmental Tobacco Smoke
GB	Green Building
GBA	Green Building Alliance
GeoDA	Geographic Data Analysis
GPS	Global Positioning System
HB	Historic Building
HCHO	Formaldehyde
HEPA	High Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
I-O	Indoor-to-Outdoor
LCA	Life Cycle Assessment
LCG	Larimer Consensus Group
LED	Light Emitting Diodes
LEED	Leadership in Energy and Environmental Design
LOD	Limit of Detection
LWOL	Living Waters of Larimer
LSD	Least Significance Difference

MEP	Mechanical, Electrical, and Plumbing
NAAQS	National Ambient Air Quality Standards
NACD	The National Association of Conservation Districts
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NOx	Oxides of Nitrogen
NSF	National Science Foundation
NYC	New York City
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Administration
PCBs	Polychlorinated Biphenyls
PENNDOT	Pennsylvania Department of Transportation
PM	Particulate Matter
PNC	Particle Number Counts
PWSA	Pittsburgh Water and Sewer Authority
QOL	Quality of Life
RFA	Request for Applications
RH	Relative Humidity
ROCIS	Reducing Outdoor Contaminants in Indoor Spaces
SBS	Sick Building Syndrome
TOC	Theory of Change
TRI	Toxic Release Inventory
TVOCS	Total Volatile Organic Compounds

URA	Urban Redevelopment Authority
US DOE	United States Department of Energy
US EIA	United States Energy Information Administration
US EPA	United States Environmental Protection Agency
US GBC	United States Green Building Council
UTCM	Urban Transition Cities Movement
VAV	Variable Air Volume
VOCS	Volatile Organic Compounds
WHO	World Health Organization
WHO-QOL	World Health Organization Quality of Life

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1.0 Introduction

1.1 Motivation and Rationale

Air pollution, which is known to degrade building materials and infrastructure (Kumar and Imam 2013), also plays a significant role in affecting the health and quality of life (QOL) of people. Air pollution is recognized as the largest environmental risk to health and leading contributor to burden of disease worldwide (WHO 2014). Exposure to indoor and ambient air pollution increases incidence of stroke, heart disease, lung cancer, and chronic respiratory diseases and accounts for 7.3 million premature deaths per year (Pope and Dockery 2012, Gumy and Prüss-Üstün 2016). In the U.S., combustion emissions - primarily from fuel and energy production (i.e., power plants and mobile sources) - constitute the largest source of ambient air pollution (Dedoussi and Barrett 2014). But, considering Americans on average spend 90% of their time indoors, warrants further investigation of the infiltration potential of compromised outdoor air into indoor spaces as well as the characterization of internal factors influencing indoor air quality (IAQ).

Pollutant concentrations indoors have the potential to be two to three times larger than outdoor concentrations (Nazaroff 2008, Massolo, Rehwagen et al. 2010); indoor air also contributes to over 90% of human exposure to pollution and varies across both space and time (Ott, Steinemann et al. 2006). The United States Environmental Protection Agency's Consolidated Human Activity Database (CHAD) condensed findings from several studies and report over the course of a day, Americans spend 17 hours at home and 7 hours in between non-residential commutes and work (Hodas, Loh et al. 2016). In office and work environments' printers and copiers off-gas volatile organic compounds (VOCs) and emit particulate matter (PM) (He, Morawska et al. 2007), while the IAQ in residences is more impacted by various cooking methods and source fuels (i.e., gas, electric) (Jetter and Kariher 2009). Additionally, air exchange rates - the volume of air added or removed from a space - are much lower in residential buildings compared to non-residential structures. Non-residential structures have more complex systems that supply fresh air to a much larger volume of space, meaning a more constant dilution of indoor air throughout the space. Residential buildings on the other hand, utilize much smaller heating, ventilating, and air conditioning (HVAC) units, and in some cases, substitute centralized air conditioning and heating for window air conditioning units and convection radiators, thus limiting the supply and volume of fresh (filtered) air into indoor spaces. Exposure to indoor air pollution is unique across both residential and office environments, not only as a direct function of time spent, but also as a result of the myriad of factors that influence IAQ.

1.2 Theme and Communities

The over-arching theme of this work is to explore indoor air quality in two communities and two building types: an energy conservation district (ECD) focusing on commercial buildings and a marginalized community focusing on residential buildings.

The first community, the Pittsburgh 2030 Districts, consists of 102 property partners (506 buildings) working to achieve a 50% reduction in water use, energy consumption, and carbon emissions by the year 2030. 2030 Districts are emerging as a new model for urban environmental sustainability as Pittsburgh leads the nineteen other energy ECD nationwide (GBA 2015). Changes made to improve energy consumption, such as air-sealing and natural ventilation, can also negatively impact indoor air quality (Fazli and Stephens 2018); therefore, synergies should be explored in tandem. Unique to the Pittsburgh 2030 Districts is also the development of an indoor air quality metric to implement in existing buildings to benchmark improvements in indoor air quality over time.

The second community consists of a group of disadvantaged neighborhoods situated in the East End of Pittsburgh. The East End of Pittsburgh has been identified as an environmental justice community that struggles with issues of deteriorating infrastructure, community disinvestment, high traffic density, and an inverse racial make-up when compared to the rest of the city (US CENSUS 2013). Environmental justice communities face multiple social (i.e., support and resources) and environmental (i.e., air and noise pollution) stressors which have a cumulative impact on quality of life, and create barriers that limit access to these communities (Corburn 2005). Accessibility barriers, fueled by distrust in outside institutions, limits the reach of academic research and the implementation of long-term interventions. Through residential indoor air quality assessments, local ambient air quality monitoring and a quality of life (QOL) survey, this research also seeks to determine social and environmental factors that contribute to quality of life in environmental justice communities, while promoting environmental consciousness through citizen science and community-based research.

Although the test beds represent two different populations, this research overall seeks to quantify emissions and understand air quality in environments where people spend the majority of their time (residence and offices). The research will also build capacity in communities to partner with academia, while informing the translation of air sensor data to advance individual and broader policy decisions.

1.3 Aims, Goals, and Objectives

This work aims to provide data-driven and evidence-based recommendations that enable communities to consider IAQ monitoring and evaluations as a priority in the commercial and residential sectors.

Related to the ECD, this research informs the broader 2030 Districts in North America, considering Pittsburgh is the largest of the 19 established ECDs by committed square feet, and the first to implement an IAQ component. **The goal of this research was to develop and implement a scalable *IAQ framework* to investigate air quality in buildings.** The protocol was developed to be replicable by other ECDs. The *IAQ framework* has several elements – first, seasonal indoor air quality monitoring was conducted in eight pilot buildings. Second, concise and practical recommendations were determined to improve IAQ based on the results from the pilot. Third, a *checklist* was created that categorized IAQ management and recommendations into tangible action items. Last, the checklist was formalized into a *survey* instrument to establish a baseline among

506 participating buildings to evaluate the state of current measures taken to address indoor air pollution within the ECD. With this knowledge, the Green Building Alliance (GBA) – the organizers of the ECD – are able to work close with buildings that underperform and raise to an expected standard or above baseline in subsequent years. A key outcome of this work was developing an actionable IAQ program for ECDs.

Related to the marginalized/environmental justice community, there are two goals. **The first goal was to develop a neighborhood initiative that enhances the capacity of underserved communities to address environmental justice issues through citizen science and community-based research. The second goal of this research was to explore the quantitative relationship and potential impacts of IAQ on QOL.** The relationship between IAQ and QOL has been neglected in the literature, due to a focus on physical health and in part due to accessibility barriers. This research fills a gap in the literature by investigating the effects of air pollution through the evaluation of built environment conditions and several QOL aspects (i.e., socio-economic development, human development, sustainability, and personal utility).

The following research questions were explored to address the research goals:

Energy conservation district with commercial buildings

1. What are the primary sources of indoor air emissions of the pilot buildings in the ECD?
2. Given the identified sources and building types, how can this information be scaled across the entire ECD and measure IAQ improvements over time?

Environmental justice community with residential buildings

3. How can community-based research be used to advanced environmental justice issues in underserved communities?
4. What sociodemographic variables correspond to the magnitude of internal and external emission sources, in and near homes?
5. Does the IAQ in residential structures influence the QOL of residents, and if so to what extent?

To achieve the research goals and address the aforementioned research questions, the following objectives are:

Energy conservation district with commercial buildings

A. Conduct seasonal indoor air quality assessments in pilot commercial buildings and provide data-driven recommendations to the pilot buildings to improve IAQ.
B. Synthesize the IAQ results with existing rating systems to develop an *IAQ survey* to benchmark and then monitor progress over time.

Environmental justice community with residential buildings

C. Using a TOC approach, develop a neighborhood initiative that enhances the capacity of underserved communities to address environmental justice issues through citizen science and community-based research.
D. Collect indoor and ambient air quality data in targeted environmental justice communities.

E. Investigate the independent and interaction effect of indoor and outdoor air quality on quality of life.

1.4 Broader Impacts

This dissertation presents an interdisciplinary effort between university faculty and students, community liaisons, and local organizations to advance the translation of air quality data, and build competency in communities. A key outcome of this research was to develop an actionable IAQ program for energy and climate conservation districts, such as the emerging 2030 Districts. Through the involvement with the GBA, this research has far reaching impacts to inform the 2030 Districts in North American, considering Pittsburgh is the largest of the 19 established ECDs by committed square feet and the first to implement an IAQ component. The second portion of this research identifies shortcomings of science participation in low-income and minority communities. Working closely with community-based organizations (CBO) helped to bridge gaps and leverage interconnection between academia and the public's understanding of environmental stewardship. Collaboration with CBO's has also helped to establish long-term partnerships whereby future doctoral students can gain unique hands-on learning experiences as well as skills regarding leadership and communication. Last, the alignment of large institutions with communities has implications for regulatory action, and land-use and policy decisions that enhance sustainable and healthy communities. Overall this research demonstrates the importance of transferring engineering and technical knowledge from academia to the broader public and professional communities.

1.5 Intellectual Merit

This research addresses needs within the building science and sustainable engineering communities by characterizing a range of exposure scenarios across various building archetypes (i.e., historic, conventional and green buildings), including diverse indoor environments (i.e., residence, commercial office) and localized ambient air quality data.

ECD with commercial buildings: The sampling campaign and data management strategies offer improvements to sampling methodologies by evaluating the variability of pollutant concentrations with respect to intrazonal flows within buildings and the development of a standardized indoor air quality protocol for ECDs. Currently there are no consistent metrics or guidelines for assessing IAQ in commercial buildings.

Environmental justice community with residential buildings: The research approach expands beyond the traditional norms of community-placed research through the development of a TOC model, which utilizes the community's ecology (input) in the research process. The field of environmental justice benefits from this work because it establishes a replicable framework that addresses air quality concerns in vulnerable communities. Compared to the research devoted to the physical health effects of air pollution, studies on psychological consequences and quality of life are less represented; this research aims to fill the gap in the literature.

1.6 Dissertation Organization

This thesis begins with general background information related to indoor and ambient air quality, environmental injustice, and QOL in communities. Chapter 3 addresses Objectives A and B, which are to develop and implement an actionable IAQ program and framework for Energy Conservation Districts (ECDs). Chapter 4 addresses Objective C, which is to develop and implement an environmental justice framework to create environmental consciousness in underserved communities. This work was published in *Sustainable Cities and Societies* (Rickenbacker, Brown et al. 2019).Chapter 5 addresses Objectives D and E, collecting indoor and ambient air quality data in targeted communities to investigate the effect of air pollution on quality of life. Conclusions of the overall results and recommendations for future work are discussed in Chapter 6.

2.0 Background and Literature Review

Amid substantial research on global warming and the effect on public health, addressing the impacts of climate change on indoor environments has warranted less public attention. Recent research has shown that concentrations of indoor pollutants (i.e., gases and particles) often exceed health or safety standards and are linked to climate change impacts (Logue, McKone et al. 2011, Fazli and Stephens 2018). Buildings that were designed to operate under current climate conditions may not function well under future scenarios which affect the health and wellbeing of those who live and work in these spaces (Institute of Medicine 2011). Given that people are the most valuable assets in buildings reaffirms these three multidisciplinary topics (air pollution, climate change, and civil engineering structures) as growing research priorities (Kumar and Imam 2013, Steinemann, Wargocki et al. 2017).

2.1 Ambient Air Quality

More recently known for strengths in education and medicine, Pittsburgh initially established precedence as a technological pioneer and economic power during the industrial revolution. Still, in present days, the unintended consequences of progress, in addition to the historic reliance on fossil fuels, loom heavy as the region struggles to meet federal air quality standards for criteria air pollutants (i.e., particulate matter and ozone). The American Lung Association (ALA) (2019) ranks Pittsburgh 7th highest for annual particle pollution out of 184 metropolitan areas. Legacy and current point sources (i.e., power plants, coke, and steel industries) dominate regional emissions inventories. Residents in Greater Pittsburgh (i.e., Allegheny County) are at twice the cancer risk of surrounding counties (US EPA 2005, Tunno, Shields et al. 2015, Rickenbacker, Collinge et al. 2016). U.S. industrial and federal facilities are required by the United States Environmental Protection Agency (USEPA) to report toxic chemical releases annually to the Toxic Release Inventory (TRI) database. These TRI facilities emit 2.1 million pounds of air emissions in Allegheny County; neighboring Ohio has a total of 1,369 TRI facilities and is tied for first in the nation, producing 738.2 million pounds of on-site hazardous air pollutants (HAPS) (US EPA 2015). These factors along with mobile sources significantly impact the urban center of the city and residents that reside in some of the more disadvantaged neighborhoods along the Monongahela and Allegheny River Valleys.

2.2 Indoor Air Quality (IAQ)

2.2.1 Commercial Building

Sick building syndrome (SBS) has been the primary driver for early research on indoor air quality in commercial buildings. SBS can be described as situations in which building occupants experience various health symptoms attributed to time spent in buildings (Wargocki, Wyon et al. 1999, Bako-Biro, Wargocki et al. 2004, Fang, Wyon et al. 2004, Seppanen, Fisk et al. 2006), which impacts employee performance and organizational efficiency. Twenty-three percent of U.S. office workers (15 million workers) have reported suffering from at least two Sick Building Syndrome symptoms (Brightman, Womble et al. 1997, Fisk 2000). The most common cited SBS symptoms include itchy and burning eyes, respiratory irritation, headaches, and mental fatigue (Fisk and Rosenfeld 1997). A 1993 study conducted by Nunes et al. (1993) found that workers who reported any SBS symptoms had a 30% higher error rate in a computerized neurobehavioral test. Similarly, Wargocki (1999) and Largercrantz et al. (2000) performed an evaluation of performance outcomes in work environments that contain indoor pollutant sources (i.e., aged carpet). A meta-analysis of the two studies reported a 6.5% decrease in typing performance and a 18% higher error rate from exposure to indoor air pollution (Wargocki, Wyon et al. 2002). In conclusion, the association between indoor air pollution and SBS has been well documented. As SBS is also connected to operational cost (employee salaries and health insurance) in commercial buildings, improvements in IAQ should be made to drive indirect financial gains while fundamentally advancing employee performance.

The World Health Organization (WHO), USEPA, Occupational Safety and Health Administration (OSHA), and National Institute for Occupational Safety and Health (NIOSH) set target thresholds for health and comfort effects from outdoor and indoor air pollutants. But while several national and international organizations offer standards and guidelines for pollutant values, there are no consistent metrics or methods for assessing and monitoring the IAQ (Steinemann, Wargocki et al. 2017). Furthermore, to what extent building stakeholders (i.e., owners, tenants, and designers) understand the impacts of improved IAQ is still unknown (Hamilton, Rackes et al. 2016). In fact, a recent survey of 112 industry stakeholders across the U.S. found that commercial building owners do not link improved IAQ with increased productivity (55%), absenteeism (77%), and/or health benefits (61%). The literature on indoor air quality in large and mixed-used buildings (i.e., commercial, institutional) is also much less complete, yet it is these types of buildings that are pursuing substantial energy conservation measures. With a global economic shift to more office-oriented service and knowledge-based sectors (Haynes 2008, Al Horr, Arif et al. 2016), there is a need for a replicable framework that monitors and assesses IAQ in a wide range of buildings (Ng, Musser et al. 2012, Persily and Emmerich 2012, Andargie and Azar 2019), so that the benefits of improved IAQ can be fully achieved.

2.2.2 Residential Buildings

A number of environmental factors have been related to poor IAQ and associated health risks in the residential sector (Clougherty, Levy et al. 2006, Logue, Price et al. 2012). Some of the most cited environmental exposures include mold and environmental tobacco smoke (ETS) (Klepeis, Nelson et al. 2001). A systematic review of sixteen cohort and case-control epidemiological studies determined the presence of mold as a causal agent related to a 50% increase in risk of asthma development (Quansah, Jaakkola et al. 2012). The Institute of Medicine also found sufficient evidence of a relationship between asthma exacerbations and exposure to household contaminants, such as dust mites, pet dander, and cock roach/rodent antigen (Institute of Medicine (US) Committee on the Assessment of Asthma and Indoor Air 2000). Similarly, exposure to ETS indoors has been linked to respiratory illness in infants and further development of chronic respiratory symptoms in adolescents (Berglund 1992, Flouris, Vardavas et al. 2010). In fact, Walker et al (2004) observed a change in breathing and sensory impacts when exposed to ETS-respirable suspended particles at as low as 58 $\mu g/m^3$. The contribution of indoor air pollution to upper respiratory and cardiovascular disease, as well as various cancers, has led to a recent focus on dose response relationships and field verified exposure assessments in the residential sector. Although environmental factors are known and present within homes, a number of socioeconomic (i.e., poverty) and sociobehavioral (i.e., anxiety) factors also contribute to increased susceptibility at the individual and neighborhood-scale (Kattan, Mitchell et al. 1997, Clougherty, Levy et al. 2006, Payne-Sturges, Korfmacher et al. 2015).

The major point is that psychological stressors (i.e., fear of crime, racial discrimination) make individuals more vulnerable to illness through weakening of the body's immune responses (Williams 1999, Krieger and Higgins 2002, Gee and Payne-Sturges 2004). Additionally, air pollution is viewed as an environmental stressor and can worsen the effects of stress on emotional and physical changes in individuals. Cohen et al. (1991) conducted an investigation to examine whether psychological stress suppresses resistance to infection; 394 healthy subjects completed questionnaires to assess levels of stress and were injected with one of five respiratory viruses. In conclusion, a relationship was observed between psychological stress and an increased risk of respiratory illness. In the context of air pollution, Zhang et al. (2017) and Bullinger (1989) evaluated the potential effects of ambient air on mental health and well-being. Zhang et al. (2017) found that air pollution exposure reduces hedonic happiness and increases depression. These results suggest a plausible association between air pollution and quality of life. Nevertheless, compared to the research devoted to the physical health effects of air pollution, studies on psychological consequences and quality of life are less represented.

2.3 Environmental Justice

Since the early 1980s, research has shown that low-income communities and ethnic minorities are imposed with a higher burden of environmental contamination from industry and consumer practices (Lave 1970, Bullard 1976, US EPA 2005, Mohai, Pellow et al. 2009). The dumping of 120 million pounds of soil contaminated with polychlorinated biphenyls (PCBs) in Warren County, North Carolina - the county with the highest proportion of African Americans in the state - sparked a social movement that is most known for the rise of interest in environmental justice research (Bullard 1990). More recent national events, like the water crisis in Flint, Michigan, or the Dakota Access Pipeline protest, have caught the attention of main stream media, yet cases of environmental prejudice affect low-income and minority communities every day.

Historically, industrial development has flourished in areas where land is inexpensive and controversy is likely to be avoided. Communities more prone to dispute such actions are those with higher educational attainment and financial resources (Bullard 2004), resulting in minority neighborhoods being targeted and disproportionately impacted by the environmental and health burdens associated with the location of polluting industries. New York City (NYC) presents a prime example of this case. Maantay (2001) examined the increase and decrease of industrial zone size and location for 4-decades in NYC to compare the change in population and demographic characteristics overtime. Maantay found that between 1961 to 1998 neighborhoods in NYC were rezoned to increase manufacturing industries in areas with higher minority populations (Maantay 2001). Similarly, Morello-Frosch and Jesdale (2005) performed a risk assessment of 309 metropolitan areas encompassing 79% of the U.S. population, and concluded that racial/ethnic segregation affects the level of pollutant burden. In summary, industrial land use patterns and ambient air pollution exposure show strong evidence for persistence in the growth of environmental health disparities across socioeconomic strata.

Ethnic minorities have also been forced to migrate to neighborhoods with some of the highest incidents of urban poverty which correspond to the housing conditions in which they reside. Poorly maintained housing may lead to variety of health-related problems, including risk of injury, and illness due to presence of disease vectors (Bashir 2002, Krieger and Higgins 2002, Gee and Payne-Sturges 2004). Substandard housing is also susceptible to the penetration of air pollution from outdoors (increasing road traffic dust generation and diesel particulates), as well as frequent outbreaks of mold growth and pest infestation (Chew, Carlton et al. 2006, Flores, Bridon et al. 2009). Without financial resources to support proper maintenance and repairs, aged infrastructure (e.g., homes and roads) becomes subject to poor environmental quality and places a cumulative burden on residents. These conditions connect the built-environment to health and quality of life in communities.

While the literature documents known barriers to research participation in low-income and minority communities, there are still very few evidence-based strategies that have successfully addressed gaps regarding recruitment and retention (Ceasar, Peters-Lawrence et al. 2017). Research shows that minorities may believe that research results could be used to negatively impact their communities (George, Duran et al. 2014). Furthermore, researchers have lacked the economic and cultural background of the communities they wish to engage, leading to a disconnect and mistrust in academic institutions (Scharff, Mathews et al. 2010). The field of environmental justice would benefit from the establishment of a replicable framework that expands beyond the traditional norms of community-placed research and utilizes the community's ecology (knowledge) in every stage of the research process.

3.0 Indoor Air Quality in Energy Conservation Districts

This chapter focuses on the assessment of indoor and ambient air quality in the commercial sector and fulfills ***Objective A*** through ***B***. Appendix A provides supporting information to this chapter.

3.1 Introduction

While progress has been made to address the impacts of climate change, most building industry discussions center around building performance and efficiency alone. Newly emerging conservation initiatives like the Architecture 2030 Challenge (2018), Climate Mayors (2018), the National Association of Conservation Districts (NACD) (2018), and the Paris Climate Agreement (United Nations 2015), have all taken a community approach to address the cumulative effects of cities on climate change and public health (i.e., resource use, water consumption, traffic emissions, etc.). To date, close to half of the world's population lives in urban centers; and as this number is expected to increase (McGranahan and Satterthwaite 2003, Pincetl, Chester et al. 2014), the demand to develop district-scale solutions is immediate.

Pittsburgh, Pennsylvania, USA, is one of twenty-two ECDs in the U.S. participating in the 2030 Districts Network, implementing Architecture 2030's 2030 Challenge goals. The 2030 District Challenge strives to "transform the built environment from a major contributor of greenhouse gas emissions to a central solution to the climate crisis (Architecture 2030 2018)." Architecture 2030's call to action has prompted aggressive goals to be set by cities to decrease energy consumption, water use, and carbon emissions from transportation 50% by the year 2030. The Pittsburgh 2030 District is a program convened by the GBA, the local chapter of the US Green Building Council (USGBC), and a Pittsburgh nonprofit that advances innovation in the built environment by empowering people to create environmentally, economically, and socially vibrant places. Pittsburgh is a 2030 District leader with 518 buildings and 83 million square feet of commercial, government, multi-family residential, and nonprofit real-estate actively participating at the time of this writing **(**Figure 1**).**

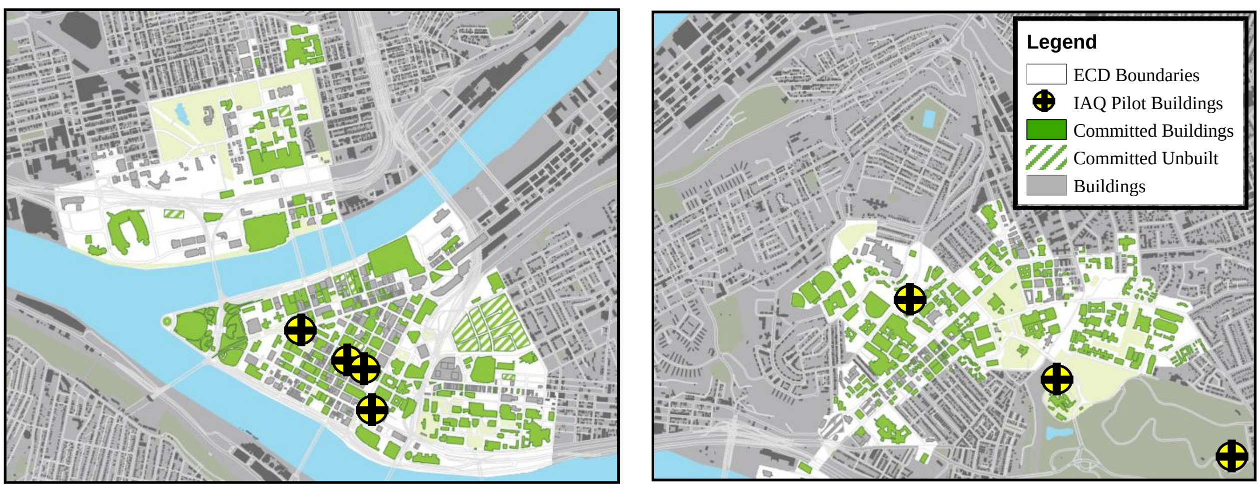

Figure 1. The Pittsburgh 2030 District's geographical boundaries - Pittsburgh 2030 Districts committed properties, and IAQ pilot buildings; image credit Green Building Alliance (GBA).

3.2 Materials and Methods

3.2.1 Indoor Air Quality Framework

In 1994, the BASE study was conducted in which IAQ assessments were performed in 100 randomly selected public and commercial offices in ten different climatic regions across the United States (Womble, Girman et al. 1995, US EPA 2003). The IAQ sampling method and measurement parameters from the BASE study was used in this research, but adjustments were made specific to the work in the Pittsburgh 2030 District. Between 2015 and 2017, indoor air quality assessments were conducted in eight pilot buildings. Selection of each pilot building was based on several parameters including age built, geographical location, height, mechanical equipment, and data availability and access; however, it was also dictated by recruiting success. The detailed IAQ sampling procedure included the following steps: (1) soliciting volunteer buildings, (2) an initial building and site visit, (3) selection of specific study areas and monitoring locations, (4) field monitoring, and (5) data synthesis (Figure 2a).

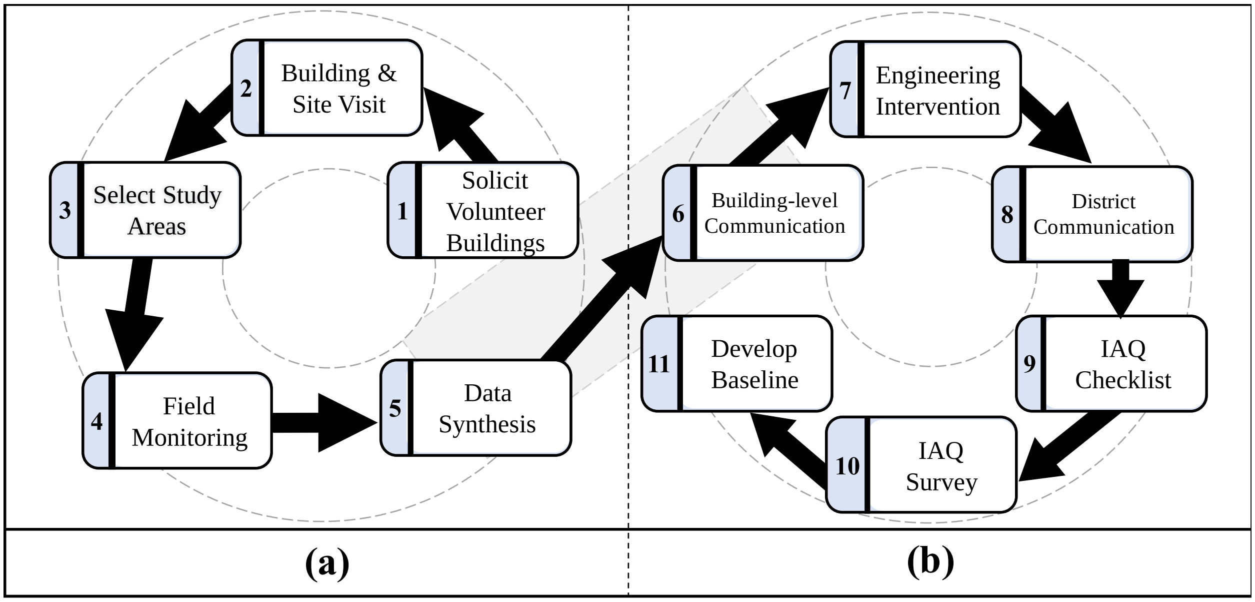

Figure 2. Eleven steps of indoor air quality framework - Indoor air quality framework broken down into two parts, the a) detailed sampling procedures and b) feedback and remediation.

The literature on risk governance and science interpretation define a dire need for two-way communication between researchers and the broader public (Renn 2008, Asselt and Renn 2011, Hubbell, Kaufman et al. 2018). To this point, the second component of the *IAQ framework* was designed to help building professionals understand indoor air quality science and translate the results into actionable remediation procedures (Figure 2b). For the next step, (6), the results were first individually presented to facility managers and staff at the eight participating buildings. Based on the raw data summaries, step (7), an engineering intervention was conducted within one of the buildings that 'underperformed' and the pre- and post- findings were communicated to the entire ECD with recommendations to address a broad range of IAQ improvements in step (8). The recommendations were condensed into step (9) for an *IAQ checklist* that categorized IAQ management into tangible action items. The checklist was later formalized in step (10) into a survey instrument or *IAQ Survey* to identify the state of current measures taken to address indoor air pollution and to establish step 11 and an aggregated baseline for over 500 participating buildings. With this knowledge, GBA is able to work closely with underperforming buildings and improve their IAQ in subsequent years. A detailed explanation of each step of the *IAQ framework* can be found in the subsequent sections.

3.2.2 Methodology

3.2.2.1 *Step 1: Solicit Volunteer Buildings*

The Pittsburgh 2030 District represent 74.3% of the total commercial, multi-family residential, and nonprofit real estate square footage within Pittsburgh urban core (GBA 2015). With assistance from GBA, researchers solicited volunteer property partners to participate in the first phase pilot. Commercial floor space within the ECD that is privately owned (owner- and non-owner occupied) amounts to 77% of the total square footage, while the other 23% is owned by governmental entities (Apte, Buchanan et al. 2008). This sector diversity in building ownership, positions GBA as an essential resource in leveraging interconnectedness and lasting partnerships across various ownership groups in the ECD.

The eight buildings within this research were constructed between 1917 and 2016. Researchers tested throughout the ECD neighborhoods and an adjacent neighborhood where an additional volunteering property was tested. The experimental buildings were divided into three building archetypes: historic, conventional, and green. Each building (or floors within the buildings) consisted of a typical office layout with open-office areas, cubicles, private meeting rooms, and hallways; housed 20 to 200 employees daily; had operating hours spanning from as early as 7:00 AM to as late as 7:00 PM, Monday through Saturday; and ranged from 3 to 34 stories in height.

The historic office buildings were constructed between 1917 and 1931 and were originally designed with primarily open-plan spaces. They have each seen many renovations over the years; however, none received a uniform upgrade of the entire building and very few renovations were well-documented. Operable windows and window air-conditioning units provide comfort cooling in the warmer months, while radiant steam and convection heaters offer warmth during the colder seasons. Occupants' work ranged from clerical activities to municipal and administrative tasks, leading to additions of partition walls and cubicle-style office furniture, which eventually led to an exceedance of the design occupant load and created overcrowded work environments. Many of the spaces within these buildings feature vintage file rooms, aged floor carpets, and scattered photocopiers and printers that may act as source points and sinks for indoor air pollutants (e.g. particles) that have settled on interior surfaces over the buildings' life.

Within this research, the distinguishing factors that separate historic buildings from the conventional and green buildings (constructed from 1970 to 2016) are the year each structure was built and the resulting forced air supply provided to the indoor environments through mechanical ventilation. The HVAC systems for the conventional and green buildings supply filtered and conditioned outside and recirculated air throughout entire buildings; roof air-handling units are equipped with standard air filters rated between 20 – 35% dust spot efficiency. Participating green buildings were owned by 501(c)(3) tax-exempt organizations and were awarded some of the highest international green building certifications from the Living Building Challenge, Leadership in Energy and Environmental Design (LEED), and the International WELL Building Institute. Both green facilities are net zero energy systems that house on-site photovoltaic solar panels and wind turbines, contain high performance insulation and low-e windows, and incorporate underground geothermal wells working in conjunction with rooftop energy recovery units. Both green buildings also operate dual-purpose natural ventilation systems that work in tandem with mechanical ventilation to optimize energy consumption. The only changes made in the buildings during the sampling period were related to long-term intervention strategies used to assess the effectiveness of pre- and post- evaluations; no major services (renovations) or relevant exposure events occurred over the monitoring period.

Table 1 provides the descriptive characteristics of the 8 pilot buildings. The buildings are identified with a unique code where the first two letters represent the archetype [i.e., historic building (HB), conventional building (CB), green building (GB)] and the number is a differentiation for each building in the pilot.

Table 1. Data regarding the sampling month and year age, size, envelope, research location, occupancy, and ventilation type.

Build -ing ID	Sampling Period (month, year)	Year Built	Building Gross Floor Area (ft^2)	Building Envelope Material	Number of Floors	IAQ Sample Floors	No. of Occupants on Sample Floors	Venti- lation Type
HB1	Dec-14	1931	235,302	Masonry	7	1, 5, 6	90	None
HB2	Mar-15	1917	152,350	Masonry	10	1, 3, 6	80	None
HB3	Nov-15	1917	152,350	Masonry	10	1, M, 2	77	None
CB1	Nov-15	1971	419,000	Concrete	15	B, G, 2, 3, 7	200	VAV
CB2	Nov-15	1902 (renovated 2009)	26,848	Masonry	3	1, 2	50	VAV
CB3	Feb-15	1975	544,000	Glass	34	19	65	VAV
GB1	Oct-14	2013	24,350	Wood and Metal	2	1, 2	25	Hybrid
GB2	Feb-17	2016	16,440	Wood and Metal	3	1, 2	25	Hybrid

*Variable Air Volume (VAV); Dual-purpose natural ventilation systems (Hybrid); No mechanical ventilation (none)

3.2.2.2 *Step 2: Building and Site Visit*

During an initial site visit, researchers met with building engineers and maintenance staff to establish a working relationship and to collect available floor plans and mechanical drawings. The drawings were used to examine the test area and understand the functional capabilities of the existing HVAC system. After the site visit, the study areas were characterized, identifying potential IAQ pollutant source points, labeling outdoor hotspots, and recording any recent building upgrades and renovations.

3.2.2.3 ***Step 3: Select Study Area***

Predefined locations were selected such that response variables are measurable. An essential component was identifying source points throughout the building that may influence the occupant's personal exposure, near supply and return vents, windows, storage closets and kitchenettes, printers and/or copiers, and high-traffic areas. Locations were at least one-half (0.5) meter from these internal sources (US EPA 2003).

3.2.2.4 ***Step 4: Field Monitoring***

Indoor locations were measured in the morning and afternoon in ten-minute intervals. A three-to-five-minute period between locations was also required for sampling instrument stability. On each subsequent testing day, the testing procedures were repeated, but testing locations were randomized with respect to time to minimize any nuisance factors that may influence testing variables. For example, the morning and evening rush hours could have a significant impact on the level of the response variables due to the increase of traffic-related air emissions that enter buildings through leaky envelopes, passive ventilation (open windows), and/or mechanical systems.

Data was also collected outdoors to capture ambient environmental parameters and coupled with meteorological and air data from the Pittsburgh National Weather Service station and Allegheny County Health Department stationary monitors. Outdoor monitoring locations were near the fresh air intake of the primary air handling unit (AHU) (if present) to be representative of the ambient air that permeates interior air vents. The AHU location was often on the roof or at ground level.

Air monitoring was conducted over the course of three days during the 8-hour work schedule. To further assess variations in pollutant concentration throughout the workday, continuous samples were collected overnight. Continuous overnight readings when employees were absent allowed for comparisons to be made in order to also understand the impact occupancy (i.e., resuspension) had on IAQ.

The research team deployed the Graywolf 3016 Handheld airborne particle counter that measures particulate matter in six size channels, 0.5 µm, 1 µm, 2.5 µm, 5 µm, 10 µm, and > 10 µm, using a flow rate of 0.1 cubic feet per meter (CFM). The Graywolf AdvancedSense Probe was used to capture measurements of total volatile organic compounds (TVOCs), carbon dioxide (CO2), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), relative humidity (RH), ozone (O3), and temperature (T). The AdvancedSense Probe is a WiFi enabled 1 lb 8 oz rugged polycarbonate plastic smart meter, simultaneously connected to a DirectSense electrochemical gas sensor probe, that detects environmental exposure levels in real-time (GrayWolf Sensing Solutions 2018). Additionally, the research team utilized a Graywolf FM-801 formaldehyde (HCHO) meter to measure HCHO at readings as low as 5 ppb (GrayWolf Sensing Solutions 2018). Black carbon (BC) samples are collected using AethLab's Micro-aethalometer. Real-time analysis is conducted by measuring the rate of change in absorption of transmitted light due to the continuous collection of aerosol deposits on Teflon-coated borosilicate glass fiber filter strips (Ng, Musser et al. 2012). Dylos particle counters are also used to detect the number of fine (0.5 μm to 2.5 μm) and coarse (> 2.5 μm) particles in specific locations over the sampling period. Dylos particle counters are inexpensive and lightweight, so are used as roamers to expand the coverage area to intake vents, streetscape, and simultaneous monitoring of multiple floors at once. Table 12 in Appendix A details the size range and instrumental resolution for the various devices. Each sensor was attached to a mobile cart (Appendix A, Figure 19) and setup at approximately 1.5 m height, as recommended by the USEPA BASE study (Womble, Girman et al. 1995, US EPA 2003). Finally, each sensor was sent to the manufacturer on an annual basis and calibrated according to National Institute of Standards and Technology (NIST) standards.

3.2.2.5 *Step 5: Data Synthesis*

Once the sampling was complete, data was synthesized for further analysis. Data sets were analyzed in Microsoft Excel and Minitab18 software programs (2018). In-depth data management and analysis was essential to evaluate and ensure the validity and completeness of the IAQ assessment. Indoor air quality and ambient pollutant concentrations were compared to acceptable levels published in ANSI/ASHRAE 62.2016 Ventilation for Acceptable Indoor Air Quality (2016b), ANSI/ASHRAE 55.2016 Thermal Environmental Conditions for Human Occupancy (2016a), and the USEPA's National Ambient Air Quality Standards (NAAQS) (2016); some of these standards are intended to provide comfort, minimize adverse health effects, and to respect the imperative of sustainable buildings. In addition to summary statistics, inhalation exposure at each building was investigated. Using Equation 3-1, inhalation dose is expressed as mass of contaminant per unit of body weight overtime:

$$LADD = \frac{C_{air} \times InhR \times ET \times EF \times ED}{BW \times LT}$$

(3-1)

In Equation 3-1, *LADD* is the lifetime average daily dose from air (μg/kg-day), C_{air} is the concentration of contaminant in air (μg/m^3), *InhR* is the inhalation rate (m^3/hour), *ET* is the exposure time (hours/day), *EF* is the exposure frequency (days/year), *ED* is the exposure duration, and *BW* is body weight (kg), and *LT* is life time (converted to days) (US EPA 1992).

3.2.2.6 *Step 6: Building-Level Communication*

A report was prepared along with a follow-up meeting and presentation with the building owner and operations site personnel to disseminate the results and outline tangible recommendations.

3.2.2.7 *Step 7: Engineering Intervention*

Analysis of variance (ANOVA) was used to evaluate pollutant levels (1) across buildings and (2) "hotspots" within individual buildings among floors and microenvironments. Comparisons across the eight buildings were then performed using Fisher's least significance difference (LSD) procedure. Based on the overall findings, one building of focus was further investigated over a two-year period. The research team provided concise and practical recommendations to the building managers who later performed an intervention. In the building that performed the worse, follow-up seasonal testing was performed during the concurrent non-heating months and a third-round of monitoring during the subsequent heating season, for a total of three sampling campaigns.

For comparability, a second round of seasonal samples was also collected in two other pilot buildings to better represent the three different archetypes (historic, conventional, green), meaning a total of three buildings were assessed in Winter 2014, Summer 2015, and Winter 2015. To distinguish between occupant-generated emission indoors and the infiltration dynamics of outdoor sources (e.g., a combustion emission from the nearby roadway or industrial source), indoor-to-outdoor pollutant ratios and black carbon measurements were also assessed at the three buildings.

3.2.2.8 *Step 8: District Communication*

Performance successes were reported quarterly to an audience of building owners, employees, and decision makers, with GBA serving as a pivotal role-player and planning nexus for direct research involvement with the ECD (Figure 3). As a result, co-generation of knowledge by researchers and building stakeholders over months of data collection and results interpretation led to change in local conditions, along with new knowledge. Literature documents this need for two-way communication between science experts and community members to successfully interpret scientific data and translate the results into risk governance (Asselt and Renn 2011, Hubbell, Kaufman et al. 2018). The method of two-way communication was rooted in TOC concepts (Connell, Kubisch et al. 1995, Rimer and Glanz 2005, Connell and Kubisch 2013). TOC makes explicit the need for a radical change at a systems scale that must be married with social change (social sciences) to advance technical solutions (natural sciences) (Lowe, Whitman et al. 2009, Lowe, Phillipson et al. 2013). Ultimately, the translation of engineering and science to the broader public and professional community offered sound guidance regarding ongoing building O&M, allowing both the long-term technical and communication goals of this effort to be met.

Figure 3. Pittsburgh 2030 District progress report meetings - The translation of engineering and science to the broader public and professional community; image credit Green Building Alliance.

The findings from the monitoring campaign, engineering intervention, and communication of results, informed the development of an *IAQ Checklist* and *Survey*.

3.2.2.9 *Step 9: IAQ Checklist*

For many reasons including time constraints, property owners' liability concerns, and/or inability to financially support the assessments, indoor air quality monitoring could not be conducted in all of the more than 500 properties within the ECD; however, the richness of data from the seasonal monitoring and pre- and post- building intervention in the tested buildings helped to improve the general understanding of IAQ issues that would be scalable across the rest of the ECD. Based on the findings, an *IAQ Checklist* was developed to outline building management guidelines regarding how to address each problem. The *IAQ Checklist* was designed to support property managers by pinpointing tangible action areas that address IAQ specific to this region, while also promoting awareness of air quality concepts and terminology to a somewhat unknowledgeable audience. Each concept in the *IAQ Checklist* was then linked to a suitable section of the most recent version of a third-party, green building rating systems for additional education and resources; the elements of the *IAQ Checklist* can be found in Table 13 of Appendix A.

3.2.2.10 *Step 10: IAQ survey*

In collaboration with GBA, the research team developed the Pittsburgh 2030 District *IAQ Survey* to quantify the current state of IAQ across the ECD. Collaboration on the development of the survey allowed knowledgeable content experts an opportunity to review each question for clarity and relevance side-by-side with project stakeholders, who understand the day-to-day operations of a standard building. The rationale for eliciting feedback was to include succinct and comprehensive questions that were not exhaustive or overly technical. The survey is a self-reporting tool and was completed by building owners and/or property and facility managers. The surveys were distributed online and each question was formulated to address the elements detailed in the *IAQ Checklist*, which again was informed by the data summaries and findings. Few examples are found in the literature that use raw data and public participation (as described herein) to develop and refine questions for a quantitative survey instrument.

3.2.2.11 *Step 11: Develop Baseline*

The survey findings scaled the pilot results by quantifying the current state of measures taken to address IAQ across all buildings in the ECD. The survey results are being used to set future targets toward IAQ improvements among underperforming buildings (those below the 50^{th} percentile). Developing the 2017 baseline was critical to track building upgrades and to measure the impact of these improvements over time. The efficacy of the advocacy work will be further tested by comparing 2017 results to future 2020 responses. Providing data-driven recommendations that encourage private, public, and institutional building owners to make greater financial investments in IAQ is the motivation of this work. The full 26-question *IAQ survey* can be found in Appendix A (page 131).

3.3 Results and Discussion

3.3.1 Summary of Indoor Air Quality Results

The data collected in this research is an important start in offering information on the relation of building characteristics and pollutant scenarios in energy districts. By identifying pollution loads (related to source points and source strengths), the research provided the pilot buildings' staffs with recommendations on O&M of buildings, along with the broader District community. Beyond literature review values, providing building staff with data-driven recommendations can also augment the value of real-time air quality data and effect change in considering local conditions. Over 500,000 seasonal data points were collected over the five-year sampling campaign across eight buildings. Table 2 provides summary statistics for CO_2, TVOCs, T, RH, particle counts, and particle mass measurements at each building during the first round of heating season tests. To reiterate, over the course of three-days (and consistent with BASE study procedures) the presented results are concentrations collected between the hours of 9 AM to 5 PM (8-hour workday when the buildings are occupied) to reflect personal exposure scenarios. The data collected during the first round of testing (Winter 2014 – 2015) was an important step to identify one building as an underperformer and to later work with facility managers there for implementation of interventions and remedial procedures within this space. Additionally, the complete dataset was used to inform each question expressed in the IAQ Survey.

Figure 4 illustrates the yearly risk of exposure to PM associated with time spent in the work environment at each pilot building. Using the 24-hour averaged $PM_{2.5}$ samples at each building, the inhalation dose was estimated using Equation 1. Equation 1 is expressed as mass of contaminant per unit of body weight overtime. Monitoring results are compared to acceptable levels published in the US EPA NAAQ standards; acceptable exposure limits of $PM_{2.5}$ are 35 $\mu g/m^3$ (24-hours) and 150 $\mu g/m^3$ for PM_{10}. The mean indoor concentrations of PM_{10} were 81.35 $\mu g/m^3$, 13.01 $\mu g/m^3$, and 9.36 $\mu g/m^3$ across the historic, conventional, and green archetypes, respectively.

Table 2. Summary statistics, first round of 72-hour heating season results at each building

Building	Indoor environmental parameters										
	TVOC, ppb	CO_2, ppm	Temperature, F	RH, %	0.3 – 0.5 µm, #/ft^3	0.5 – 1.0 µm, #/ft^3	1.0 – 2.5 µm, #/ft^3	2.5 – 5.0 µm, #/ft^3	5.0 – 10.0 µm, #/ft^3	0.3 – 2.5 µm (PM2.5), µg/m^3	0.3 – 10 µm (PM10), µg/m^3
HB1 (n=888)											
Mean	128.43	613.48	74.09	24.16	1133392	78304	13185	7221	1217	26.02	155.95
Min.	98.00	421.00	50.70	15.50	191234	8266	961	133	16	3.06	5.53
Max.	211.00	1062.00	85.50	81.90	2780402	230856	118752	61152	15048	118.12	1509.70
StdDev.	18.72	128.76	4.48	8.61	407567	33500	9326	5518	1328	10.45	129.69
95% CI	(127.20, 129.66)	(605.00, 621.96)	(73.79, 74.38)	(23.59, 24.72)	(1106549, 1160235)	(76098, 80511)	(12571 13799)	(6858, 7584)	(1129, 1304)	(25.33, 26.71)	(147.41, 164.49)
HB2 (n=970)											
Mean	42.77	797.13	78.38	35.21	1116087	111693	19627	7630	1005	11.75	54.15
Min.	1.00	479.00	60.60	26.30	407910	31880	4690	1050	60	4.01	10.25
Max.	511.00	1316.00	83.40	52.70	2976650	539770	108620	26090	4510	50.60	184.52
StdDev.	26.43	107.53	3.90	5.07	471008	77364	13719	3411	686	6.93	26.61
95% CI	(41.11, 44.44)	(790.36, 803.91)	(78.13, 78.62)	(34.89, 35.53)	(1086409, 1145765)	(106818, 116568)	(18763, 20492)	(7415, 7845)	(962, 1049)	(11.31, 12.19)	(52.02, 55.40)
HB3 (n=598)											
Mean	214.74	593.54	73.94	23.57	1352982	86218	10882	3915	531	8.45	27.66
Min.	146.00	420.00	64.90	14.70	415968	22200	2604	708	36	2.97	4.44
Max.	413.00	909.00	78.60	50.20	4277316	324120	41448	20220	4752	29.42	143.72
StdDev.	43.19	95.01	2.87	8.81	890824	68630	8912	3114	596	6.09	21.79
95% CI	(211.27, 218.21)	(585.91, 601.17)	(73.71, 74.17)	(22.86, 24.28)	(1281439, 1424526)	(80706, 91730)	(10167, 11598)	(3665, 4165)	(483, 578)	(7.96, 8.94)	(25.91, 29.41)
CB1 (n=400)											
Mean	0.76	563.15	75.65	30.58	473502	22086	3468	2617	748.7	3.01	26.31
Min.	0.00	355.00	66.50	16.00	98210	3490	510	120	0	0.62	1.29
Max.	22.00	1887.00	81.40	48.40	1589560	81960	16710	14580	5030	11.65	130.10
StdDev.	3.09	186.85	2.00	7.67	340060	17234	3247	2427	779	2.23	24.45
95% CI	(0.46, 1.06)	(544.79, 581.52)	(75.45, 75.85)	(29.83, 31.34)	(440075, 506929)	(20392, 23780)	(3149, 3788)	(2378, 2855)	(672, 825)	(2.79, 3.23)	(23.91, 28.71)

Table 2 (continued)

Building	Indoor environmental parameters										
	TVOC, ppb	CO_2, ppm	Temperature, F	RH, %	0.3 – 0.5 µm, #/ft^3	0.5 – 1.0 µm, #/ft^3	1.0 – 2.5 µm, #/ft^3	2.5 – 5.0 µm, #/ft^3	5.0 – 10.0 µm, #/ft^3	0.3 – 2.5 µm (PM2.5), µg/m^3	0.3 – 10 µm (PM10), µg/m^3
CB2 (n=515)											
Mean	6.60	550.10	78.07	27.55	38041	2661	428	167	31	2.70	12.85
Min.	0.00	420.00	67.10	19.10	21208	1284	206	57	4	1.57	2.00
Max.	377.00	7150.00	80.10	45.60	73154	6291	908	725	130	4.93	46.53
StdDev.	27.09	308.10	1.76	5.74	12433	1151	98	62	18	0.72	5.08
95% CI	(4.25, 8.94)	(523.50, 576.80)	(77.91, 78.22)	(27.06, 28.05)	(36965, 39117)	(2561, 2761)	(420, 437)	(161, 172)	(30, 33)	(2.64, 2.77)	(12.41, 13.29)
CB3 (n=430)											
Mean	35.85	722.11	73.40	9.23	132697	9526	2375	2299	397	1.16	14.39
Min.	0.00	547.00	51.30	7.10	45312	3155	958	805	185	0.43	5.95
Max.	1244.00	1009.00	77.60	12.30	425495	32200	7614	7476	1578	3.33	51.88
StdDev.	85.33	63.12	1.74	1.36	114386	8724	1329	877	160	0.82	5.78
95% CI	(27.76, 43.93)	(716.13, 728.10)	(73.24, 73.57)	(9.10, 9.35)	(121854, 143539)	(8699, 10353)	(2249, 25001)	(2216, 2382)	(381, 412)	(1.08, 1.24)	(13.84, 14.94)
GB1 (n=958)											
Mean	141.04	489.74	76.65	38.03	33954	942	140	63	14	1.56	4.74
Min.	117.00	372.00	73.30	32.80	3580	213	53	15	3	0.27	1.60
Max.	191.00	619.00	80.00	41.10	233588	6631	848	349	47	10.66	26.70
StdDev.	14.46	44.93	1.85	2.31	43988	1183	146	62	9	1.96	4.75
95% CI	(140.12, 141.95)	(486.89, 492.58)	(76.54, 76.77)	(37.88, 38.18)	(31165, 36743)	(867, 1017)	(131, 149)	(59, 66)	(13, 14)	(1.44, 1.69)	(4.44, 5.04)
GB2 (n=490)											
Mean	40.76	451.02	68.251	23.19	15454	1588.6	536.8	403	74	2.07	25.75
Min.	0.00	316.00	42.90	15.30	5962	548	110	49	2	0.60	2.54
Max.	130.00	788.00	79.70	61.50	61107	4402	1987	1978	431	6.36	133.96
StdDev.	22.92	80.42	5.91	6.65	7244	812.4	441.4	382	93	1.30	27.70
95% CI	(38.73, 42.80)	(443.89, 458.16)	(67.73, 68.78)	(22.60, 23.78)	(14811, 16097)	(1517, 1661)	(498, 576)	(369, 437)	(66, 83)	(1.96, 2.19)	(23.29, 28.21)

*PM mass concentrations are produced from the optical particle counter via an internal algorithm, which allows density and refractive index corrections to ensure accuracy

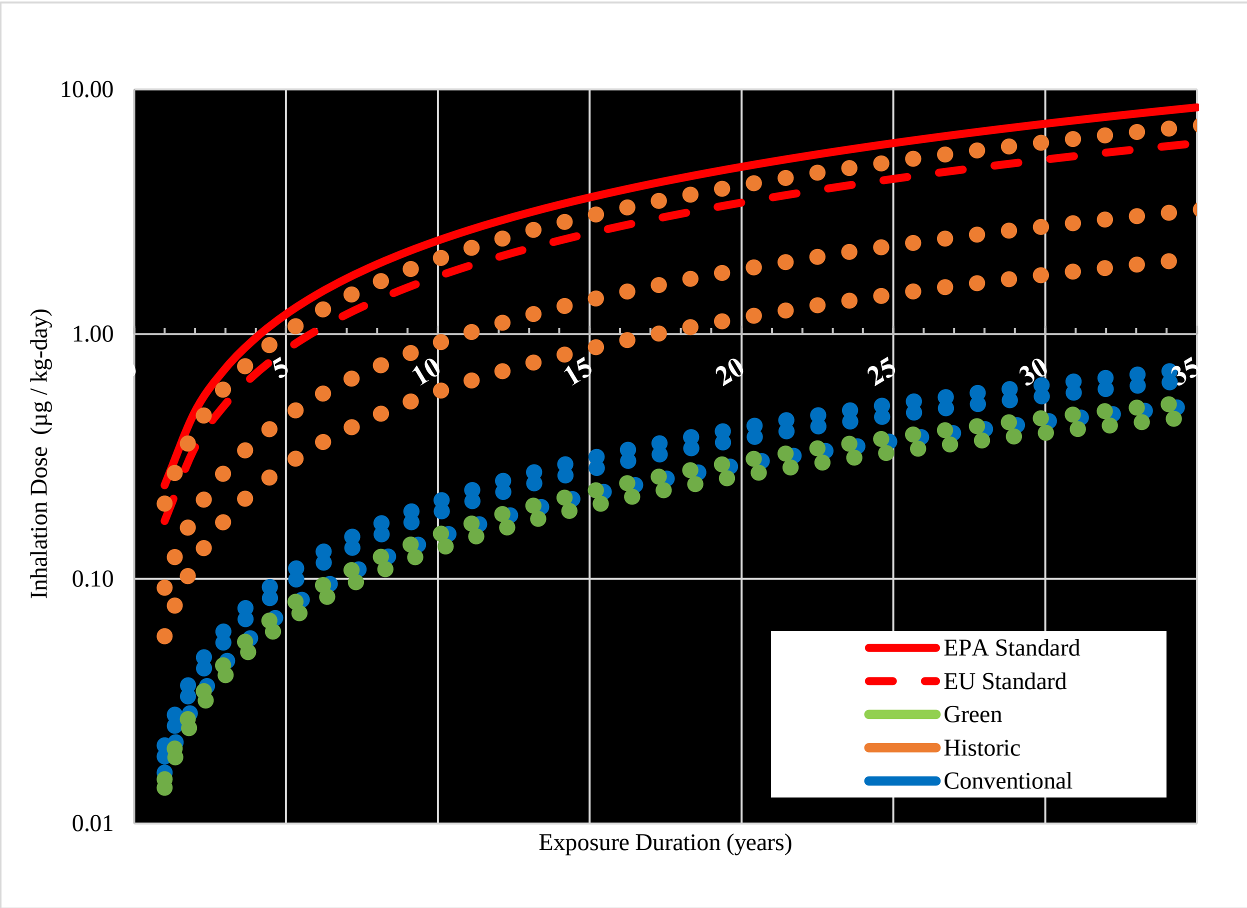

Figure 4. Average lifetime exposure concentrations of PM - PM concentrations range from 2.1 µg/m3 in conventional buildings to as high as 29.4 µg/m3 in historic structures.

3.3.2 Effects of Interventions on PM Concentrations

There is a mounting evidence indicating PM is a leading contributor to upper respiratory (American Thoracic Society Committee of the Environmental and Occupational Health 1996, Gouveia and Fletcher 2000, Peng, Chang et al. 2008) and cardiovascular disease (J Schwartz and Morris 1995, Wang, Tu et al. 2015, Munzel, Sorensen et al. 2017, Xu, Xu et al. 2018), as well as cancers (Ole Raaschou-Nielsen, Mark Nieuwenhuijsen et al. 2013, Yorifujia and Kashimab 2013, Steinle, Reis et al. 2015), which prompted us to consider this as the pollutant of main focus. The difference between HB1, which showed the highest value of $PM_{(0.3\text{-}10)}$, and GB1, the lowest value, is 151.21 µg/m^3 (96.96 %). ANOVA results show that $PM_{(0.3\text{-}10)}$ concentrations across the eight pilot buildings differed significantly. Fisher's LSD test (Table 3) results express that Building HB1 'underperformed' when compared to the other structures, therefore a yearlong intervention was performed in HB1.

Table 3. Grouping Information Using the Fisher LSD Method and 95% Confidence

Building	N	$PM_{(0.3\text{-}10)}$ Mean (µg/m^3)	Grouping				
HB1	888	155.95	A				
HB2	978	54.15		B			
HB3	598	27.66			C		
CB1	400	26.31			C		
GB2	490	25.75			C		
CB3	430	14.39				D	
CB2	515	12.85				D	
GB1	958	4.74					E

Given the logistical challenges of whole building infrastructure upgrades (i.e., upfront financial cost or work disruptions for HVAC retrofits, carpet replacements, etc.), non-infrastructure strategies were prioritized to reduce PM concentrations in the studied building. To this point, the findings are reported as the aggregated effects of all measures taken, none of which were investigated independently since this was a real-life intervention and not a controlled exposure study. Initial pre-intervention testing was performed in December 2014 and post-intervention testing was performed in November of 2016. It was important to consider both physical upgrades and the longevity of behavioral interventions as effective approaches to decrease indoor PM concentrations. As such, the following 7 interventions were considered: (i) use of standalone air filters near emission sources; (ii) installation of walk-off mats at entranceways; (iii) development and implementation of green cleaning program; (iv) weekly spotlight cleaning of occupant workspaces and mechanical equipment (window air-conditioning units and radiant heaters); (v) enactment of building-wide smoking ban near intake vents and entrances; (vi) restriction of window opening during peak rush hours; and (vii) enforcement of no idling at loading dock.

Figure 5 allows a comparison of sample locations in Building HB1 and shows the effect of all considered interventions on improving indoor PM concentrations. Taking into consideration the potential effects of infiltration and/or exfiltration on indoor PM and the variable nature of PM across seasons, indoor-to-outdoor (I-O) ratios were used to normalize the results and compare between different years. I-O ratio is a widely-used concept that represents the interaction between indoor and outdoor particles and is defined as the ratio C_{in}/C_{out}, where C_{in} and C_{out} are the indoor and outdoor concentrations, respectively (Chen and Zhao 2011). The raw values or average concentrations at each location is also presented on the secondary vertical-axis in Figure 5. The average I-O ratio of $PM_{(0.3-10)}$ from the pre-intervention sampling across all 16 locations was 1.93 and the 72-hr average was 155.95 µg/m^3. I-O ratio results were greater than one at 13 of the 16 locations (or across 81% of the sample). Notably, the pre-intervention $PM_{(0.3-10)}$ concentration at each sample location exceeded the US EPA's NAAQs 24-h standard (150 µg/m^3) at 9 of the 16 locations and the WHO's ambient air quality guidelines (50 µg/m^3) at ***all*** the locations. The average I-O ratio of PM post-intervention was 0.80 and was greater than one at 4 of the 16 locations (or across 25% of the sample). The post-intervention average was 31.97 µg/m^3 and no location exceeded the US EPA's NAAQs 24-h standard or the WHO's ambient air quality guidelines.

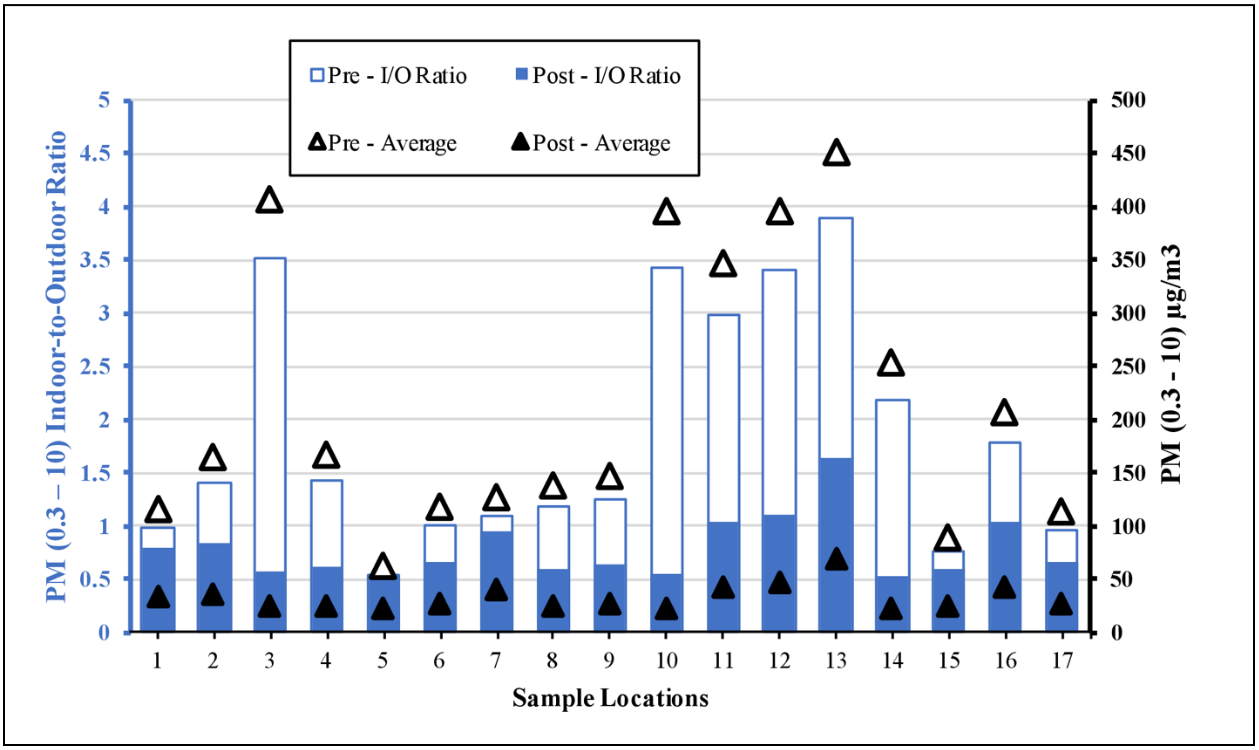

Figure 5. 72-hour pre- and post- intervention results - PM results at individual sample locations in building HB1.

As the results suggest, the cumulative effect of the tested interventions improved IAQ with an overall PM reduction of 79% between the pre- and post- results. Although the generality of the findings is noted, such interventions are easy to implement and given that the cost is low, were recommended to other building managers as IAQ improvements practices to adopt at the bare minimum.

3.3.3 Basic Environmental Parameters Provide Some Insight on Criteria Air Pollutants

Throughout this research, concentrations of CO_2 was considered a surrogate for lack of adequate ventilation. Subtracting ambient or outdoor CO_2 (~350 - 400 ppm) concentrations from daily average levels indoors allows us to calculate a differential. A CO_2 differential can be used to pinpoint instances of overcrowding as well as indicate excess humidity and building emission sources (i.e., printer use). ASHRAE suggest excessive CO_2 concentrations are those greater than 350 ppm above background outdoor levels (> 700 ppm) and are associated with complaints of odors and stuffiness. The recommended maximum indoor concentrations is set at 1000 ppm; exceeding this threshold can cause headaches and decrease in mental acumen (ASHRAE 2016a, ASHRAE 2016b).

One-minute CO_2 concentrations across the eight pilot buildings during hours of operation (9 AM – 5 PM) averaged 606.25 ppm (Max 7150.00 ppm), 256.25 ppm above outdoor levels. To further analyze these results, the buildings were also grouped by archetype, with the distinguishing factor then being the presence or lack of ventilation and the mechanical functionality of each system. Historic buildings (no central air) on average had higher CO_2 concentrations than conventional buildings (central forced air heating and/or cooling); green buildings (dual or hybrid systems) on average had lower CO_2 concentrations overall. Average CO_2 concentrations were 681.16 ppm, 608.99 ppm, and 476.64 ppm for the historic, conventional, and green buildings, respectively. Through demand response, the hybrid systems found in most green buildings intermittently pump fresh air into the indoor dwellings based on CO_2 sensors in the HVAC system, which is the most likely explanation for the difference between the green and conventional buildings. On the other hand, older buildings rely on window air conditioning units and a leaky envelope to supply “fresh” air into a space, which in most cases does not reach the required ventilation rate per person for adequate airflow and becomes problematic in situations of overcrowding.

Figure 6 summarizes CO_2 and PM $_{(0.3\text{-}10)}$ concentrations across the individual sample locations (n=89) of each pilot building as well as the indoor-to-outdoor (I-O) $PM_{(0.3-10)}$ ratio. Average $PM_{(0.3\text{-}10)}$ concentrations are arranged in descending order. A strong association (Pearson r = 0.867) was observed with respect to CO_2 and $PM_{(0.3\text{-}10)}$ based on correlation coefficients expressed in Table 4 and also evident from the linear slope line in Figure 6.

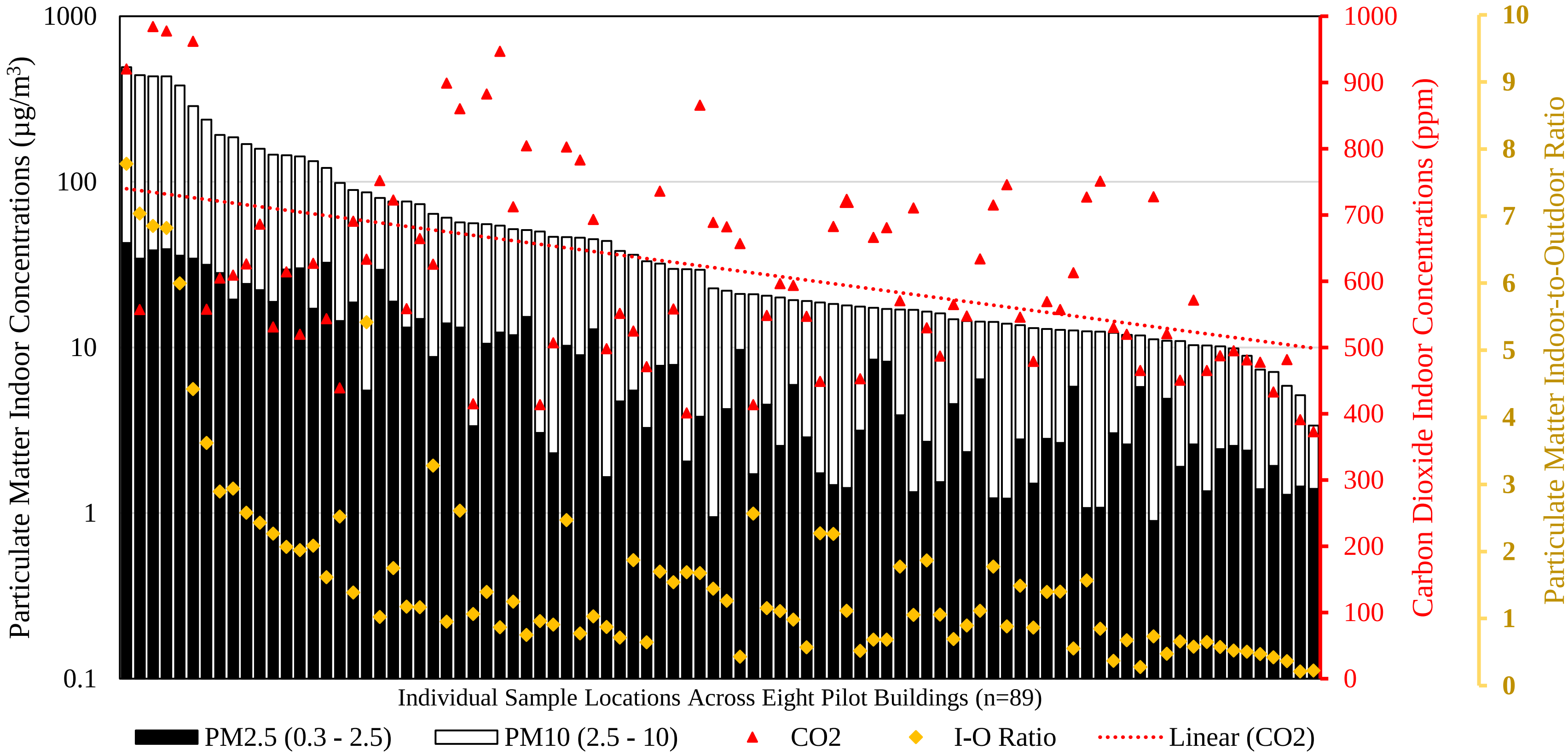

Figure 6. $PM_{(0.3-10)}$, CO_2, and PM indoor-to-outdoor ratio and spot measurements - Indoor-to-outdoor ratio and spot measurements represent a duration of 30 minutes across three-days, at individual test locations in the eight pilot building.

Table 4. Pearson correlation coefficients between indoor environmental parameters.

	TVOC	CO_2	Temp.	RH	$PM_{2.5}$
CO_2	0.187	-	-	-	-
Temp.	0.44	**0.842**	-	-	-
RH	0.401	-0.017	0.299	-	-
$PM_{2.5}$	0.559	**0.837**	**0.755**	-0.104	-
PM_{10}	0.545	**0.867**	**0.806**	-0.061	**0.987**

Concentrations of indoor particles also depend on the fraction of outdoor particles that infiltrate the building envelope or are brought indoors through the HVAC system or other sources (Zaatari and Siegel 2014). In order to accurately investigate I-O ratios, outdoor samples were collected near the fresh air intake of the primary AHU to be representative of ambient air that permeates interior air vents. Co-located outdoor air measurements made near the indoor environment were important, as high outdoor PM concentrations make it difficult to interpret the factors influencing I-O ratios. Additionally, community stationary monitors often produce inadequate and much lower estimates of local exposure. See Table 14 in Appendix A for on-site and community measurements of ambient PM for comparison.

Typical I-O ratio values lie between 0.1 and 0.3; values greater than unity (>1) are an indicator of indoor sources influencing the indoor environment (Figure 6). I-O ratios exceeded unity at 35%, 15%, and 27% of the locations within the historic, conventional, and green buildings, respectively. Next, comparing the I-O ratio at each individual location with elevated CO_2 concentrations (>700 ppm) was a way to delineate if the sources of PM were from occupant generated activities (i.e., vacuuming, active movement, printing, cleaning); this was an important differentiation to make before performing interventions. A moderate association ($r = 0.416$) was observed between I-O PM ratio and CO_2 across the sample; anthropogenic patterns and overcrowding were acknowledged as the key factors influencing PM generation among the pilot buildings.

During follow-up, seasonal testing and the intervention, black carbon samples were used to enrich the analysis. As BC is primarily of outdoor origin (i.e., traffic and industry) (Janssen, Miriam Gerlofs-Nijland et al. 2012, Tunno, Shields et al. 2015), elevated levels indoors would be indicative of infiltration dynamics (leaky envelope), rather than internal sources. Activity diaries were kept by researchers to track indoor source events (i.e., active movement) in order to focus on influencing factors. Simultaneously exploring minute-to-minute PM I-O ratios and CO_2 concentrations (in addition to black carbon concentrations alongside activity diary data) became an effective approach to quantify the source of PM at individual locations within each building. In summary, PM values exceeded the 95th percentile in areas adjacent to printers and copiers, heating radiators and convectors, filing and clerical tasks, overcrowded workspaces, and domestic activities (i.e., cooking, cleaning, smoking).

Pearson's correlation was used to measure the strength and direction of associations between the other indoor air quality parameters including TVOCs, T, and RH. In Table 4, positive values indicate two parameters increased together, negative values indicate one parameter increased as the other decreased. The stronger correlations closer to one are denoted in bold. Strongest associations were recognized between $PM_{2.5\ (0.3-2.5)}$ and $PM_{10\ (0.3-10)}$ (Pearson r = 0.987; P-value: <0.0001), which is intuitive, due to particle resuspension and transformation properties (phase changes and indoor chemistry) (El Orch, Stephens et al. 2014, Ji and Zhao 2015, Hodas, Loh et al. 2016) and one is the constituent of the other. A strong-to-moderate correlation was found between several other parameters. The highest correlations were found between CO_2 and $PM_{10\ (0.3-10)}$ (r = 0.867, P-value: <0.0001), CO_2 and temperature (r = 0.842, P-value: <0.0001), and $PM_{10\ (0.3-10)}$ and temperature (r = 0.806; P-value: <0.0001). This brought to realization that higher indoor temperatures and humidity introduced through human respiration and perspiration may create a favorable environment for higher concentrations of dust and bioeffluents (Seppanen, Fisk et al. 1999). Moderate correlations were found between TVOCs and $PM_{10\ (0.3-10)}$ (r = 0.545, P-value: <0.0001), TVOCs and RH (r = 0.44, P-value: <0.0001), and TVOCs and T (r = 0.401, P-value: <0.0001). These are important implications because VOCs also change from gas to particle phase in reaction with RH and T.

As most conventional buildings routinely monitor and store temperature, CO_2, and relative humidity data through building automation systems (BAS), these results may be of large interest beyond the research and academic communities. BAS information is often stored in a data suite, yet can be used to address indoor environmental quality (IEQ) beyond thermal comfort. With basic BAS IAQ data readily available, this could be an initial start to “informed” indoor air improvements in cases where organizations do not have the financial means to purchase robust equipment and monitor localized IAQ data over time. Lastly, the results discussed above informed *IAQ Survey* questions 9, 10, 13, and 15 (see Appendix A).

3.3.4 Natural Ventilation May Increase PM Exposure

Figure 7 shows the ratio of I-O PM counts for the smallest size bin (0.3 – 0.5 µm) of five of the eight pilot buildings over a 24-hour period. *Note, the smallest size range is attributable to combustion-related particles, prominently of outdoor origin, therefore, in this case, an I-O ratio greater than 1 could suggest infiltration (uncontrolled and unintentional airflow) of polluted outdoor air into the indoor space rather than an episodic indoor source event.* The five buildings that were monitored in the Winter 2014 – 2015 were included in this analysis for continuity, due to the spatiotemporal characteristics of particulate matter across seasons. The values are normalized to an outdoor air site within a 3-mile radius of each building. The I-O ratio represents co-located samples collected simultaneously at indoor and outdoor locations for each site. Although conclusions are difficult to draw from I-O ratios, dominant nearby outdoor sources (e.g., dense bus transit hubs and interstate corridors) surround the testbed, which supports the assumption of outdoor-generated PM infiltration indoors.

The smallest I-O ratios were observed at Building CB3, which had excellent filtration and air intakes located 68 meters above the ground – and away from point and mobile sources. I-O ratios at Building GB1 and HB3 exceed unity on several occasions throughout the day. Note that Building HB3 is a historic structure, does not have mechanical ventilation, and relies on operable windows (natural and unfiltered ventilation) to provide recirculated air to occupied work areas; inadvertently, a leaky envelope also delivers outdoor air circulation. To the contrary, the hybrid system in Building GB1 purposefully implements passive ventilation to increase outdoor air supply and reduce the energy needed to condense or heat recirculated air. Additionally, the CO_2

sensors used in Building GB1 respond to the number of occupants within the space but do not consider ambient concentrations of criteria air pollutants (i.e., $PM_{2.5}$, O_3, NO_2) before increasing outdoor air. As a result, the indoor air becomes a reflection of the polluted outdoor air.

A common feature of green building projects is to locate buildings near urban centers to minimize transportation emissions and/or cost (Steinemann, Wargocki et al. 2017); however, earning green credits for locality may put occupants at a greater risk of exposure to poor outdoor air quality should filtration and controls not be adequately be considered (Ścibor, Balcerzak et al. 2019). Drawing conclusions from Figure 7, this phenomenon may occur in other green buildings with natural ventilation systems, and should therefore be further investigated to address the potential health concerns. From this work, it is evident that the O&M of mechanical systems are just as important as functionality and can largely impact the presence of outdoor-generated pollutants indoors. Energy efficiency at the expense of IAQ has the potential to adversely impact health and wellbeing. The results discussed above informed *IAQ Survey* questions 3, 8, 11, and 14 (see Appendix A).

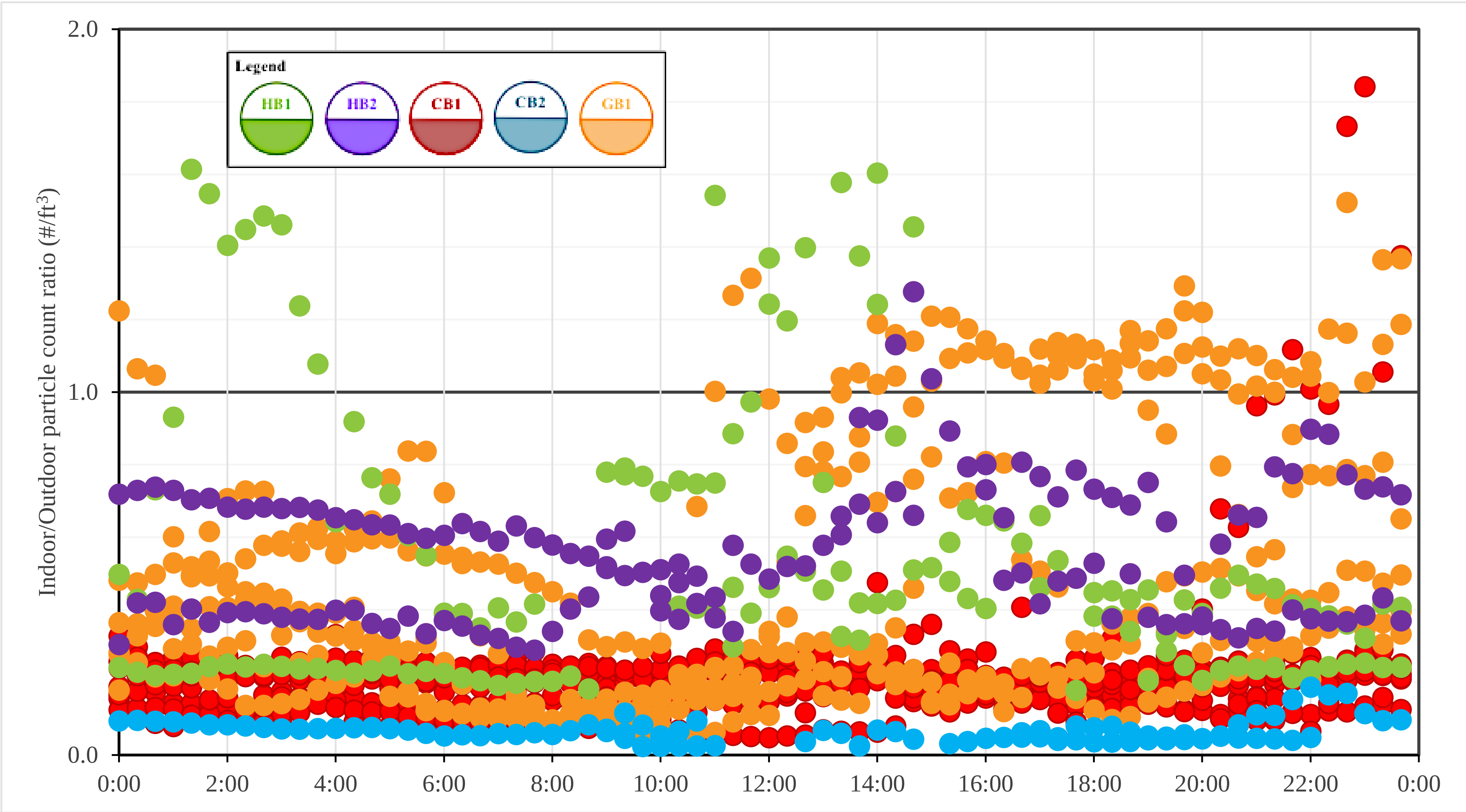

Figure 7. Indoor to outdoor ratios of PM across five pilot buildings - I-O PM counts for the smallest size bin for PM (0.3 – 0.5 µm) of five of the eight pilot buildings over a 24-hour period. The buildings are identified with a unique code where the first two letters represent the archetype (i.e., historic building (HB), conventional building (CB), green building (GB)) and the number is a differentiation for each building in the pilot.

3.3.5 Persistence of VOCs in New buildings

Figure 8 shows one-minute continuous TVOC concentrations collected over the 72-hour sampling duration in building GB2; a similar plot for CO_2 concentrations is included to reflect background concentrations for the absence of employees in the building overnight. Although the observed TVOC levels are moderate, there is a constant gradient increase in the concentration between the hours of 6 PM and 6 AM when the building is unoccupied. Overnight TVOC concentrations reach a maximum of 156 ppb, approximately a 4-time increase in the average concentration recorded during the hours of operation (39 ppb). There is a buildup of TVOCs and off-gassing of building materials overnight. Once the building is occupied on the subsequent morning, this prompts the ventilation system to turn on, a flush out of the indoor space, and an immediate reduction of TVOC concentrations by an order of magnitude over the course of a 3-hour period.

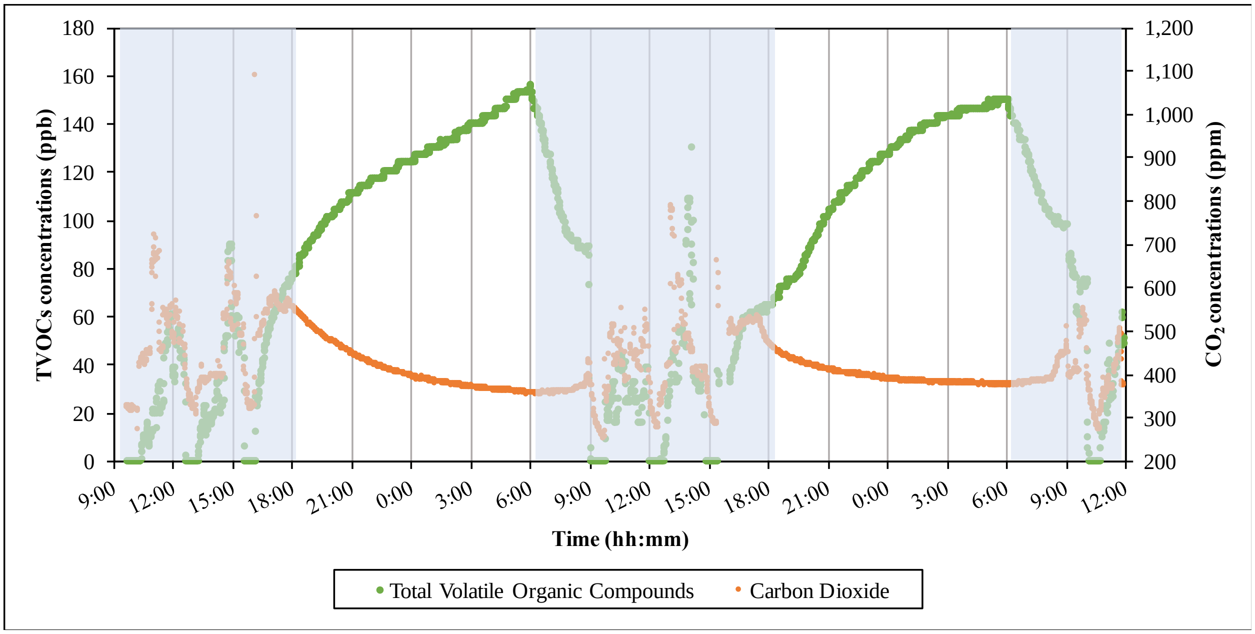

Figure 8. TVOCs and CO_2 concentrations in Building GB1 - Results reflect data during hours of operation and overnight.

To prevent the excess use of energy when the building is unoccupied, sensors in the supply air ducts adjust outdoor air and ventilation requirements based on the demands of the space, meaning when the building is unoccupied (lower CO_2 concentrations from human exhalation) the automatic control systems are off. In this case, ventilation is not tied directly to occupancy sensors or an exact measurement of occupants in a room, but rather to CO_2, RH, and T setpoints. The average indoor temperature during hours of operation is 68° F (consistent with the recommended

ASHRAE 55-2016 minimum thermostat temperature set point during heating seasons), but increases to maximum values of 72° F throughout the night. Additionally, the relative humidity decreases moderately from a maximum of 23% to a minimum of 18%. Although there are no established lower humidity limits, it is clear that this is a very low humidity environment. As a result, higher temperatures and low humidity typically maximize off-gassing, causing reactions between oxidants in indoor air and those absorbed on surfaces (Xiong, Wei et al. 2013, Fazli and Stephens 2018, Thevenet, Debono et al. 2018, Tian, Ecoff et al. 2018), which means that VOC emission rates of building materials in this newer green building are likely tied to the observed indoor temperature and relative humidity.

In general, many green building rating systems primarily focus on material use and energy efficiency, with less emphasis on healthy indoor air quality. To this point, the use of refurbished building materials benefit building designs from an embodied energy perspective, but can be controversial from a public health perspective, as recycled materials may reemit chemicals that were absorbed on their surfaces and used in the recycling process (Steinemann, Wargocki et al. 2017). Although emissions from building materials decline over several months, sportive surfaces and furnishings can re-release a significant fraction of taken up VOCs within a space. Due to their ubiquitous nature, VOCs can also interact with particulate matter and shift from the gas phase to the particle phase, which calls for actionable remediation practices in environments such as office buildings where prominent indoor PM sources exist. With the constant growth in high performance buildings, consumers and researchers alike should call for stricter guidelines for green products as well as required third-party verification and active monitoring of emission profiles and the effect on IAQ. The results discussed above informed *IAQ Survey* questions 6, 17, 18, 21, and 22 (see Appendix A).

3.3.6 Indoor Air Quality Survey Used to Establish a Performance Baseline

The *IAQ Survey* was used to establish a performance baseline of 506 buildings. A total of 306 buildings (48.1 million square feet) participated in the initial survey, an overall response rate of 60%. Individual responses remain anonymous, but GBA has access to the raw data to track building improvements on an individual basis. Figure 9 provides a summary of the responses from 15 of the 26 questions covering aspects of O&M.

297 buildings report having a smoking policy in place, and of those, 54 prohibit smoking on the premises entirely. Interestingly, a small percentage (2%) do not have designated smoking areas and allow smoking indoors to some degree. Although smoking is not permitted in most buildings, seasoned employees reported frequent incidents of smoking indoors prior to stringent building codes.

Not surprisingly, 91% of the participating sample does not perform annual testing of common indoor pollutants. In like manner, 88% do not have a mechanism for evaluating occupant comfort. Occupant comfort surveys and complaint logs can easily be implemented to evaluate occupants' perception of their work environment and act as feedback loops to upper management; however, they are not common practice in existing buildings.

In addition to standard 'yes' and 'no' response sets, each dichotomous survey question included a 'some' and 'do not know' response option. 'Do not know' responses can be thought of as missing or ambiguous data and can be used to inform knowledge gaps. 'Some' responses are a valid assessment of lack of consistency across buildings. For example, 24% of facility managers' report no knowledge of a moisture and mold management program at their respective buildings. This is an important finding and should be an immediate ask of District partners considering the variety of known health impacts from mold exposure.

Five of the questions from the *IAQ Survey* offered the option to expand upon "yes" responses. For example, Question 9 'Does your building address pollutants caused by copiers and printers?' revealed that only 11% of the reporting buildings designated printer and copier rooms that were separately ventilated outdoors. In office and work environments' printers and copiers off-gas VOCs and emit PM (He, Morawska et al. 2007), and therefore needs to be addressed accordingly. Respondents were also asked their intentions to pursue WELL Building Certification Air credit, a university/research IAQ project, and/or a longitudinal IAQ assessment, to which 89% indicated that they were interested in the feasibility. A transfer of knowledge and interest in air quality monitoring has likely occurred as a result of participation in the survey itself.

Researchers and GBA are in the process of refining each question and re-administering the IAQ survey in 2020. Based on individual owner survey results, GBA is working with District partners to address visible areas of improvement. Based on the observations, immediate improvements should be enforced through building-level policies and district-wide practices. These improvements include the establishment of a green (low-VOC) cleaning program, relocation of office equipment to separately ventilated rooms, installation of walk-off mats at all entry and exit ways, the utilization of High Efficiency Certified Air (HEPA)-certified vacuums in all buildings, updating building filtration to MERV 8 or higher, and required routine moisture assessments.

Because addressing IAQ is voluntary for most building stakeholders, the *IAQ Survey* aimed to spur an understanding of IAQ beyond the traditional research communities enabling ECDs, and building owners, to consider IAQ monitoring and evaluations as a priority in the building sector. Prioritizing IAQ management is connected with costs, less money can be spent on health claims while profits are maximized as with increased productivity. Addressing indoor air pollution has the potential to positively advance corporate culture and performance. The cost savings could also generate greater future financial investments toward building upgrades and future IAQ improvements (Sharmin, Gül et al. 2014).

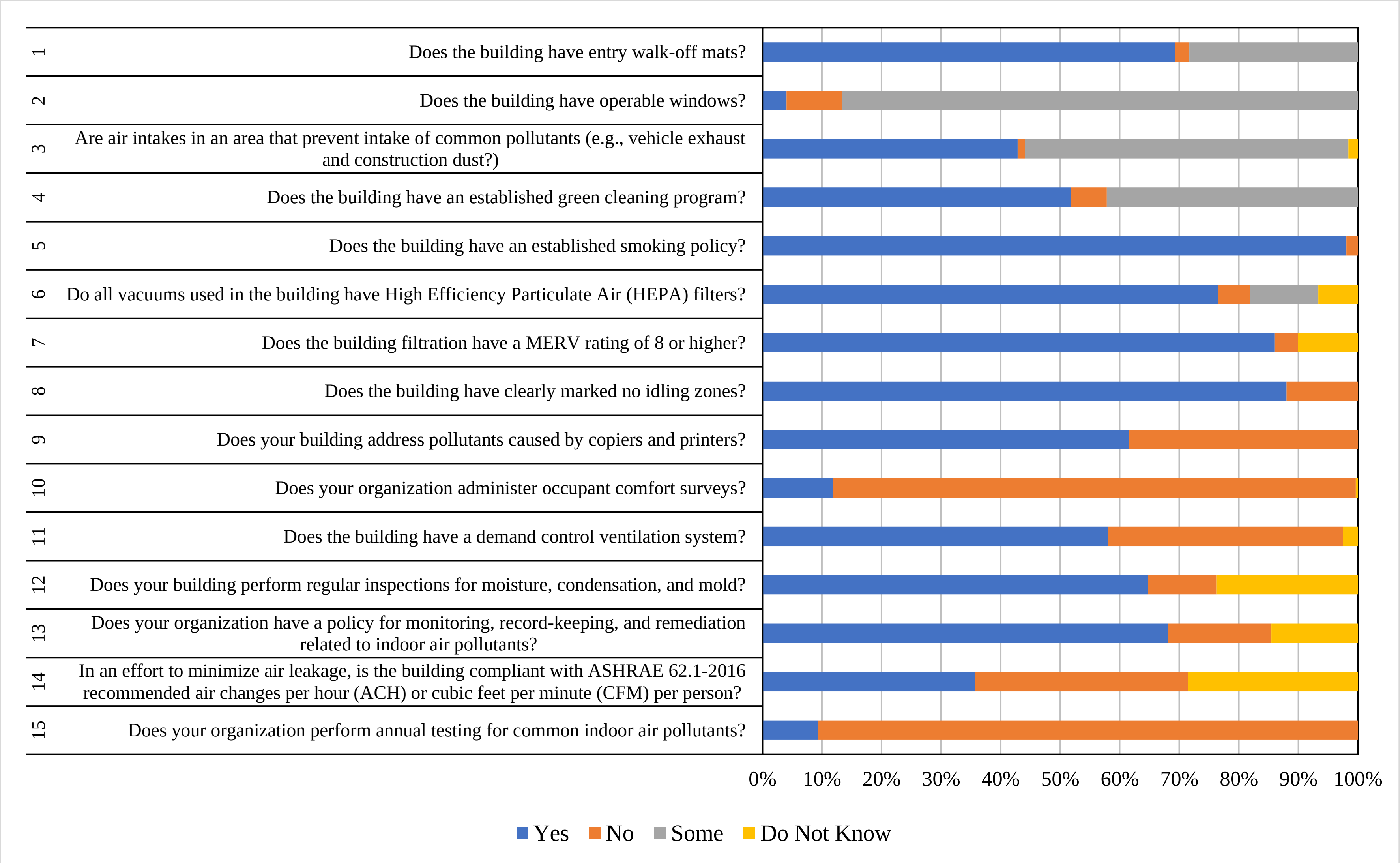

Figure 9. Baseline IAQ survey - 2017Y results from IAQ survey (n = 306).

3.4 Limitations

One limitation of the comparability of the results may be the exclusion of air exchange rate (AER) during the indoor air sampling as a measure of ventilation, given the intrusive nature of these procedures. This research was designed with practicality in mind and to minimize work disruptions as much as possible. Although the building data and results should not be generalized, some plausible conclusions were drawn.

3.5 Conclusions

Some of the earliest published research in IAQ dates back to the early 1900s, and since that time the number of peer-reviewed articles has increased from less than twenty to thousands. However, there remains no widely accepted metrics for monitoring and addressing IAQ across a broad range of buildings. This research highlights the development of a replicable framework to measure and assess IAQ in an ECD, while also aiming to advance the translation of air quality science to build long-term competency in communities.

The experimental data from the research was used to provide recommendations to pilot building stakeholders. Most green building frameworks recognize increasing ventilation as the primary method to improve IAQ (Steinemann, Wargocki et al. 2017); therefore, the synthesis of the expanded work was used to inform building stakeholders of other IAQ mitigation and reduction strategies. Providing building operations staff with evidence-based and data-driven recommendations, augmented the value of real-time air quality data and impelled change to local conditions. Moreover, combining data from seasonal sampling campaigns and co-located outdoor air data provided a robust data set to inform strategies for source control and reduction.

Unlike outdoor air regulatory networks, there are no routine measures in place to monitor indoor air. Field measurements of air quality are also expensive, intrusive, and time intensive. Considering these obstacles in improving IAQ, the framework development and data collection helps to address IAQ issues in a local ECD. The development of the *IAQ survey* also offers an entry-level alternative to long-term testing. Just as with building energy conservation and benchmarking approaches in the U.S., quantifying the state of current measures taken to address indoor air pollution through a survey can help establish a baseline and lead to benchmarking improvements over time. The success of this research in the Greater Pittsburgh region is expected to have significant positive implications considering local residents rank in the top 2% for cancer risk from air pollution in the United States (ALA 2019).

4.0 Environmental Justice and Community-based Research

The following chapter focuses on environmental injustice and community-based research in underserved communities and fulfills ***Objective C***. The content of this chapter is reproduced from an article published in the journal *Sustainable Cities and Society* with the citation:

Rickenbacker, H.; Brown, F.; Bilec, M., Creating environmental consciousness in underserved communities: Implementation and outcomes of community-based environmental justice and air pollution research. *Sustainable Cities and Society* **2019,** *47*, 101473.

The article appears as published per the copyright agreement with, Elsevier Ltd., publisher of *Sustainable Cities and Society*. Appendix B provides supporting information for this chapter.

4.1 Introduction

A number of environmental justice studies have sought to quantitatively assess the degree of exposure to environmental contaminants in vulnerable (low-income and minority) communities; however, once the problem is identified, researchers and community partners are inclined to seek policy-based approaches to solve the problem (i.e., top-down). Environmental injustice, similar to most structural problems, cannot be solved by the same level of consciousness that created it. To this end, bottom-up principles (i.e., individual- and community-level) are as important when addressing environmental justice issues and should be undertaken as a continuous and long-term process, and not in the context of short-term projects which often fail or are viewed as tokenism. The benefits of community-based participatory research (CBPR) have been well documented and reaffirm the significance of grassroots capacity building (O'Fallon and Dearry 2001, O'Fallon and Dearry 2002, Ali, Olden et al. 2008, Minkler and Rubin 2008, Balazs 2013).

This research is also founded on the "Theory of Change (TOC)" process, incorporating key components of CBPR. TOC makes explicit the need for a radical cultural shift at the community-level, which starts by "understanding the cultural backgrounds and life experiences of community members" (Rimer and Glanz 2005). Unyielding issues from income gaps to educational attainment are at the forefront of underserved communities; thus, researchers must first understand community perception of environmental health benefits to inform and guide the process of goal-setting and influence a willingness to act among residents. To also ensure commitment is long-standing, it is imperative to recognize that "people both influence and are influenced by, those around them (Rimer and Glanz 2005)", meaning the research must be culturally relevant (O'Fallon and Dearry 2001). Furthermore, in order to change physical and social constructs, there must be multiple spheres of influence and a shared vision; through community-based research building trust and sustaining networks play an essential role in transforming culturally sensitive issues at the community-level.

In 2009, the US EPA solicited a request for applications (RFA) to engage universities in cumulative risk assessment research in the context of environmental justice communities. Payne-Sturges et al. (2015) performed a concise review of community engagement strategies executed across the seven awarded projects and provided recommendations on how future programs should equitably involve all partners in the research process. The findings of this work highlight evidence-based strategies to strengthen community engagement in academic research. Yuen (2015) went further to define core modes of engagement with respect to the level of participation of the community, from minimum involvement to strong leadership and decision-making authority. The programmatic elements of the research model was characterized with reference to 4 of the 5 engagement modes defined by Yuen (2015, 2015): outreach, consultation, involvement, shared leadership/participatory, and consultation. Although Yuen's continuum (2015) prescribes parameters for community engagement informed the researchers, each element of the research model stands independently, and will be discussed herein.

This chapter presents an interdisciplinary effort between university faculty and students, community liaisons, and local organizations. A community initiative was developed in Pittsburgh, Pennsylvania: the Environmental Justice Community Alert Matrix (EJCAM). EJCAM includes programmatic elements of both citizen science and community engagement and has four core areas: (1) Outreach; (2) Involvement; (3) Participatory Research; and (4) Consultation (Figure 10). Working intimately with a local nonprofit, EJCAM was developed to educate underserved communities about environmental risks and to provide practical responses to mitigate these risks. A purposeful selection was made to focus the implementation of the EJCAM model around the topic of air pollution due to its long and entrenched history in the Pittsburgh region.

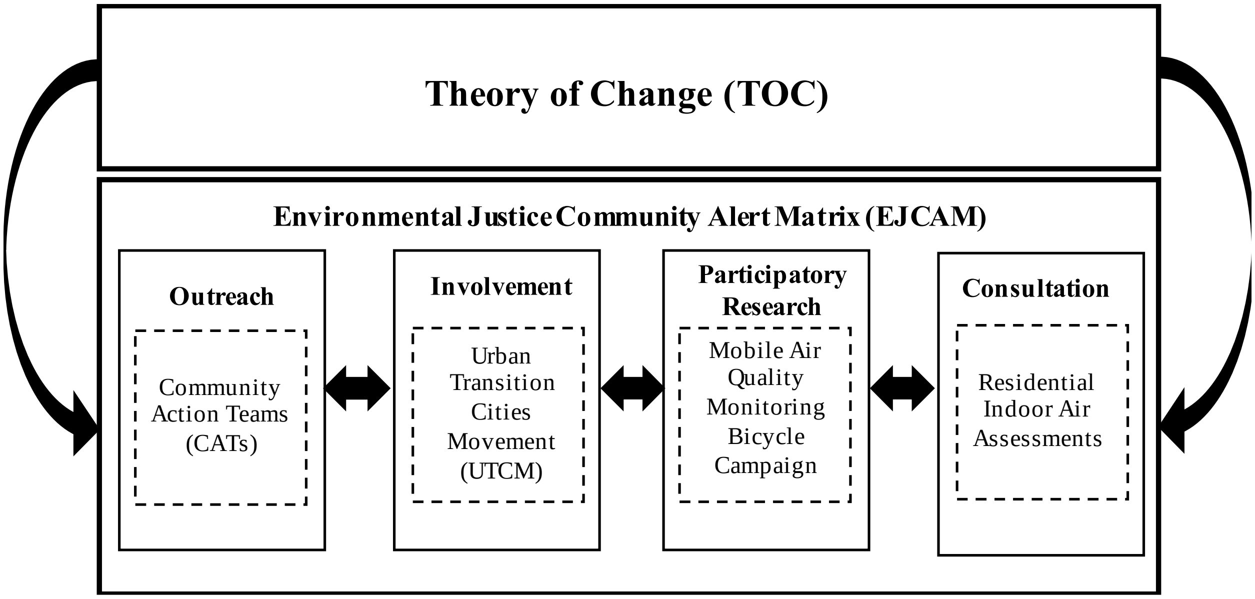

Figure 10. Environmental Justice Community Alert Matrix programmatic elements - The theory of change paradigm encompasses multiple spheres of influence at both the individual- and community-level. Dashed rectangles represent programmatic elements of EJCAM and the larger rectangles characterize each element as a core mode of community engagement.

The Consultation component (4) of the larger research requires conducting air quality assessments in the surrounding community collecting seasonal indoor and ambient samples of NO_2, SO_2, CO_2, carbon monoxide (CO), PM, BC, RH, ozone (O_3), T, HCHO, and TVOCs. Consultation should be a data-driven method of assessment completed by a professional or expert to formally assist and improve a stated problem.

This chapter reports on core areas of engagement and outdoor analysis, components 1 – 3.

4.2 Materials and Methods

4.2.1 Environmental Justice Community Alert Matrix (EJCAM) – Air Pollution

Community engagement on complex environmental justice issues require holistic research strategies embedded into an existing community structure. To this purpose, the research team collaborated with a local nonprofit and community-based organization (CBO), the Kingsley Association, to broadly support sustainable development practices in underserved communities in and throughout Pittsburgh. The CBO's long-standing presence motivated the research within the community and proved pivotal in the establishment of an authentic community-academic partnership. The CBO has served the Pittsburgh community for over 120 years reaching over 160,000 people annually and engaging residents from 26 Pittsburgh zip codes. A majority of the service area is a group of neighborhoods situated in the East End of Pittsburgh where the research was conducted.

The East End of Pittsburgh has been identified as one of Pittsburgh's most disadvantaged neighborhoods, and is an environmental justice community that struggles with issues of deteriorating infrastructure, community disinvestment, high traffic density, and an inverse racial make-up when compared to the rest of the city. The following demographic information was obtained from the US Census Bureau at the census tract and neighborhood spatial scale (US CENSUS 2013): 77% percent of the population is African American, while the Caucasian population is 13%, compared to 67% for the city as a whole. Between 2000 and 2010, the East End lost more than 2,400 units of housing, and nearly 900 units were rated in poor/derelict condition. Post-secondary education is significantly underrepresented, 12.9% of East End residents having college degrees. This educational gap correlates with the income gap; 32% of residents live below the poverty line compared to the 14.5% of citizens nationally. A map of the service area can be found in Appendix B, Figure 20.

EJCAM can be used for the management of a vast array of environmental injustice issues, such as water quality, food scarcity, energy sacrifice zones, contaminated sites, and air quality. Fundamentally, a community must first identify a specific environmental stressor, determine what effects it may cause, and then consider to whom it may harm. This differentiation can be made from fact-based (best available science) or value-based inputs (local knowledge) (Failing, Gregory et al. 2007). Problem identification is the first stage which develops the basis for the next step, intervention. Interventions must be culturally sensitive and aimed at improving the overall quality of life of the community. Community interventions must also create a positive experience through relevant social and educational activities, the goal being to increase knowledge and understanding of the issue and facilitate solutions to the problem.

In the context of EJCAM, four activities or interventions took place to address the topic of air pollution; three of the four core areas are: (1) Outreach with Community Action Teams, (2) Involvement through the Urban Transition Cities Movement, and (3) Participatory Research via Mobile Air Quality Monitoring Bicycle Campaign. A discussion of the general constructs of each method of engagement is also detailed to encourage replicability of the model in other context and with other topics of environmental justice.

4.2.2 Outreach - Community Action Teams (CATs): Trust Building and Grassroots Capacity

Outreach is defined as technical communication between academia and the community at large (Payne-Sturges, Korfmacher et al. 2015). Outreach can be initiated in various forms but essentially should be a series of activities aimed at first defining individual needs in the bigger picture of community priorities. Community priorities often differ from university goals, therefore engagement from project inception is key. In EJCAM, outreach first commenced through tabling events at the CBO. The research team also attended community events, such as health fairs, church gatherings, and neighborhood watch meetings to recruit residents. At these events a short pre-survey was also administered to determine which environmental sustainability topics were salient at the community-level and of greatest interest to community members. The pre-survey helped establish a baseline to assess current knowledge about environmental issues while also providing a vehicle for engagement. A copy of the survey questions can be found in Table 15 of Appendix B. Based on this insight, the need was established for an embedded community training approach to first increase the environmental consciousness of vulnerable populations. Trainings were then developed with resident's competency and prior understanding of environmental concepts in mind.

Community Action Team (CATs) trainings were conducted in the East End of Pittsburgh to first mobilize residents and inextricably link the topics of air quality, energy, and water. It is implied that a heightened risk of exposure to air pollution is contingent upon upstream combustion and the extraction of natural resources (i.e., natural gas and electricity generation) used to produce energy and to treat drinking water. Keeping in mind that these areas intersect, trainings detailed the co-benefits of addressing the three topics at the nexus of climate change adaptation. Environmental injustice discussions focused on a regional intersection of trends in water quality, air pollution, fossil fuels, renewable energy, and local hyper-consumption of resources. In addition to the broader discussion of localized issues, advocacy groups and nonprofit organizations administered hands-on activities that equipped community members with the technical expertise to adequately assess environmental risk in their homes and the surrounding physical environment. Hands-on activities included the use of low-cost air monitoring equipment, energy auditing and weatherizing homes, and environmental preferable purchasing or the use of natural products for prevention of chemical-induced diseases, to name a few.

The formulation of CATs advanced the knowledge of neighborhood residents while guiding the development of multi-level points of intervention and collective action to address local environmental injustice issues. CATs were formed, purposely comprised of residents from the neighborhoods most affected, to act as liaisons and aid the research team in further recruitment and retention efforts that informed the larger research. The main objective of the CATs trainings was to engage residents and to start the initial community dialogue around environmental sustainability, therefore no quantitative measures were used to assess the effectiveness of the trainings beyond a short paper evaluation, a question and answer period, and a group discussion after each session. Direct feedback from the CATs also guided the development of the Urban Transition Cities Movement (UTCM) workshop. No incentives were given to residents beyond the knowledge they gained from participation and food and beverages provided at each event.

4.2.3 Involvement - Urban Transition Cities Movement (UTCM): Collective Genius and Honoring Differences

The potential to sustain the interest of community members around environmental injustice topics is dependent on creating a sense of ownership for the overall project (Wolff and Maurana 2001). With other pressing issues at the forefront of these communities, a sense of ownership can only be created when community members are directly involved in programming and messaging. Local knowledge also helps to fit the execution of a project into daily life priorities (Meade, Menard et al. 2011). Community members are local experts who know “what will work and what will not (Schensul 1994)” and to this point, should be treated as equal partners and be directly involved in organizing moving forward. Involvement is a significant ingredient to advancing environmental justice and in this research, was commenced through the development and implementation of the UTCM.

The Transition Model based in Devon, United Kingdom (Dingle and Franklin 2002), is an intergenerational and multidisciplinary initiative that seeks to build community resilience in the face of societal challenges like climate change and economic decline. In 2009, program directors and staff at the CBO received training in the U.K. to become certified International T4T Trainers and thus developed an urban model that encompassed a cultural context and principles of diversity. In the spring of 2012, the UTCM workshop was designed and implemented to connect unlikely stakeholders and resolve environmental justice issues at the community-level. Local community members, non-profit leaders, small businesses, universities, governmental agencies, youth, and public officials joined the initial launch; the pilot workshop provided multiple perspectives to foster change and identify short-term outcomes for further evaluation. Many communities enact environmental sustainability initiatives in the absence of integrated, long-term strategies; hence, collaboration across networks (i.e., non-profits, local government) and an early start are necessary to create a balanced win-win situation for all stakeholders (Khare, Beckman et al. 2011, Dionisio, Kingham et al. 2016).

Separate from but building on the CATs trainings, the UTCM workshop was developed to be accessible to the entire Pittsburgh region. CATs trainings were carried out by content experts to first increase the knowledge base of vulnerable populations in the East End of Pittsburgh; subsequently, the UTCM workshop consisted of formal lectures and hands-on activities, but sessions were now co-facilitated by the trained and empowered CATs liaisons. The UTCM workshop was designed to promote a peer to peer education approach, extending the transfer of knowledge from citizens for citizens, through direct dialogue and engaged participation. The topics covered in the UTCM workshop were developed with the community's ecology in mind and were best informed from the CATs training.

The workshop spanned over a two-day period and consisted of panel discussions, formal presentations, mind-mapping exercises, and a culminating keynote address. The efficacy of the trainings was assessed through pre- and post- assessments consisting of eighteen multiple-choice questions developed from the information taught during the formal lectures. When examining correspondence between increases in environmental consciousness, student t-test was used to report statistically significant differences in pre- and post- results. The research team also compiled a brief evaluation to apply after the workshop; the evaluation was comprised of eleven questions using a five-point Likert scale, and open-ended responses (Appendix B, page 145). Inductive reasoning was used to group the open-ended responses into open codes; the open codes were then analyzed to identify common themes. The evaluation ultimately sought out to critically examine the program to improve the overall effectiveness.

Since conception in 2012, four UTCM workshops were held, for the purpose of this research the results from the fourth and most recent workshop are discussed.

4.2.4 Participatory Research – Mobile Air Quality Monitoring Bicycle Campaign

Participatory research is defined as a grassroots undertaking that combines science with action, the science of data collection and interpretation, with the action of improving local conditions (Krasny and Bonney 2004, Pritchard and Gabrys 2016). Participatory research balances scientific rigor and the need for data with the personal goals and interest of communities. This can be used as a tool to identify environmental contamination and pinpoint its effects to a particular location. Once the problem is recognized, the data and results should also be used to educate local residents and act as evidence to engage polluters and local authorities (i.e., health department). A highlight of participatory research is the fact that it is "hands on" which is useful in underserved communities where there are cultural barriers and often mistrust in outside institutions. In the context of EJCAM, the participatory research goals were executed through a Mobile Air Quality Monitoring Bicycle Campaign.

An air quality monitoring campaign was mobilized in Larimer, one of the seven neighborhoods of the East End; the CBO is also located in Larimer. Mobile air quality monitoring was initially used to explore the benefits of community engagement and for researchers to establish visibility in the community; however, monitoring was also used for air quality data collection and analysis. Particles with aerodynamic diameters of between 0.5 and 2.5 microns ($PM_{2.5}$) were measured in the summer of 2015 and 2016 (with frigid temperatures in the winter and shorter days, a spring/summer campaign was most feasible for the engagement goals). Eight Dylos particle counters were retrofit to bicycles and used to simultaneously collect one-minute averaged particle counts. A 3-km bicycle route was repeated twice on each sampling day. Repeated measurements collected along the same bicycle route allowed for additional data for summary statistics later used to understand potential exposure levels. Dylos air quality monitors are often used in citizen science applications due to their affordability and ease of use (Dacunto, Klepeis et al. 2015, Manikonda, Zíková et al. 2016, Klepeis, Bellettiere et al. 2017).

Uncertainty exists when comparing Dylos measured particle counts to mass concentrations published in the US EPA’s NAAQs; calibration curves have been used across experimental studies as an alternative method when using low-cost monitors for exposure assessments in place of expensive gravimetric sampling methods (Dacunto, Klepeis et al. 2015). A reference instrument is used to define the linear relationship between both devices which provides an accurate mass estimate of PM concentrations. For the mobile air monitoring bicycle campaign, this approach was not taken, but instead, the results are reported and assessed based on the Air Quality Chart ratings issued by the Dylos Corporation. $PM_{2.5}$ estimates are calculated by subtracting the large particle counts (> 2.5 µm) from the small particles counts (> 0.5 µm). Small count readings are characterized into six channels and assigned a qualitative description (e.g., excellent, very good, good, fair, poor, very poor); each qualitative score correlates to a quantitative range (e.g., 0 – 75, 75 – 150, 150 – 300, 300 – 1050, 1050 – 3000, 3000 +) which is designed to adhere to optimal health and environmental protection standards.

Comparisons were conducted among three sampling periods; the temporal resolution was fixed and considered the morning (0700 - 0900), afternoon (1200 - 1400), and evening (1700 - 1900) rush-hours. This approach aimed to evaluate the temporal and spatial characteristics of neighborhood-level air quality. During each route, one participant was also equipped with a HERO 4 Silver Go Pro camera to identify singular events throughout the sampling period and determine possible outliers that may have acted as explanatory factors (e.g., idling buses). Pocket Earth Global Positioning System (GPS) Navigation Software was used to track the route duration and to log longitude/latitude point estimates along with time stamps to interpret particulate matter samples later. The apparatus designed to support the Dylos particle counters was attached to a standard bicycle's seat post and seat tube, with a predefined height of 145 cm - 183 cm above the ground, representative of the average human inhalation zone (Migliano and Guillon 2012).

Using approximately 86,000 one-minute averaged data points, and deterministic interpolation methods within ArcGIS 10.5, a set of smoothed contour lines were developed to produce predictive GIS maps of particulate matter dispersion across the research area. A mobile platform allowed for more flexibility and ease of use, in addition to, access to small areas and residential streets.

4.3 Results

4.3.1 Community Action Teams (CATs)

The CATs trainings provided residents with the technical knowledge to substantiate environmental concerns within their homes while outlining the mutual benefits of simultaneously addressing water use, energy consumption, and air pollution. CATs enhanced co-learning between the university, community members, and local organizations and established a trained network of empowered residents. Individuals were treated as equal partners and valued for what they can contribute which made them more likely to donate their time and energy. Establishing community liaisons and creating a win-win relationship, one that specifically benefits everyone involved, was important. This was also important because building trust in the urban setting is a slow process that requires grassroots capacity and a long-term commitment. Ultimately, CATs instilled strong relationships of mutual trust between academia and community members to better inform the UTCM workshops.

Twenty-four local residents participated in the CATs trainings. Sixty-six percent were African American and the remaining 33% were white. All 24 residents represented environmental justice neighborhoods identified on the map in Appendix B, Figure 20. Table 5 details when the CATs trainings took place, provides a description of each session and highlights the collaborative powers shared among partners across universities, organizations/agencies, and local municipalities. A question and answer period, as well as verbal discussion, commenced after each training to assess areas of improvement; paper evaluations reflected positive feedback and overall satisfaction with the CATs.

Table 5. Community Action Teams (CATs) trainings overview and technical partners.

Topic	Title	Institution/Community Partners	Description
Energy (08/22/2015)	Energy for Our Community	DeMarco & Associates	Localized issues around fertile ground, biodiversity of species, human population, fossil fuel combustion, renewable energy, and local hyper-consumption of resources
	Cut Costs, Not Comfort, with Energy Efficiency	Conservation Consultants Inc.	Ductwork retrofits, introduction to ENERGY STAR appliances and programmable thermostats, cleaning techniques for refrigerator and freezer cooling coils, proper washer and dryer venting to impede exhaust air flow, ventilation of attics and crawl spaces to minimize condensation, conductive heat loss, and structural damage
	Affordable Do It Yourself Weatherization Assistance	Lindsey Cashman, Weatherization Specialist	Benefits of indoor lighting install of compact fluorescent lights (CFLs) and light-emitting diodes (LEDs), weather stripping of doors and window seals, and efficient air sealing measures
Air Quality (09/19/2015)	Environmental Consciousness: Mitigating Air Quality Risk in Your Community and Home	University of Pittsburgh	Indoor environmental parameters that affect occupant comfort (ozone, carbon monoxide, sulfur dioxide, volatile organic compounds, and particulate matter), and provided information on household plants that sequester air toxins, HEPA and MERV filter efficiency rating, and passive ventilation strategies
	Healthy You, Healthy Homes, Healthy Communities	Women for a Healthy Environment	Natural alternatives to chemical-laden cleaning products, environmentally preferable purchasing techniques, do-it-yourself personal care product recipes, and recycling alternatives that reduce downstream bisphenol A (BPA) production and air pollution
Water (10/17/2015)	Where is Our Water?	Living Waters of Larimer (LWOL)	Innovative rainwater management strategies ranging from rain barrel installation to storm water landscape design and aquaponics, community overflow alert tools, water quality awareness and lead testing, understanding the hydrological cycle and the groundwater table, and hydroelectricity
	What about our Drinking Water?	Pittsburgh Water and Sewer Authority (PWSA)	
	Rainwater as a Resource	Storm Works	
	Why Care About our Watershed	The Penn State Center	
	Larimer Leading the Way to Healthy Streams and Rivers	Allegheny County Sanitary Authority (ALCOSAN)	

4.3.2 Urban Transition Cities Movement (UTCM)

A total of 72 community members participated in the 4th UTCM workshop. Eighty-two percent of the UTCM attendees had not previously participated in EJCAM activities (13 of the 72 attendees were a part of the original CATs). Recruiting and engaging new community members over the course of this research was successful. Of the environmental justice communities identified as areas in need of economic growth and urban renewal (Appendix B, Figure 20), more than half (64%) of the 72 workshop participants represented these targeted neighborhoods, additionally, 61% identified as African American. Fifty-two percent of the participants were between the ages of 19 and 25, and 30% over the age of 40. A dominant presence from the millennial audience proves promising for the growth trajectory of transformational leaders; an early start reinforces sustainable and growing networks while establishing a resilient commitment to environmental justice reform. Developing local engagement and a skill base to participate in research, particularly among those people who have survived extreme levels of environmental and economic disparity can also offer a positive example to the city and ignite a paradigm shift.

There was a 68% response rate for the workshop evaluations. When participants were asked to rate their overall satisfaction with the workshop on a Likert scale from 1 to 5, with 'extremely dissatisfied' corresponding to 1 and 'extremely satisfied' corresponding to 5, most of the participating community members were 'extremely satisfied' (61%) or 'satisfied' (39%) with the workshop and rated their experience as "relevant and relatable." Forty-three percent of the respondents deemed the technical information as translatable to real-life applications, while 22% were ‘neutral’ about transferability.

The research goal was to determine whether the peer-to-peer education approach would effectively elicit the transfer of knowledge from community members to community members. Pre- and post-education assessments were administered to understand the efficacy of the UTCM workshop in the form of a paper-based multiple-choice questionnaire. Pre- and post- assessments determined a statistical significance in the difference of the means ($p < 0.05$), defining quantitative measures of success and growth in green literacy (Table 6); the percentage of increases range from 10 to 67 (average 34).

Table 6. Urban Transition Cities Movement (UTCM) Workshop Pre- & Post- assessment Results (n= 39).

		Average (%)			Significance
	Questions	Pre-Assessment	Post-Assessment	Difference	P-value
1	More than _______ percent of Pittsburgh public school students live with Asthma?	15	72	57	**< 0.0001**
2	What air pollutant have adverse health effects over long-term exposure, directly related to cancer?	50	93	43	**0.013**
3	_______ is considered highly respirable particles that easily infiltrate the upper respiratory tract and lead to chronic health impairments and cancer at high concentrations.	21	46	25	**0.05**
4	_______ generally do not by-pass the mucous membranes of the nose, throat, and eyes, and consequently are minor contributors to known chronic respiratory diseases.	43	57	14	0.294
5	On average, how much time do Americans spend indoors?	18	85	67	**< 0.0001**
6	Allegheny County residents are _______ times the cancer risk of surrounding counties?	44	54	10	0.371
7	Pittsburgh is ranked _______ for annual particle pollution out of 277 metropolitan areas.	23	44	21	0.056
8	Indoor pollutants may be _______ times higher than outdoor pollutant levels.	46	93	47	**0.0001**
9	What measurement scale was designed by the American Society of Heating Refrigerating and Air Conditioning Engineering (ASHRAE) to rate the efficiency of air filters?	21	72	51	**< 0.0001**
10	Emissions of particulate matter in Allegheny County are dominated by which sector?	61	71	10	0.406
11	Ground level ozone is formed in the presence of NOx, VOCs, and _______.	14	75	61	**< 0.0001**
12	Increasing the amount of fresh air brought indoors helps reduce pollutant levels, this environmental sustainability technique is called _______.	61	82	21	0.079
13	During the Summer months, your thermostat should be set between ______ to optimize energy use and occupant comfort?	18	55	37	0.085
14	During the Winter months, your thermostat should be set between ______ to optimize energy use and occupant comfort?	46	73	27	0.212
15	What is one energy efficiency rating metric used throughout industry for household appliances?	100	100	0	1
16	What type of light bulbs should homeowners use to maximum efficiency while to minimizing end of life disposal impacts?	64	100	36	**0.038**
17	What is one way to collect rainwater at your home for reuse?	100	100	0	1
18	Pittsburgh is a part of the _______ Districts, designed to improve energy, water, and air quality metrics amongst businesses and residents.	47	73	26	0.082
	Overall	44	75	31	**0.0003**

4.3.3 Mobile Air Quality Monitoring Bicycle Campaign

Figure 11 (a) depicts the summary particle counts and change in distribution across the geographical areas averaged across three temporal scales. Spatial variation was observed across the 3km bicycle route; a significant difference from background $PM_{2.5}$ levels was found near an auto body shop and adjacent to a public transportation hub (bus/fleet facility). Ambient air quality data for the research area was also retrieved from a stationary monitoring site on the roof of the CBO. The data collection began after the bicycle campaign in 2017 and therefore was not included in the summary results to produce the GIS maps, but current data reflect constant spikes in particulate matter and nitrogen dioxide during operating hours of the aforementioned point sources.

As shown in Figure 11 (b), relatively higher concentrations of $PM_{2.5}$ were observed during the morning rush-hour (0700 - 0900), with mean and maximum $PM_{2.5}$ values of 853 and 4004 raw counts per cubic centimeters, respectively. Eighty-three percent of the morning values fell within the "poor" range on the Dylos air quality rating scale which defines higher exposure to local emission sources when compared to the results from the afternoon (Mean = 424; Max = 2,342) and evening (Mean = 318, SD = 660) [Maps of the afternoon and evening rush-hours can be found in Appendix B, Figure 21]. Additionally, temperature inversion events and lower mixing heights also allow pollution to settle overnight and re-suspend in the morning as upper levels warm dramatically and morning surface temperatures remain constant.

Separate from the indicated temporal variability likely attributed to mobile sources, there was large variability in $PM_{2.5}$ as a function of time of day, specific to residential building construction. The Code of Ordinances for the city of Pittsburgh prohibits the operation of heavy diesel equipment within development areas between the hours of 1000 PM – 0700 AM; peaks in particulate matter dispersion were observed during equipment startup between 0700 AM and 0900 AM. Spatially-resolved $PM_{2.5}$ values increased from background levels by an order of magnitude or 1000 counts, near the source location (i.e., excavation site and diesel equipment). This spatial variation has significant implications regarding community-level health equity deeming the site with the highest pollution consuming a large portion of the neighborhood; the darker region is relatively distinct in Figure 11 (b).

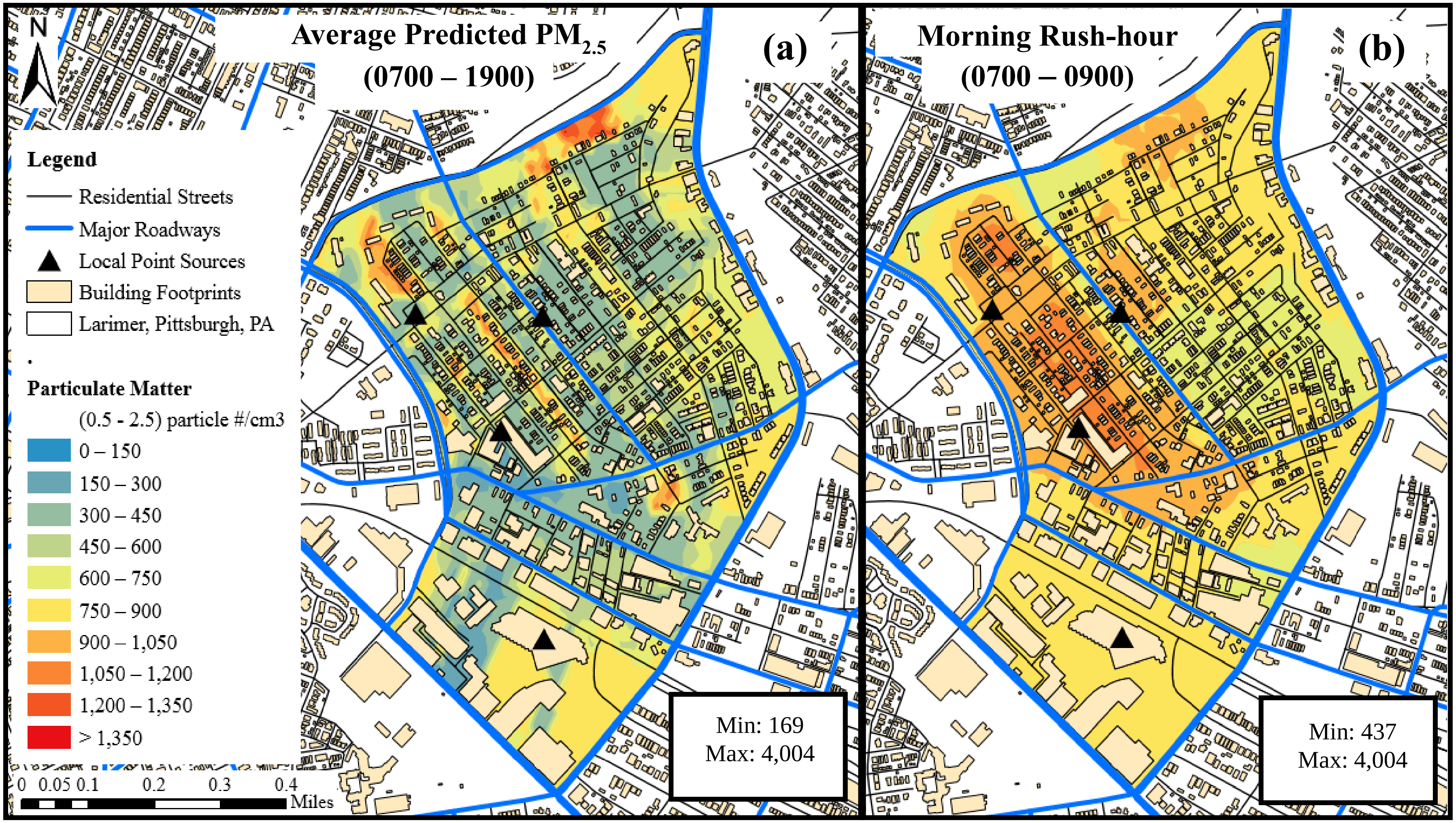

Figure 11. Average Predicted PM$_{2.5}$ Dispersion Map - 853, 318, and 424 particle counts (particle #/cm^3) were recorded during the morning, afternoon, and evening sampling period, respectively.

4.4 Discussion

4.4.1 Outreach and Involvement

While the literature documents known barriers to research participation in minority communities, there are still very few evidence-based strategies that have successfully addressed gaps regarding recruitment and retention (Ceasar, Peters-Lawrence et al. 2017). Researchers have lacked the economic and cultural background of the communities they wish to engage, leading to a disconnect and mistrust in academic institutions (Scharff, Mathews et al. 2010). Furthermore, studies show that some ethnic minorities believe research results could be used to negatively impact their communities (George, Duran et al. 2014). Having local residents and people of color co-facilitate the trainings and workshops were crucial to promote environmental justice among peers and empower participants. Additionally, the research team was diverse and composed of individuals from similar ethnic backgrounds as the community, which allowed researchers to blend and immerse completely into the social environments. This was an important factor in developing a resilient model that has lasted the past five years.

The cross-pollination of environmental justice and local knowledge facilitated behavior changes in both community members and the research team. A transfer of power occurred that reshaped the way the researchers executed their work, but also the way community members understood the technical activities being deployed in their communities. Since its inception, UTCM has evolved, resulting in strategic partnerships with institutions that deepened researcher's ability to obtain authentic data (social significance) which supported the implementation of community-driven ideas. UTCM provided vulnerable populations with opportunities to transform the community from the ground up.

However, while people are supportive of good causes, very few are willing to sacrifice on an individual basis for the benefit of society at large (Pickett-Baker and Ozaki 2008, Khare, Beckman et al. 2011). Therefore, in order to permanently change physical and social constructs, multiple levels of influence must first be initiated; thus, promoting collective genius required transparency, honoring differences, and intentional relationship building through community-based learning. EJCAM was distinct from traditional community engagement approaches, employing local knowledge in every stage of the research process and expanding beyond the norms of "community-placed" research; "community-placed" research being defined as a short-term academic driven project taken place in a community, where community members aren't actively involved (Green and Kreuter 2005, Harris, Pensa et al. 2016). EJCAM instead utilized the community's ecology through "community-based" research (Israel, Schulz et al. 1998, Wallerstein and Duran 2006), a combination of rapport and intimate local knowledge, where the CBO acted as a research hub in collaboration with academic institutions forming a long-term academic-community partnership.

The findings of this research suggest that to understand further the cumulative impact sociodemographic factors have on environmental health, may require diverse and multifaceted programming that enable the equitable distribution of both micro- (i.e., interest groups, community partners) and macro-level (i.e., universities, endowments) resources in vulnerable communities. Research projects and/or the duration of funding opportunities (grants) often differ from engagement support needs (Payne-Sturges, Korfmacher et al. 2015). Therefore, the alignment of large institutions and multi-level resources with CBO and the people they serve ultimately can influence long-term land-use decisions and regulatory activities that affect environmental contamination at the neighborhood scale. EJCAM expanded the depth and breadth of local residents through leveraging access to organizations committed to addressing environmental justice issues. With unyielding issues from income gaps to educational attainment at the forefront of vulnerable communities, community-based research has the potential to touch individuals, motivate research that is locally relevant, and then influence a willingness to act.

4.4.2 Participatory Research

Mobile measurements have been used to quantify the dispersion of particulate matter and are integrated in air quality studies for their high spatial resolution in urban environments (Elen, Peters et al. 2012, Hagler, Thoma et al. 2012). Measurement of daily exposure to particulate matter is often done at a coarse scale (stationary monitoring sites), which may not represent resuspension and emission trends at the community-level. Mobile measurement campaigns are being applied in research to estimate human exposure to air pollution at a more granular scale. Characterization of fine particles at a higher spatial resolution allows for a better understanding of local factors that influence the transport and dispersion of particulate matter in urban environments (Ortolania and Vitaleb 2016). Similar studies have considered proximity to highways and bus hubs, as well as the temporal variability in urban air pollution as leading factors for the growth of reliability in mobile monitoring networks (Elen, Peters et al. 2012, Hankey and Marshall 2015).

Traditional approaches to exposure assessment typically do not include local residents in the science and identification of known hazards (Sansom, Berke et al. 2016, Shamasunder, Collier-Oxandale et al. 2018). Within this research, the involvement of community members in data collection and the synthesis of scientific research helped bridge gaps and leverage interconnection between academia and the public's understanding of environmental stewardship. The mobile platform enabled us the opportunity to reach a broader audience when recruiting participants for subsequent trainings, workshops, and on-going residential indoor air quality assessments. Research has shown that allowing community members to be involved in the collection of raw data through substantive participation prove useful as a hands-on teaching tool and integral component of effective community-based research (O'Fallon and Dearry 2002).

4.5 Conclusions

The challenges of involvement from minority groups and low-income communities in environmental health research are significant. Some of these challenges may be competing priorities (Adamkiewicz, Spengler et al. 2014), while other known hurdles are lack of community immersion, less diverse research teams, and absence of local input in the decision-making process. This research adds value to developing areas of environmental health research through the establishment of a replicable environmental justice framework that: (1) includes multivariate analysis and a method for clustering communities as prioritized areas of investment; (2) further promotes air quality awareness through citizen science and ambient air quality measurement tools; (3) integrates extensive and long-term training workshops co-facilitated by vulnerable subpopulations; and (4) includes long-term residential indoor air quality assessments to act as an intervention and consultation for vulnerable populations. This research has also strengthened the reach of community-based research by ensuring the findings were presented at key venues among both the academic and professional communities. Authors have presented research results to the Pittsburgh Mayor’s Office, to national funding agencies (i.e., Garfield Foundation, The Heinz Endowments), and at several academic conferences. EJCAM included programmatic elements of both citizen science and community engagement and reaffirms the significance of grassroots capacity building and partnership development in order to stimulate environmental consciousness and local action.

Building partnerships require all stakeholders to have a vested interest in the success of the relationship while building actual lasting partnerships, not just hosting singular community events. From 2012 to 2017, the UTCM workshops have fostered relationships and interconnectivity between over 1,500 residents and 70 local and national organizations. UTCM is a comprehensive community engagement strategy that identifies community stakeholders and then places them in strategic relationships that move community-based ideas from concept to reality. In 2012, UTCM launched its inaugural movement with 37 people of color participating. This effort is responsible for supporting leadership that in 2014 received a $30 Million-dollar CHOICE Neighborhoods award based on creating one of the first communities in the country, led by people of color, to create a sustainable community design model based on green technology and infrastructure. The most telling impact of this community-academic partnership was reflected in the impression the community members left on government staff who interviewed the community leaders during the CHOICE neighborhoods review process. Federal reviewers indicated that community members were just as informed and knowledgeable about green materials, infrastructure, and land use practices as many of the staff conducting the actual interviews. A measure of this research's success is also documented in resident's active involvement in management of forthcoming landscape features in new housing developments, and pollution control schemes (i.e., controlling airborne dust generation) in conjunction with the local Urban Redevelopment Authority (URA).

While additional research is needed to document if the knowledge obtained from EJCAM was sustained past the five-year period, this research strongly suggests that expanding beyond the traditional norms of "community-placed" research is valuable to reverse the disfranchisement of environmental justice communities in research and problem–solving. TOC also reminds us that in order for long-term societal goals to be met, there must be multiple spheres of influence and a shared vision from communities and researchers alike. Goals that are developed and executed from a community's definition of needs, ensures participation from project inception through to evaluation.

5.0 Indoor Air Quality and Quality of Life in Communities

This chapter focuses on an assessment of indoor and ambient air quality, and quality of life in the residential sector which fulfills ***Objective D*** and ***E***. Appendix C provides supporting information to this chapter.

5.1 Introduction

The World Health Organization (WHO) recognizes air pollution as a leading environmental risk to health and major contributor to burden of disease worldwide (Forouzanfar, Afshin et al. 2006). Americans consume approximately 2.7 kg of food and 1.5 kg of water per day (Mike Saltmarsh 2008, Pimentel, Williamson et al. 2008), while on average breathe 10 kg of air per day; therefore, the quality of the air that individuals breathe is vital in environments where they live, work, and play. Although the quality of outdoor air remains a pressing issue, current research has shown that indoor air contributes to close to 90% of human exposure to pollution (Ott, Steinemann et al. 2006). This is due in part to the amount of time spent indoors, and to the many sources in the microenvironments, in which individuals spend their time.

The Environmental Protection Agency's (EPA) Consolidated Human Activity Database (CHAD) report the overall mean time spent at home is 17 hours a day compared to 7 hours between residential commutes and work (Hodas, Loh et al. 2016). Some common residential indoor sources of pollution include paints, aerosol sprays, cleansers and disinfectants, and building materials and furnishings (US EPA 2017). Rudel et al. (2003) analyzed indoor levels of volatile organic compounds (VOCs) and other endocrine disruptors in 102 homes and found concentrations of over 30 compounds. Compounds were at highest concentrations in indoor air and dust; inhalation exposure exceeded ambient air concentrations. The authors concluded that indoor sources of chemicals and slow indoor degradation processes caused frequent and large episodic exposure in homes (Rudel, Dodson et al. 2010). Similarly, Wallace et al. (2000) identified gas ovens and burners as the primary source of fine inhalable particles indoors, and indoor concentrations as high as episodes of air pollution outdoors. Further characterizing the magnitude of indoor emissions, in residences, where people spend a substantial amount of time, ultimately motivated this research.

Some of the most cited environmental exposures in and around homes are mold, environmental tobacco smoke (ETS), diesel particulates, and nitrogen dioxide (Klepeis, Nelson et al. 2001, Squizzato, Masiol et al. 2018), and have been linked to physical health risks. A systematic review of sixteen cohort and case-control epidemiological studies determined the presence of mold as a causal agent related to a 50% increase in risk of asthma development (Quansah, Jaakkola et al. 2012). The Institute of Medicine also found sufficient evidence of a relationship between asthma exacerbations and exposure to household contaminants, such as dust mites, pet dander, and cock roach/rodent antigen (Institute of Medicine (US) Committee on the Assessment of Asthma and Indoor Air 2000). Similarly, exposure to ETS indoors has been linked to respiratory illness in infants and further development of chronic respiratory symptoms in adolescents (Berglund 1992, Flouris, Vardavas et al. 2010). Although the existing literature clearly established a relationship between the built environment and its effects on physical health (B. Berglund 1992, Samet 1993), no studies to date have examined indoor air pollution and its effect on quality of life (physical and mental health) (Hoisington, Stearns-Yoder et al. 2019). Following previous work on environmental justice and community engagement in underserved communities, utilizing the Environmental Justice Community Alert Matrix (EJCAM) framework (Rickenbacker, Brown et al. 2019), this research examines the relationship between the built environment, air quality, and quality of life (QOL) in 30 neighborhoods and 51 residences in the greater Pittsburgh region.

A recent literature review exploring the effects of outdoor air pollution on the etiology of mental disorders found that long-term exposure to PM and NO_2 increases the risk of new onsets of depression (Buoli, Grassi et al. 2018), but the authors called for further studies to support the results. Moreover, Zhang et al. (2017) and Bullinger (1989) evaluated the potential effects of ambient air on mental health and well-being and concluded that exposure to pollution reduces hedonic happiness and increases depression. Recently, Shah et al. (2018) investigated indoor characteristics such as housing quality or pest infestation and the effects on mental health. The results suggest the health impacts of housing expand beyond physical health. But despite these findings and the connection to both physical mental health, the researchers failed to measure indoor air pollutants which may also affect QOL outcomes (physical and mental health). A recent literature review reaffirms this notion, and suggest the inclusion of social and emotional well-being in forthcoming indoor air research (Hoisington, Stearns-Yoder et al. 2019). This paper posits that a relationship exists and aims to fill the gap in the literature.

5.2 Materials and Methods

The study provided residential indoor air quality assessments, quality of life and home characterization survey development and implementation, neighborhood-level ambient air quality monitoring, and an intervention community workshop. Figure 12 illustrates the progress through phases of our research study.

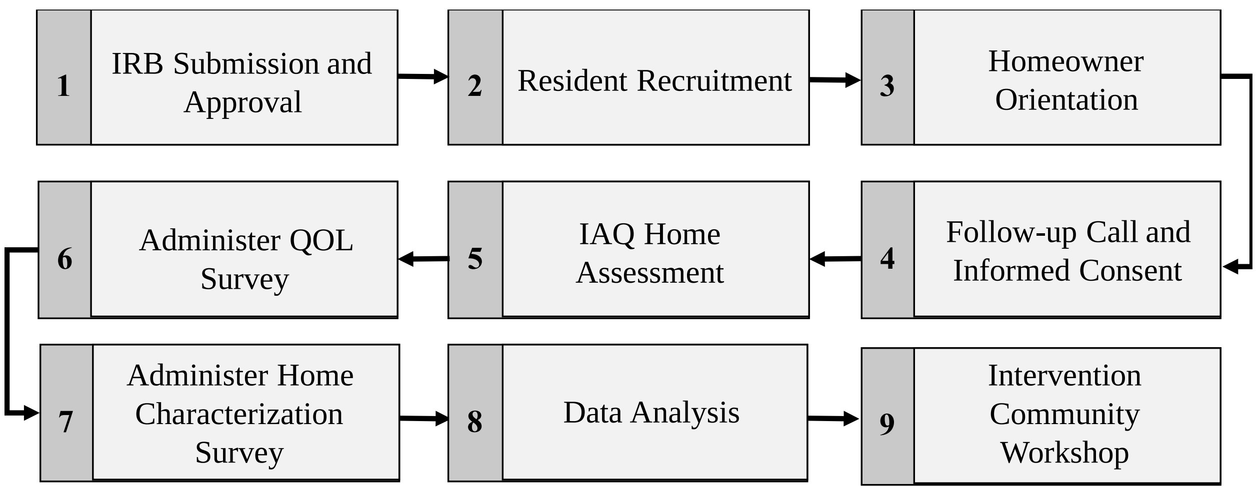

Figure 12. Study flow diagram - Progress through phases of the residential IAQ study.

5.2.1 Research Design

Households entered this study on a rolling basis through existing partnerships with local community-based organizations (CBO). The community-academic partnership is summarized in the prior work (Rickenbacker, Brown et al. 2019). Local residents were recruited at various tabling events, through door-to-door canvasing, and by word of mouth. After potential participants provided contact information to recruiters, a list was compiled and the research coordinator followed up via phone. Specific information detailing the indoor air quality monitoring procedures and involvement in the yearlong study were provided during the phone conversation. Full completion of the study required informed consent as a part of the University of Pittsburgh's Institution Review Board process (IRB #PRO15060520); attendance at a homeowner orientation and final educational workshop; the completion of a quality of life (QOL) survey, home characterization survey, educational workshop pre- and post- assessment and evaluation; and two-phases or seasonal indoor air quality monitoring at each home. Each household received a non-coercive, payment bonus in the form of two university WePay debit cards (to total $80.00) after the completion of each seasonal monitoring period as well as a combination of mitigation devices such as free-standing air filters, high efficiency particulate air (HEPA) vacuum cleaners, de-humidifiers, and low-VOC cleaning products.

IAQ assessments were done in each respective home over a year during both the heating (November to April) and cooling (May to September) months. The research was limited to 13 residential assessments due to the time-sensitive nature of the study; there was a compressed timeframe for continuous monitoring when competing with seasonal parameters (heating and cooling month window). Nevertheless, the sample size is consistent with existing spatial and community epidemiology studies in the Pittsburgh area where purposive samples have been collected and reported in peer-reviewed literature (Tunno, Shields et al. 2015).

The residential assessment data from the EJCAM study was then complimented with data from a local initiative, Reducing Outdoor Contaminants in Indoor Spaces (ROCIS). ROCIS was launched in 2015 to "explore and clarify the value and application of low cost monitoring devices to address indoor air pollution" in the Greater Pittsburgh region (ROCIS 2015). Through citizen science approaches, monitoring equipment is loaned over a 3-week period for local residents to collect indoor and outdoor samples of particulate matter (PM), carbon dioxide (CO_2), radon, temperature, and relative humidity (RH). PM was collected using Dylos laser particle counters (Dylos Corporation 2019); radon was measured using AirThings digital radon detectors (Air Things 2019); and CO_2, T, and RH were monitored using TIM10 non-dispersive infrared diffusion sensors (CO2 Meter 2019). ROCIS has conducted over 50 air handler diagnostics and retrofits city-wide to encourage investments in low-cost interventions, as well as educational workshop to inform participants about mitigation and source reduction techniques. One-hundred and forty-five building owners (commercial and residential) participated in ROCIS, 122 of which represented households. Of the parameters measured across both studies, PM was chosen as the primary pollutant because the instrumentation used to collect samples across both studies was identical. Moreover, PM is recognized by the EPA as a criteria air pollutant and major contributor to burden of disease worldwide. Table 7 provides a brief summary of study parameters consistent across both studies for clarity. The collaboration with ROCIS was a notable opportunity to combine two complimentary data-sets and explore the degree of exposure to indoor air pollution and the impact on QOL. Additionally, the collaboration with ROCIS provides building scientist an opportunity to view and interpret air quality research through a social science lens, a recent call to action from the research community (Corsi 2015, Hubbell, Kaufman et al. 2018, Hoisington, Stearns-Yoder et al. 2019).

Table 7. Parameters consistent across both studies

Study parameters	
EJCAM study (n = 13)	ROCIS study (n = 38)
Indoor air PM*, BC, Radon, TVOCs, HCHO, RH, T	**Indoor air** PM*
Outdoor air PM*, NO_2, NO, O_3	**Outdoor air** PM*
Survey & Evaluations QOL Survey* Home Characterization Survey* Activity Diaries Intervention Workshop Evaluations	**Survey & Evaluations** QOL Survey* Home Characterization Survey*

Two stationary monitoring stations were installed on the roof of the CBO to obtain spatio-temporal estimates of outdoor air quality data. Continuous 24-hour samples of PM, nitrogen oxide (NO_x), ozone (O_3), nitrogen dioxide (NO_2), temperature, and RH were collected and made accessible to participants via the internet. Met One Neighborhood light-scattering nephelometer was used to measure $PM_{2.5}$ (Met One Instruments 2019), and AQMesh electrochemical sensors and light-scattering optical particle counter measured NO_x,O_3, NO_2, T, RH, PM1, $PM_{2.5}$, PM_{10}, and TPC (AQMesh 2019). Additionally, co-located outdoor PM samples were collected with Dylos particle counters at individual households enabling the assessment of pollutants at the hyperlocal level. Outdoor PM samples that corresponded with specific time-of-day were paired with indoor values to explore indoor-to-outdoor ratios as well as plumes of poor air quality. One-hundred and forty-five samples were collected across the Pittsburgh region at various sites (Figure 13), compared to 11 regulatory monitoring sites throughout Allegheny County, Pennsylvania. The analysis from this research aims to provide new understanding of comprehensive long-term monitoring as well as a larger spatial coverage with localized insight.

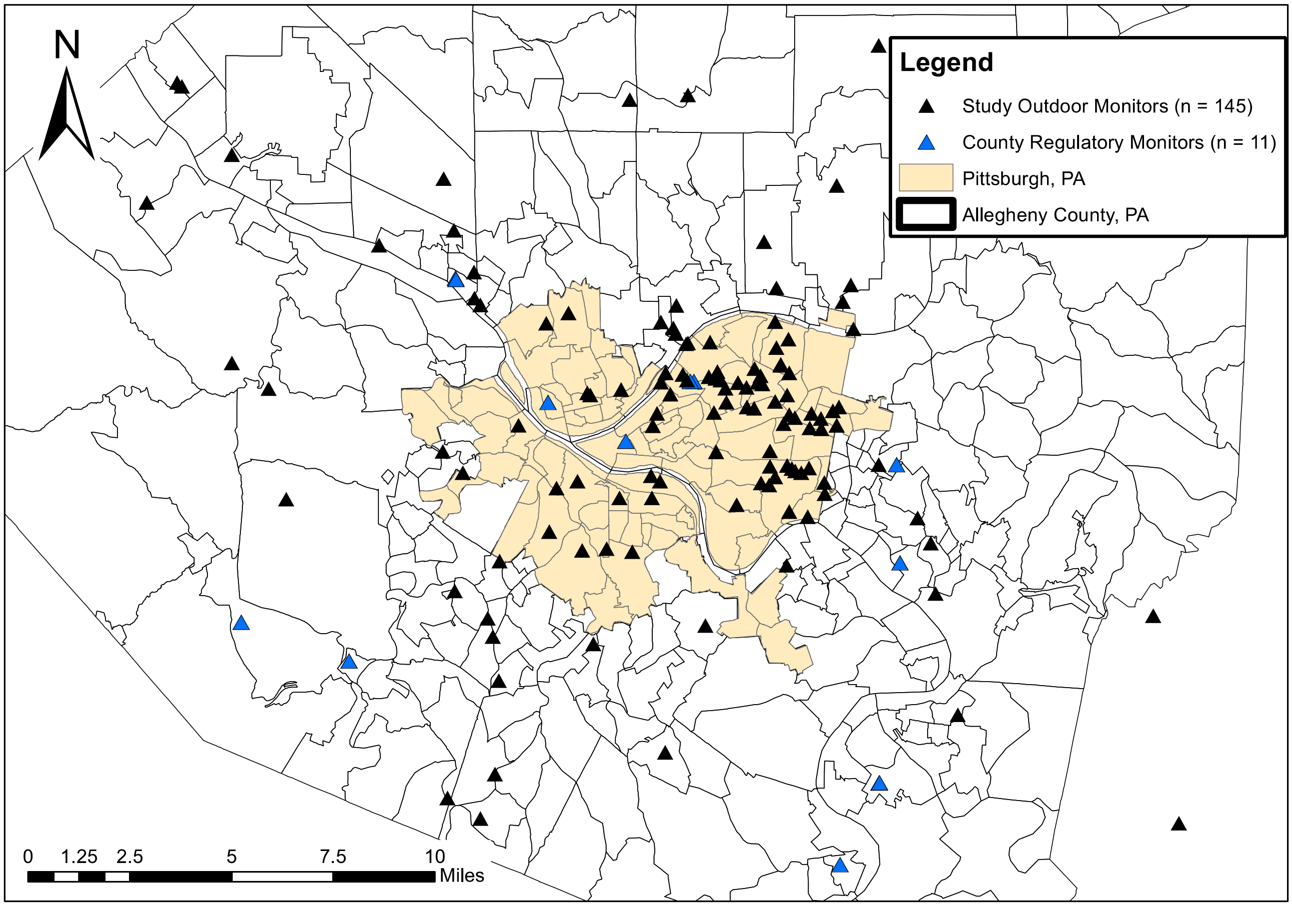

Figure 13. Outdoor air quality monitoring sites - One-hundred and forty-seven samples were collected across the Pittsburgh region at various sites, compared to 11 regulatory monitoring sites throughout Allegheny County, Pennsylvania.

5.2.2 Measurements and Devices

Each of the 13 homes in the study was monitored for 7 – 31 days collecting continuous samples of CO_2, PM, black carbon (BC), RH, radon, temperature, formaldehyde (HCHO), and

TVOCs. Air sampling equipment include National Institute of Standards and Technology (NIST) calibrated Graywolf 3016 Handheld airborne particle counter, Graywolf FM801 formaldehyde detector, Graywolf AdvancedSense Probe, AethLab Micro-Aethalometer, Corentium Digital Radon Gas Detectors, and Dylos particle counters. The installation of each device was a simple process; five devices ran on AC power and one device was battery operated. Each device was stored on an equipment stand 0.6 meters above the ground located in the common space or main activity room of each home and at least 0.5 meters away from windows and combustion or heat sources. The equipment installation and home visit lasted about one hour. During this initial visit, informed consent was received and a Quality of Life (QOL) survey was administered. A home characterization survey was administered in-person on the final sampling day.

5.2.3 Quality of Life Survey

During the initial home visit, following the equipment set up, the research coordinator met with the self-identified head of the household to assist as needed in completing a QOL survey. The QOL survey was intended to evaluate subjective wellbeing and was developed from two well-established instruments, the Center for Disease Control and Prevention's Behavioral Risk Factor Surveillance System Questionnaire (BRFSS) (CDC 2014) and the World Health Organization Quality of Life Instrument (WHO-QOL) (WHO 1998). The QOL survey covered four domains: socio-economic development (household income, unemployment, type of jobs, quality of jobs, cost of living, poverty, and homelessness); human development (satisfaction of higher and lower order needs); sustainability (resident health, and sustainable ecosystems); and personal utility (social life, leisure life, family life, spiritual life, etc., and community conditions and services) [IRB #PRO15060520] (WHO 1998, CDC 2014).

Each survey contained 41 fixed-response and dichotomous questions, and Likert items; dichotomous response sets cover topics of human development and sustainability, and were used to characterize qualitative aspects of the physical and social environment. Likert scale items assigned a weight or intensity to point responses, which were used for quantitative merit. For example, taken from the QOL survey, Question #31, 'To what degree does the quality of your home meet your needs?' – 'Not at all' (1), 'A little' (2), 'A moderate amount' (3), or 'An extreme amount' (4). Survey results were analyzed in aggregate, in which responses cannot be identified individually. The collection of sensitive information about subjects is limited to the amount necessary to achieve the aims of the research, and the de-identified data was only assessed by the research team. A copy of the QOL survey can be found in Appendix C (page 147).

The data sharing agreement and collaboration with ROCIS was initiated three years after its inception. To this point, QOL surveys were distributed electronically as an additional component to the resident's prior commitment to ROCIS. Of the 122 participating households, 38 responded to the survey link. Combining the 13 homes from the individual assessments (EJCAM study) made for a total of 51 homes. After accounting for incomplete surveys, a final sample of 41 homes was used to associate indoor PM and QOL.

5.2.4 Home Characterization Survey and Activity Diaries

The self-identified head of the household completed a home characterization survey which included items on household infrastructure and housing composition, details on stove fuel type (i.e., gas, electric), HVAC characteristics, foundation type, number of windows, and frequency of window opening, to name a few. A copy of the home characterization survey can be found in Appendix C (page 157). Participants were also required to keep an activity diary to log and track the time and frequency of indoor source events (i.e., smoking, cooking, cleaning).

The home characterization survey was created by ROCIS and the accompanying QOL survey was approved by the University of Pittsburgh Institutional Review Board (#PRO15060520).

5.2.5 Data Analysis

5.2.5.1 *Indoor and Outdoor Air*

Indoor and outdoor air quality data summaries were compiled in Microsoft Excel, Minitab Express version 1.5.1., and R programming software. Among the analysis employed were descriptive statistics including line plots, Spearman correlation coefficients, ANOVA, and linear regression.

Outdoor air quality dispersion maps were rendered in ArcGIS 10.5. Kriging, a popular geostatistical procedure used for interpolating spatial data, was used to generate prediction surfaces of particulate matter dispersion across the specified geographical area. The Kriging technique weights the surrounding measured values to derive an estimate for unmeasured locations. The underlining equation is formed as a weighted sum of the data:

$$\hat{Z}\,(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

(5-1)

In Equation 5-1, $Z(s_i)$ is the measured value at the *i*th location, λ_i an unknown weight for the measured value at the *i*th location, s_0 the prediction location, and *N* the number of measured values (ArcGIS 2019).

5.2.5.2 *Quality of Life*

The overall objective of this research was to compare the effect of indoor air quality on QOL. The literature shows that it is difficult to categorize measures of QOL because individuals define QOL based on personal experiences, social and physical environments, and several different aspects of wellbeing (Post 2014). To this point, QOL is multidimensional; therefore, individual variables from the QOL and home characterization surveys, and their effect on the overall QOL rating were examined first. Forty-two questions were rated by participants; the correlation among individual survey questions responses and the overall QOL score was assessed. A regression equation was created from a subset of variables (or survey questions) based on the strength of each association to the overall QOL rating. The influence of air quality results on individual question responses and the overall QOL score was than analyzed by multiple linear regression in SPSS Statistics software package.

5.3 Results and Discussion

5.3.1 Sociodemographic and Environmental Characteristics of Each Home

Table 8 shows sociodemographic characteristics for the study group. In this sample, 62% were female, 27% were above the age of 60, and 47% had a four-year college degree. The majority of study participants were employed, yet close to half (39%) earned less than $50,000 per year in annual income. In total, *60% of the study participants suffered from a non-communicable disease and 23% had two or more chronic health conditions*; the most commonly occurring conditions being asthma (19%), arthritis (15%), depressive disorder (13%), cancer (10%), and diabetes (10%).

More than half of the study participants suffered from preexisting health conditions. From this, the conclusion is drawn that citizen science efforts are driven by a desire to learn but also personal concerns. Chi-square test results reinforced this conclusion and confirmed that participants were more likely to enroll in this study due to concerns about general health ($p < .001$). Citizen science campaigns also help to create motivated community members and berth local action. Sixty-seven percent of study participants agreed that “being involved in this study has influenced the development of local action to reduce air pollution exposure and improve public health". Lastly, the literature recognizes challenges in the engagement of local residents in academic research, largely fueled by distrust in outside institutions. When asked if "being involved in this study has affected interactions with academic researchers and instilled trust in traditional air quality monitoring", 76% of participants agreed to a 'moderate and extreme amount'. These results reinforce the contribution of citizen science and social science in understanding air quality research; community-based research and other methods of engagement can shape risk perception and risk governance.

Table 9 presents environmental characteristics of each household covering aspects of infrastructure and housing composition. The range of housing varies in fuel use, year built, nighttime occupancy, smoking status, heating and air conditioning system, flooring type, and pet ownership. The average household size was 3 persons and the majority of the homes were owned by the occupants, with only 18% living in rented housing. More than half (67%) of the homes were built before 1940; however, 66% of participants rated the infrastructure (i.e., roads, buildings, homes) in their community as safe and in good condition. Only 8% recorded smoking indoors while 58% owned pets.

Table 8. **Demographic characteristics**

Characteristic	No. (%)
Gender	
Male	18 (38.30)
Female	29 (61.70)
Age, y	
18 - 29	7 (15.56)
30 - 39	7 (15.56)
40 - 49	8 (17.78)
50 - 59	11 (24.44)
> 60	12 (26.67)
Race/ethnicity	
White	29 (65.91)
African American	13 (29.55)
Other	2 (4.55)
Education	
Grade 12 or GED (High school graduate)	3 (6.67)
College 1 year to 3 years (Some college or technical school)	8 (17.78)
College 4 years (College graduate)	21 (46.67)
Post graduate (Masters or PhD)	13 (28.89)
Employment	
Employed for wages	26 (59.09)
Self-employed	6 (13.64)
Out of work for 1 year or more	1 (2.27)
Homemaker	1 (2.27)
Retired	9 (20.45)
Unable to work	1 (2.27)
Household annual income	
0 - $29,999	11 (25.00)
$30,000 - $49,999	6 (13.64)
$50,000 - $99,999	14 (31.82)
$100,000 - $349,999	13 (29.55)
More than $350,000	0 (0)
Child < 18 y in household	
Yes	15 (30.61)
No	34 (69.39)
Health Conditions	
None	16 (33.33)
Two or more	11 (22.92)
Asthma	9 (18.75)
Arthritis	7 (14.58)
Depressive Disorder	6 (12.50)
Cancer	5 (10.42)
Diabetes	5 (10.42)
Allergies	3 (6.25)
Chronic bronchitis	2 (4.17)
Functional disorders (i.e., Gastrointestinal)	2 (4.17)
High blood pressure	2 (4.17)
Chronic obstructive pulmonary disease (COPD)	1 (2.08)
Lupus	1 (2.08)
Hypoglycemia	1 (2.08)
Pulmonary embolism	1 (2.08)

Table 9. Environmental characteristics

Characteristic		No. (%)
Homeownership		
	Own	38 (77.55)
	Rent	9 (18.37)
	Other Arrangement	2 (4.08)
Year built		
	Before 1940	32 (66.67)
	1940 - 1990	12 (25.00)
	1990 - newer	4 (8.33)
The infrastructure (i.e., roads, buildings, homes) in your community is safe and in good condition.		
	Not at all	4 (8.51)
	A little	12 (25.53)
	A moderate amount	28 (59.57)
	An extreme amount	3 (6.38)
Smoking status		
	Every day	4 (8.33)
	Some days	0 (0)
	Not at all	44 (91.67)
Stove type		
	Electric range	15 (30.61)
	Gas range	34 (69.39)
Heating System		
	Boiler	7 (16.28)
	Zonal	3 (6.97)
	Furnace	28 (65.12)
	Central heat	3 (6.97)
	None	2 (4.65)
Air conditioning system		
	Central AC	21 (45.65)
	Room AC	12 (26.09)
	Other	6 (13.04)
	None	7 (15.22)
Nighttime occupancy		
	1	12 (24.49)
	2 - 3	26 (53.06)
	4 ≧	11 (22.45)
Percent carpeted flooring		
	< 50 %	32 (64.00)
	≧ 50 %	18 (36.00)
Pets		
	Yes	29 (58.00)
	No	21 (42.00)

5.3.2 Summary of Indoor Air Quality Parameters – EJCAM Study

To illustrate diurnal patterns in indoor concentrations, one-minute samples of various pollutants were averaged by hour of day over the course of a full week. Time-resolved hourly concentrations of CO_2, TVOCs, T, RH, PM $_{(0.3-10)}$, and BC are shown in Figure 14 averaged by time of day across the thirteen samples homes between May 2016 and April 2017. Average full-week concentrations by season for individual homes can be found in Table 10.

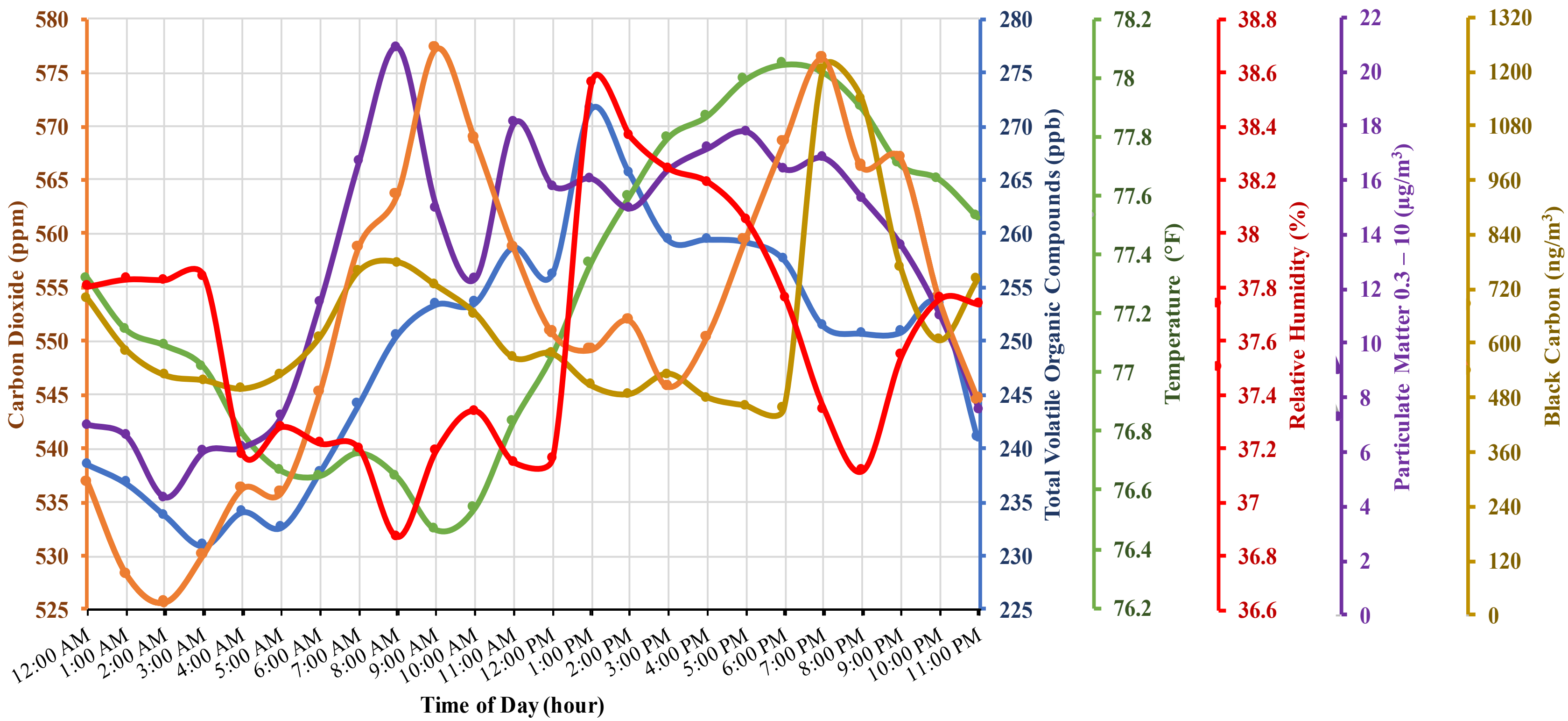

Figure 14. Time-resolved hourly concentrations of CO_2, TVOCs, T, RH, PM (0.3 – 10), and BC - Summary of indoor air quality parameters averaged by time of day across 13 homes involved in the EJCAM study.

Table 10. Summary of measured indoor air quality parameters across 13 homes in EJCAM study.

Cooling Months (May - September)

	PM2.5 (μg/m³)		PM10 (μg/m³)		BC (ng/m3)		TVOC (ppb)		CO_2 (ppm)		T (°F)		RH (%)		HCHO (μg/m³)		Radon, Basement (pCi/L)	Radon, Living Room (pCi/L)
Home	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	Mean
1	**19.1**	(17.3)	**31.9**	(39.3)	896.6	(634.1)	40.6	(39.2)	507.4	(90.4)	79.5	(4.2)	43.8	(3.1)	14.3	(1.8)	0.6	0.4
2	3.2	(4.5)	10.9	(15.4)	226.6	(672.1)	**234.8**	(158.4)	**1108.1**	(356.0)	80.2	(3.2)	42.7	(3.2)	23.8	(6.1)	2.1	1.1
3	1.8	(1.3)	4.5	(5.2)	470.9	(567.6)	159.5	(134.8)	425.6	(76.6)	75.1	(3.3)	42.2	(3.7)	**39.1**	(8.9)	1.5	0.5
4	7.2	(9.5)	8.4	(11.4)	998.4	(641.8)	221.0	(53.1)	497.4	(151.0)	76.8	(4.9)	54.2	(4.8)	18.8	(3.7)	0.5	0.2
5	3.4	(2.8)	8.1	(11.2)	807.0	(4810.6)	62.4	(19.8)	453.1	(58.2)	**83.9**	(1.9)	**56.1**	(4.0)	19.1	(7.9)	0.6	0.2
6	5.1	(4.7)	10.3	(10.0)	**1535.4**	(1918.0)	134.8	(53.3)	644.7	(60.1)	75.9	(0.7)	48.4	(2.5)	24.4	(9.9)	0.5	0.3
7	1.5	(3.0)	3.0	(8.5)	447.5	(2387.3)	161.8	(90.0)	395.8	(43.2)	81.4	(0.8)	55.2	(4.5)	-	-	1.3	1.0
8	0.3	(0.3)	0.4	(0.3)	663.9	(475.9)	100.5	(28.9)	421.8	(58.0)	77.3	(0.4)	47.3	(3.3)	19.8	(2.6)	0.5	0.5
9	8.9	(11.9)	12.8	(15.4)	-	-	162.4	(42.9)	408.6	(50.6)	80.7	(1.2)	52.2	(3.5)	26.3	(6.1)	2.6	0.9
10	15.2	(15.0)	31.6	(46.9)	615.6	(3723.3)	154.3	(67.2)	645.5	(194.2)	77.4	(1.1)	55.9	(4.7)	30.0	(4.2)	1.4	0.9
11	10.8	(29.6)	28.5	(124.7)	830.3	(1133.8)	113.0	(95.4)	585.0	(137.9)	74.0	(4.3)	45.6	(4.3)	21.6	(4.3)	**2.9**	**1.4**
12	7.26	(5.7)	17.2	(34.6)	419.1	(407.1)	74.7	(30.0)	442.5	(124.1)	69.4	(4.5)	41.3	(8.4)	17.5	(3.3)	0.21	0.13
13	12.6	(7.6)	18.7	(28.6)	459.3	(1206.2)	0.0	(0.0)	668.6	(215.8)	78.3	(1.2)	25.7	(2.8)	13.3	(0.8)	0.9	0.3
ALL	7.4	(8.7)	14.3	(27.0)	697.5	(1548.1)	124.6	(62.5)	554.2	(124.3)	77.7	(2.4)	47.0	(4.1)	22.3	(5.0)	1.2	0.6

Heating Months (November - April)

	PM2.5 (μg/m³)		PM10 (μg/m³)		BC (ng/m3)		TVOC (ppb)		CO_2 (ppm)		T (°F)		RH (%)		HCHO (μg/m³)		Radon, Basement (pCi/L)	Radon, Living Room (pCi/L)
Home	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	Mean
1	**16.8**	(18.80)	**36.1**	(38.66)	663.7	(864.1)	436.2	(121.6)	699.9	(100.4)	**83.8**	(2.2)	19.6	(6.4)	< LOD	(0)	**9.0**	0.9
2	7.5	(25.23)	21.4	(63.99)	341.0	(343.1)	**675.2**	(58.3)	**760.9**	(198.9)	77.7	(1.3)	32.3	(2.9)	14.2	(1.9)	5.7	**4.3**
3	4.1	(4.53)	8.7	(21.6)	240.8	(183.3)	199.6	(40.0)	524.2	(116.7)	80.4	(1.1)	13.3	(1.8)	< LOD	(0)	1.7	0.8
4	2.3	(1.55)	6.9	(6.43)	397.2	(567.4)	454.0	(113.3)	492.4	(179.0)	72.6	(2.0)	16.2	(2.5)	< LOD	(0)	1.6	0.4
5	4.4	(15.66)	18.6	(72.1)	159.1	(440.9)	407.0	(198.2)	488.6	(51.7)	70.8	(1.3)	24.3	(2.0)	13.0	(0)	0.8	0.6
6	2.7	(5.06)	7.1	(5.06)	874.0	(2273.0)	458.1	(99.7)	434.3	(39.3)	72.8	(3.0)	22.7	(6.4)	< LOD	(0)	0.4	0.3
7	2.0	(5.16)	5.0	(13.6)	312.9	(403.5)	491.5	(81.4)	568.7	(194.7)	74.9	(1.8)	28.4	(6.5)	< LOD	(0)	2.2	2.1
8	1.4	(1.44)	3.1	(3.27)	186.0	(452.0)	565.0	(43.6)	453.5	(41.3)	74.0	(1.2)	20.9	(3.2)	< LOD	(0)	0.6	0.4
9	3.6	(7.31)	6.9	(11.6)	**902.2**	(1,875.1)	72.6	(54.4)	504.0	(64.7)	83.7	(2.3)	**50.6**	(4.7)	17.0	(2.4)	0.9	0.8
11	1.1	(2.49)	4.7	(13.2)	311.4	(367.4)	-	-	-	-	-	-	-	-	< LOD	(0)	1.4	1.2
12	1.5	(0.90)	4.9	(3.33)	608.7	(834.5)	-	-	-	-	-	-	-	-	**17.5**	(3.1)	0.2	0.1
ALL	4.3	(7.79)	11.2	(23.4)	454.3	(5225.0)	417.7	(47.6)	547.4	(62.4)	76.7	(0.6)	25.4	(1.9)	15.4	(1.2)	2.2	1.1

*Missing data is from occupants interferring with equipment; two homes withdrew from the study during the subsequent heating months; highest concentrations in bold

5.3.2.1 *Carbon Dioxide - EJCAM*

Although CO_2 is a by-product of human respiration and not considered a pollutant, elevated levels indoors can indicate inadequate ventilation and the presence of biological contaminants (Hägerhed-Engman, Sigsgaard et al. 2009, Ramalho, Wyart et al. 2015). The lowest hourly concentration was observed from 3:00 PM – 4:00 PM when residences were largely unoccupied. The greatest concentrations of CO_2 for all investigated homes were observed in the evenings and mornings between the hours of 6:00 PM and 11:59 PM, and 6:00 AM to 11:59 AM. The highest hourly CO_2 concentration (1422.5 ppm) was recorded from 10:00 AM – 11:00 AM reflective of morning routines such as cooking and grooming. Other studies have documented higher concentrations of CO_2 overnight during sleep (Hsu, Lee et al. 2012, Stamatelopoulou, Asimakopoulos et al. 2019), but readers should note that in this research the sampling equipment was located in the living room not the sleeping zone (bedroom). CO_2 levels also differed among the three occupancy groups. CO_2 concentrations in homes with 4 or more occupants were on average 2.2 times higher than individually occupied homes. CO_2 levels also tended to be highest during the heating months (Table 10). The lower levels in spring and summer are due to frequent window opening events and its potential to dilute stagnant air. Although not shown here, minute-to-minute instantaneous readings frequently exceeded 700 ppm above ambient levels (~350 – 400 ppm) and corresponded to PM ($PM_{0.3-10}$ and BC) source events. The impact of human activities (i.e., cleaning, walking, cooking) on PM generation can also be observed by the hourly peaks shown in Figure 14.

5.3.2.2 *Total Volatile Organic Compounds and Formaldehyde - EJCAM*

The summation of all VOCs is called Total Volatile Organic Compounds (TVOCs). Although TVOC effects may be difficult to interpret, there is no doubt that the technique is useful. Early work by Molhave (1991) provides comfort ranges for TVOC levels and later work by Jokl (2000) provides odor intensities; based on these findings, comfort is achieved at < 200 $\mu g/m^3$ and perception of moderate to strong odors are noted between 200 – 3000 $\mu g/m^3$.

Seven of the monitored homes exceeded the comfort range of < 200 $\mu g/m^3$ and Home 2 had the highest concentration. Based on the home characterization survey, Home 2 purchased new furniture prior to the monitoring period and also housed three adolescents who used large quantities of fragrances daily. The average TVOC concentration across the sample during the cooling (summer and spring) and heating months (winter and fall) were 124.6 $\mu g/m^3$ and 418 $\mu g/m^3$, respectively. Seasonal effects were statistically different to the enclosed nature of homes during heating months which can produce a buildup of VOCs from cleaning/sanitizing products. In Figure 14, the gradual increase in TVOC concentrations between 5:00 AM – 1:00 PM also corresponds with increases in temperature and relative humidity. The results suggest that warmer indoor temperatures and higher humidity can cause reactions between oxidants in indoor air and those absorbed on surfaces therefore increasing the potential of chemical reactions and emissions from building materials.

One-minute samples were taken at each home and then averaged over a 7-day period for the listed environmental parameters with the exception of formaldehyde (HCHO). Formaldehyde was logged to the monitoring device in 30-minute increments, therefore, minute-to-minute instantaneous readings were not available. More than half of the 30-minute samples recorded below the limit of detection (LOD). In this case, the mode and max were used as the most representative values from the datasets to assess persistence of formaldehyde indoors. Based on literature values, summary work by the World Health Organization (WHO) sets guidelines for short-term (30-minute) sensorial irritation at 10 $\mu g/m^3$ and long-term cancer effects at 125 $\mu g/m^3$ (Paustenbach, Alarie et al. 1997, Arts, Rennen et al. 2006, Kaden, Mandin et al. 2010). The modal indoor concentrations of formaldehyde were between 14 and 40 $\mu g/m^3$, or 1.3 and 4.0 times higher than the short-term recommended exposure limit.

Among the sample, Home 3 exceeded the WHO recommendation 100% of the time from formaldehyde. From the observations, the living room space displayed a prolific amount new consumer products such as textiles, toys, and art materials. The head of the household reported repeated hospitalization of a toddler from asthma exacerbations during the weekly monitoring period, suggesting a potential relationship between formaldehyde exposure and exaggerated immune reactions or atopy. Other studies have also reported positive associations between formaldehyde and atopy (Krzyzanowski, Quackenboss et al. 1990, Garrett, Hooper et al. 1999, Rumchev, Spickett et al. 2002). Seasonal effects were significant across residences; only 4 homes recorded HCHO concentrations above the LOD during the heating months compared to 12 of the 13 homes during the cooling months. Other studies have also found a significant difference between winter and summer concentrations (Kalinic and Sega 1996, Dingle and Franklin 2002, Heroux, Clark et al. 2010). One explanation for this, as explained prior, could be from summer/spring heat and humidity increasing the chance of releases from adhesives and consumer products indoors as well as secondary formation from other VOCs in the home.

5.3.2.3 *Radon - EJCAM*

Radon is a known carcinogen and the leading cause of lung cancer among nonsmokers (WHO 2009). Most exposure occur in homes, where radon seeps through foundations and enters homes through basements and crawlspaces. The challenges of aged and deteriorating infrastructure directly impacted the results. Table 10 presents individual home results collected in both the basement and living room. Radon levels in homes built before 1940, were on average 69% higher than conventional homes built after 1940. The oldest home, Home 1 (1890) recorded the highest basement sample during the heating months at 9.0 pCi/L, which exceeded the acceptable limit recommended by the USEPA at 4.0 pCi/L. Lower radon levels were observed in the living rooms (0.8 pCi/L) when compared to the basements (1.7 pCi/L), on average 2.1 times lower, which is important considering a higher percentage of time is spent in living rooms within homes. The greatest differential between basement and living room values was observed at Home 1, 4.2 pCi/L. Uniquely, Homes 8, 11, and 12 saw a less profound difference, just 0.1 pCi/L, between living room and basement levels denoting the important role of airflow and air infiltration on exposure scenarios.

5.3.2.4 *Particulate Matter - EJCAM*

Differentiating indoor PM from indoor- and outdoor-generated sources has been carried out by many studies, but can become expensive when investigating chemical composition of particles by laser mass spectrometry and other techniques. To this point, the analysis of black carbon samples alongside activity diary data has been used as a simpler approach to determine the influence of outdoor generated particles on indoor concentrations (Nicole Biggs and Christopher Long 2016, Cox, Isiugo et al. 2018, Michael J Gatari 2019). Herein, analysis of indoor-to-outdoor ratios, size bin distributions, and home characterization survey data, were used to pinpoint PM sources and investigate peak exposure profiles.

The largest PM concentrations were observed in homes where occupants smoked tobacco and marijuana indoors (Home 1, Home 10, Home 13), and Home 11 that was occupied by pets and also reported renovation activities during the study period. The smallest PM concentrations were observed in Home 8, despite also being occupied by pets. This difference could be due to several factors. The occupants of the home reported being absent 85% of the study period and the activity diary records indicate no stove-top frying or grilling events. The home characterization survey also shows 100.0% of the home had hard-surface flooring; the positive effect of hard-surface flooring on decreased dust loading and resuspension of PM has been documented in others studies as well (Shaughnessy, Turk et al. 2002, Ferro, Kopperud et al. 2004, Hu, Freihaut et al. 2008).

Figure 15 displays the sum of the mass concentrations for particles less than 10 µg/m^3 in each size bin. The results mirror those of Abt et al. (2000) and Long et al. (2011) and show that coarse particles ($PM_{2.5-10}$) represent a major portion of indoor PM across the study home. Coarse particles are generally from indoor sources such as cooking and cleaning (Long, Suh et al. 2011), resuspension from dust reservoirs such as furniture and textiles (Ferro, Kopperud et al. 2004), or coagulation of fine particles overtime. On the contrary, fine particles (< $PM_{2.5}$) dominated indoor PM in Home 10 and Home 13. Together, fine particles (combustion-related particles) represented 63.6 % of indoor PM and based on activity diary data corresponds best to frequent smoking events indoors.

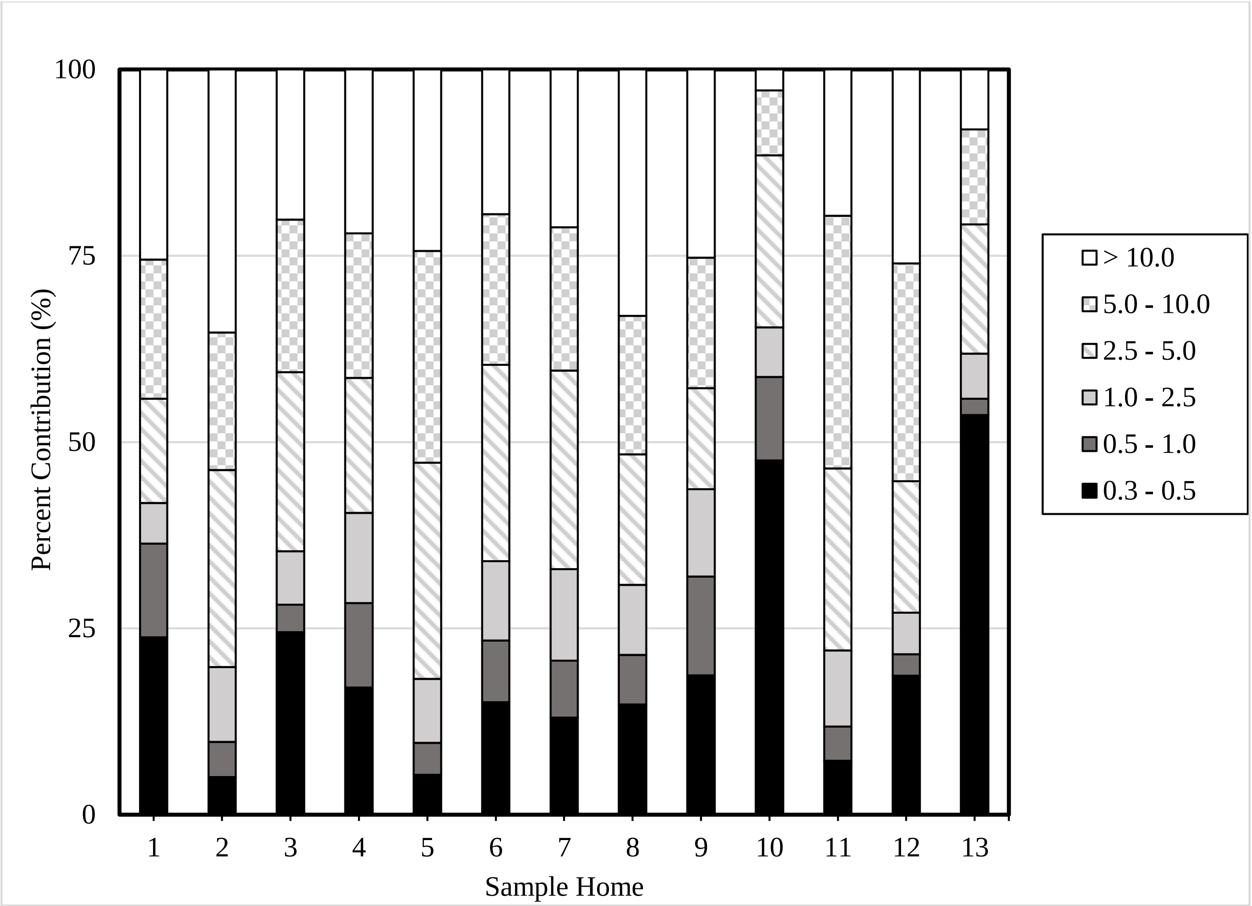

Figure 15. PM indoor concentration by bin distribution - Contribution of indoor particle mass concentrations displayed as percentage of total mass concentration sampled.

5.3.3 EJCAM and ROCIS study

5.3.3.1 *Indoor and Outdoor Particulate Matter*

Figure 16 combines data from the EJCAM study and ROCIS study and depicts average particle number counts (PNCs) across 51 homes by hour of day. Sixteen of the 51 homes are within 2 miles of a major industrial facility which operate overnight. This is reflected in larger outdoor emissions profiles overnight (Figure 16). Average PNCs were 611 and 1902 for indoor and outdoor samples, respectively; the greatest differential at an individual home was 6000 PNCs or 12 times greater.

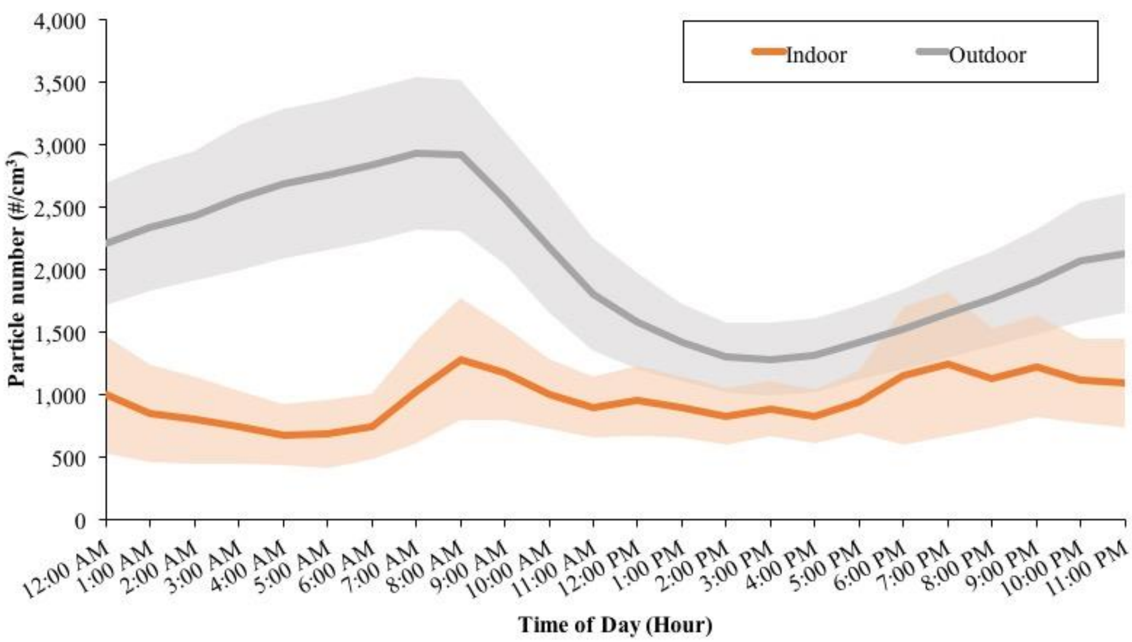

Figure 16. Comparison of indoor and outdoor $PM_{2.5}$ concentrations - Combined PM concentratins from both EJCAM and ROCIS by time of day averaged across 51 sample homes; line plot bands represent 95% confidence interval.

PNCs obtained by Dylos were converted to $PM_{2.5}$ mass concentrations for better interpretation of the results as well as future comparability with other studies. A recent publication by Franken et al. (2019) placed Dylos particle counters side-by-side with conventional gravimetric monitors and compared the statistical fit curve with results from three methods in the current literature (Semple, Apsley et al. 2013, Dacunto, Klepeis et al. 2015, Steinle, Reis et al. 2015). The method developed in the highlighted study showed the highest Pearson and concordance correlation and was therefore used to evaluate the particle diameter and mass concentrations in. The potential long-term impacts of outdoor air pollution are reflected in outdoor concentrations being on average 2.3 times higher than indoor concentrations. The average values of outdoor $PM_{2.5}$ exceed the annual (35 μg/m^3) National Ambient Air Quality Standard (NAAQS) at 37 % of the sample locations.

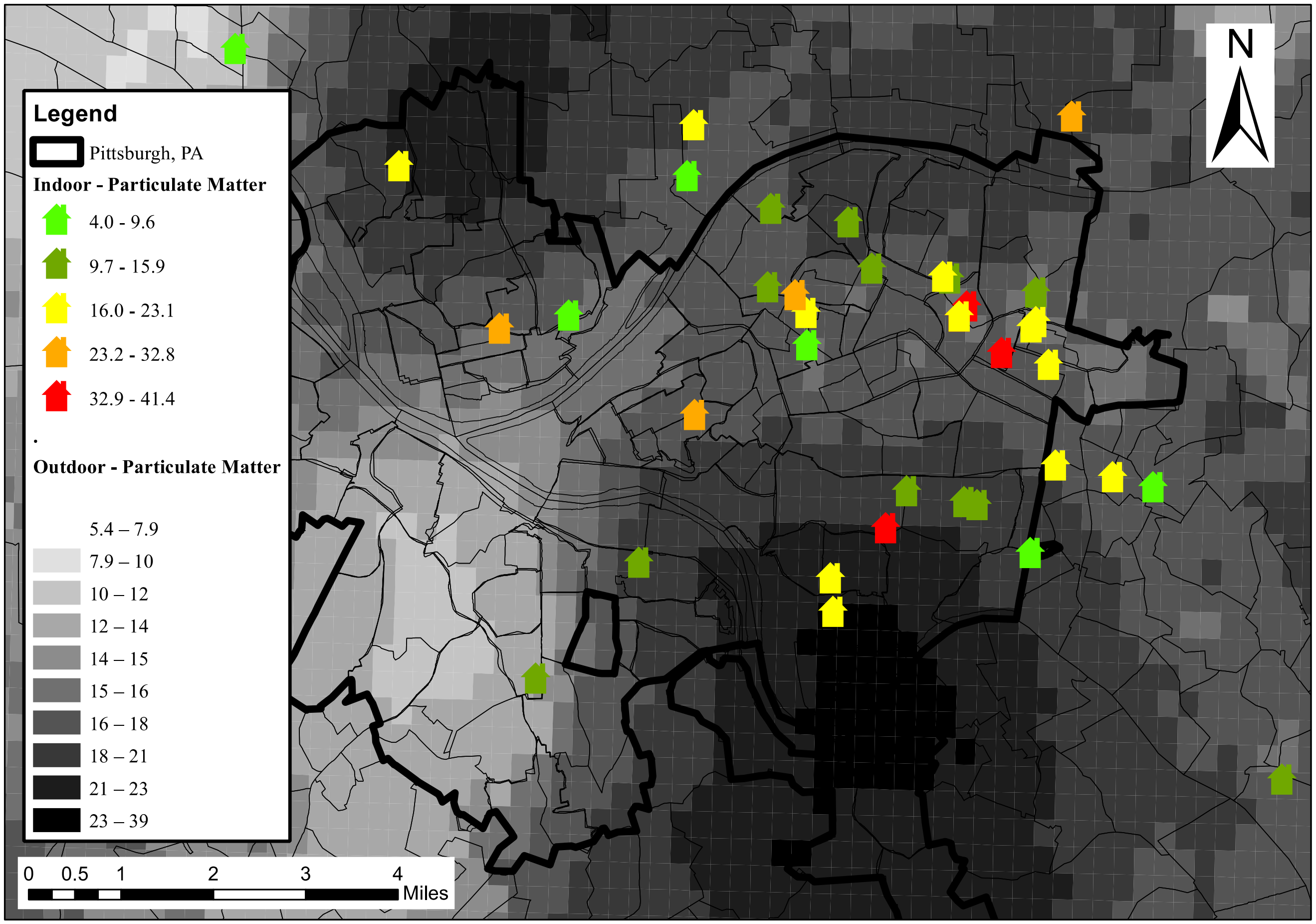

Figure 17. Map of average indoor and outdoor PM2.5 concentrations - Average indoor and PM2.5 concentrations by samples homes, and estimated outdoor PM2.5 concentrations by neighborhoods of the Pittbsurgh region and the surrounding county.

5.3.3.2 *Quality of Life*

Bivariate analysis of the 41-question QOL survey responses suggests that household income (r = 0.57), poor mental health days (r = -0.71), depression (r = -0.77), anxiety (r = -0.66), everyday functionally (r = -0.62), and living in a safe and secure environment (r = 0.52) were independently, significantly associated with the overall QOL rating. Figure 18 presents line plots for each of the six variables, comparing Likert scale or interval responses, and average indoor and outdoor PM concentrations within groups. Higher indoor PM levels were synonymous with lower Likert items made evident by the best-fit lines in each plot. For example, Figure 18 (f), 'What is your combined annual household income from all sources', indoor PM decreases as income increases. The raw data showed some minor irregularities, but this is due to the distribution or number of responses to each Likert item within questions. The visualization from the line plots indicate that indoor air quality is associated with different aspects of QOL independent from its association with the overall QOL rating.

Based on these results, multiple linear regression analyses were performed to determine the strength of the effect that the six predictor variables have on the overall QOL rating, and to forecast the effects or impacts of indoor PM. In the first model, the aforementioned predictor variables were entered simultaneously to control for their effects, and in the second model, their interaction was investigated adding indoor PM alongside the variables in model 1. In model 1, the adjusted R-square value shows that 79% of the variation in QOL is explained by the predictor variables (Table 11). In model 2, the adjusted R-squared value decreases when indoor PM is added

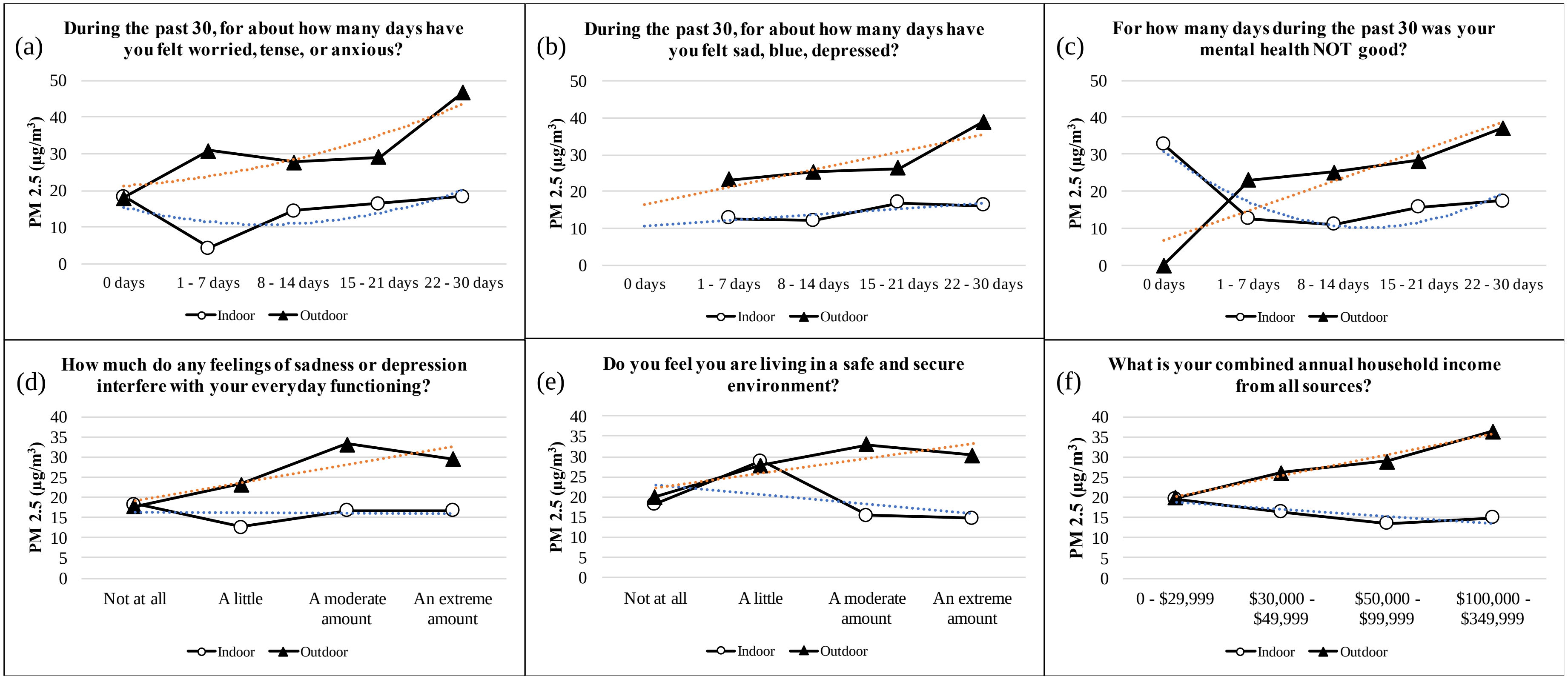

Figure 18. PM versus QOL - Mean indoor and outdoor PM values versus six QOL predictor variables.

denoting it failed to improve the model. Although the effect of adding indoor PM to the model is less profound than expected (very low and also not significant), the beta coefficient is negative supporting the prior claim that indoor PM negatively impacts QOL. Given that the sample size is small, and the multidimensional aspects of QOL, the analysis is considered the beginning of needed research in IAQ and QOL that will serve as the basis of future work and a supplement to a larger field campaign led by the research team. Lastly, open-ended responses from the QOL survey were processed into open codes. Participants were asked what aspects of life worry them most. From the qualitative responses, five categories, health, finances, employment, family, and neighborhood, were denoted as most concerning. These five categories along with the six predictor variables can be used as elements to define the multidimensional aspects of QOL and inform the survey techniques moving forward.

Table 11. Results of multiple linear regression

Variables		R	R Square	Adjusted R Square	B	Std. Error	Sig.
Model 1		0.906	0.821	0.790			
	Income				1.699	0.489	**0.001**
	Functionality				-1.667	0.899	0.073
	Environment				1.371	0.602	**0.029**
	Mental Health				-1.310	1.328	0.331
	Depression				-1.623	1.472	0.278
	Anxiety				-1.660	0.861	0.062
Model 2		0.906	0.821	0.783			
	Income				1.695	0.505	**0.002**
	Functionality				-1.664	0.916	0.078
	Environment				1.369	0.612	**0.032**
	Mental Health				-1.329	1.417	0.355
	Depression				-1.611	1.522	0.298
	Anxiety				-1.661	0.874	0.066
	Indoor Particulate Matter				-0.002	0.058	0.967

5.4 Limitations

Although the analyses provide some useful insight about IAQ and QOL, there are a number of limitations to the research. First, the sample size is small, additionally, the study participants were volunteers and therefore not generalizable to the entire sample populations. Second, the lack of multiple pollutants to compare in the larger study made teasing out statistical relationships difficult. Additionally, the PM samples in the study were obtained using light-scattering monitors, which could underestimate the results. Lastly, the research was executed with practicality in mind; due to the intrusive natural of measuring air exchange rate, it was not included in the experimental methods.

5.5 Conclusions

To date, many IAQ studies have been conducted in multifamily and public housing complexes, in part due to ease of access. However, within multifamily housing exposure to poor IAQ may originate from neighboring units and shared airspaces (i.e., hallways, elevator shafts) making it hard to quantify the origin of source events and the associated impacts. Additionally, living in apartment complexes may lead to social isolation because they lack common spaces and opportunities for interactions, which can negatively affect reported wellbeing. This research focused on single-family homes to monitor source activities under somewhat controlled conditions and to investigate household and homeowner characteristics independently. Moreover, housing is an important determinant of health and no work has been done to investigate the independent and interaction effects of indoor air quality on quality of life.

Field measurements of air quality are also expensive and time intensive. Studies simultaneously measuring both indoor and outdoor pollutants concentrations over consecutive days are sparse. The sampling campaign required a minimum of seven days of continuous monitoring during each season, with the majority of the homes monitored for longer periods of up to thirty-one days. Co-located outdoor samples were also collected at a central reference monitor and at each home. Pittsburgh, PA, is one region that has long struggled with deteriorating air quality being ranked among the worse in the nation and still not improving. To this point, the investigation of the effects of air pollution on quality of life can guide the direction in this field of research as well as support regulatory action and policy decisions that enhance sustainable and healthy communities.

6.0 Conclusions and Future Work

The overarching goal of this dissertation was to identify sources and the strength of polluting mechanisms/activities in the built environment in an effort to understand and mitigate the long-term effects of environmental degradation on community resilience and quality of life. This goal was achieved through the development and implementation of two model frameworks, one specific to IAQ in an energy conservation district (ECD) and the other in environmental justice (EJ) communities. Fundamentally, using the results from both studies, the aim was to modify behaviors and enforce activities that reduce exposure to indoor air pollution at a community scale.

Generally, air quality sampling campaigns install stationary (in one location the entire monitoring period) devices in buildings for hours and days at a time which may not be representative of exposure scenarios throughout an entire space. The sampling campaign and data management strategies used in the ECD offers improvements to sampling methodologies by evaluating the variability of pollutant concentrations with respect to intrazonal flows within buildings. An in-depth analysis of multiple microenvironments within buildings, such as individual rooms and respective floors, allow for a more detailed observation of transient events and specific emission sources inside individual buildings. Moreover, combining data from seasonal sampling campaigns provided a robust data set to inform strategies for source control and reductions. Increased ventilation is recognized as the primary method to improve indoor air quality by green building schemes (Steinemann, Wargocki et al. 2017), therefore the synthesis of the expanded work will be used to inform building managers and rating systems of other mitigation and reduction strategies. Additionally, the evaluation of indoor air pollution is strengthened by the inclusion of five of the six criteria air pollutants recognized by the Clean Air Act, in addition to various other known human carcinogens. Lastly, the involvement of high-performance and green buildings is meaningful and support growing market demands here in the United States. Green building rating systems at large have focused on energy and material reductions to lessen upstream life cycle impacts, but as the green construction sector aims to outpace traditional construction practices, establishing and sustaining good IAQ should also be kept fundamental.

Future work will include re-administration of the *IAQ Survey* in 2020 to quantify improvements from baseline results. Additionally, future IAQ assessments will be performed to expand the pilot; a vast majority of the ECD has sought interest in routine pollutant monitoring. Lastly, to evaluate life cycle environmental impacts, there is a need for a robust risk assessment approach for quantifying the health burden associated with exposure to internal sources as well as field verified measurements or real-time data opposed to the standard adoption of modeled parameters. With that being said, a life cycle assessment (LCA) framework which incorporates both external and internal factors (IAQ) should be integrated into the ongoing pilot.

Racial and ethnic minority populations have traditionally been difficult to recruit in community-based health and academic research studies, and there are still very few evidence-based strategies that have addressed gaps regarding retention. This research approach expands beyond the traditional norms of community engagement by utilizing the community's ecology in every stage of the research process. The fields of air pollution and environmental justice will benefit from this work through the establishment of a replicable framework that acts as a long-term engineering intervention and consultation for community improvements. Limited research has been conducted in vulnerable communities, in regions with poor ambient air quality, in part due to accessibility barriers and competing priorities. Pressing issues from poverty to crime are at the forefront of these communities, leaving topics of environmental sustainability untouched. Prior works have explored IAQ and its relationship to physical health, yet few studies have correlated air pollution exposures to reduced psychological wellbeing or quality of life; this research aimed to fill the gap in the literature.

The impetus of this research to explore the relationship between IAQ and QOL resulted in the recommendation to conduct a longitudinal study to further explore the relationships (both causation and association) between environmental and social factors in communities. The preliminary results are exploratory and should serve as the stimulus for future work. Additionally, expanding the EJ framework to adjacent neighborhoods and broadening the IAQ sampling campaign to include more homes is the basis of a larger study.

Appendix A Supporting Information for Evaluating Indoor Air Quality in Energy Conservation Districts (Chapter 3)

A.1 Size Range and Instrumentation Resolution

Table 12. Product specifications and limit of detection (LOD)

Equipment	Environmental Parameter	Range/Resolution	Units
Graywolf FM-801	Formaldehyde	< 5.0 - 1,000.0	ppb
Graywolf 3016 Particle Counter	Particulate Matter	0.0 - 4,000,000.0	particles/ft^3
MicroAeth AE51	Black Carbon	0.0 - 1000.0	µg/m^3
Dylos DC1100	Particulate Matter	-	counts
Graywolf Direct Sense Probe	VOCs	5.0 - 20,000.0	ppb
	Carbon Dioxide	0.0 - 50,000.0	ppm
	Relative Humidity	0.0 - 100.0	%
	Temperature: Range:	5.0 - 160.0	°F
	Ozone	0.0 - 1.0	ppm
	Nitrogen Dioxide	0.0 - 20.0	ppm
	Sulfur Dioxide	0.0 - 30.0	ppm
	Carbon Monoxide	0.0 - 500.0	ppm

A.2 Indoor Air Quality Mobile Cart

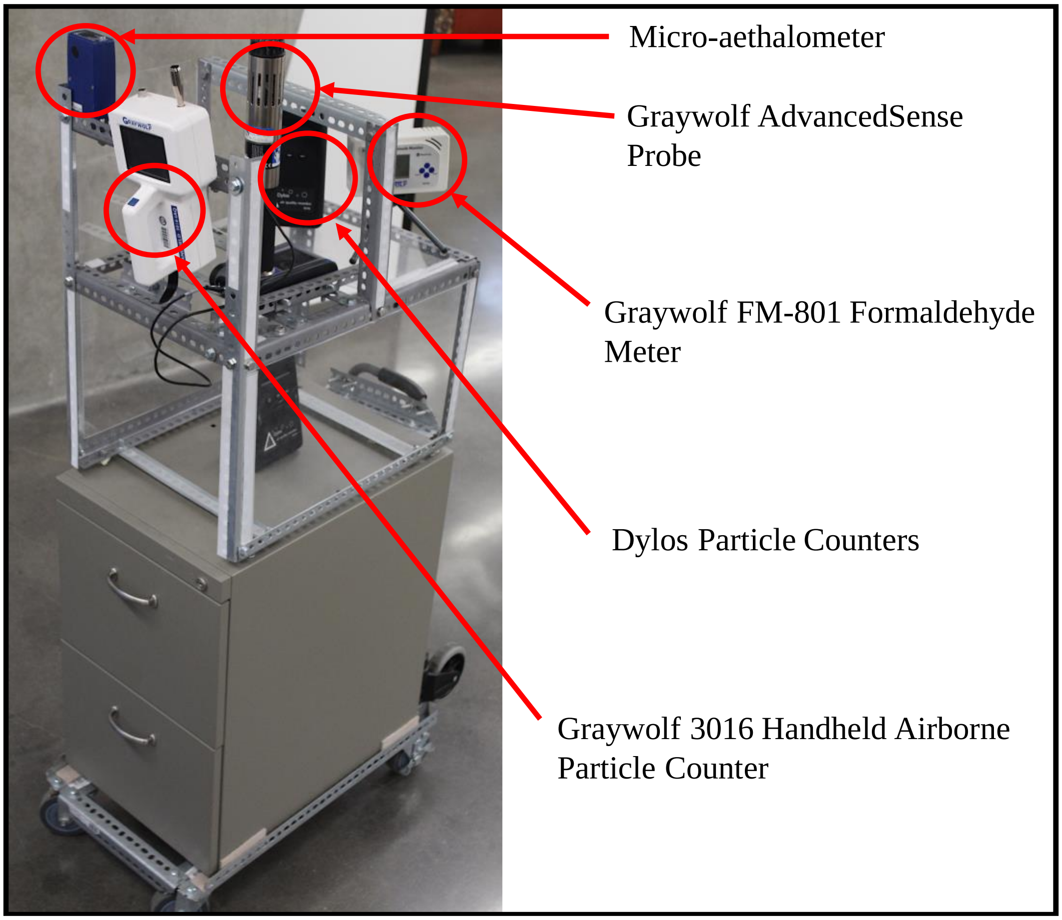

Figure 19. Mobile indoor air quality cart. A mobile cart was configured (a height of 1.5 m), which housed the air monitoring equipment, for flexibility and ease of use.

A.3 Indoor Air Quality Checklist

Table 13. The IAQ checklist designed to support property managers by pinpointing tangible action areas that address IAQ, while also promoting awareness of air quality concepts and terminology to a somewhat unknowledgeable audience.

Category	Criteria	Description	Reference
Construction	Erosion & Sediment Control Plan	An E&SC Plan is created that is site specific and conforms to the more stringent of either the EPA requirements or local erosion and sediment control standards.	LEED BD+C v4 SSp1
	Seal/protect Ducts	Ensuring ducts are closed off during construction will minimize indoor air pollutants that enter the system during construction. Otherwise, all ducts must be vacuumed out before installing distribution equipment.	WELL 07.1
	Material Moisture Protection	All materials that have absorptive qualities must be stored in a safe, dry location. This will help maintain the integrity and lifespan of chosen materials.	WELL 07.3
	Dust Management	Construction area must be divided from other spaces by a sealed media (i.e. door, window). Walk-off mats and collectors on power tools are encouraged to reduce dust.	WELL 07.4
	Air Flush	A building flush-out must be performed both before and after occupancy to ensure the complete off-gassing of new building materials.	WELL 13.1
	Clean Construction Plan	The project must have a Clean Construction Plan that is in accordance with the City of Pittsburgh's Clean Construction Diesel Operations Ordinance and the LEED BC+D: Clean Construction Credit, regardless of the size of the project.	LEED BC+D v4 Pilot credit
	Enhanced Commissioning	The project implements an improved and sustainable commissioning process for mechanical, electrical, and plumbing (MEP), and renewable systems. All systems and their components are reviewed and verified.	LEED BC+D v4 EA.C1
Building Design	Walk-Off Mats	Building install walk-off mats to minimize tracking of particles indoors.	WELL 08.1
	Low VOC Materials	Designers use low VOC paints, adhesives, flooring, insulation, and furniture to decrease human exposure to toxic chemicals indoors. Use the EPA's Environmentally Preferable Purchasing website as a reference.	WELL 04.1-04.5
	Building Material Selection	The design of the facility excludes materials that have asbestos and PCB, as well as minimize the use of products that contain lead and mercury. The International Living Future Institute has created a Red List of materials to be avoided throughout project design and construction.	WELL, LBC 10.1-10.5, M.10
	Air Intake Location	All air intakes are unobstructed and are either on the roof of the structure or above ground level to prevent intake from common pollutants (i.e. diesel exhaust, construction dust).	WELL 07.1
	MERV Filters	Upgrading existing filters to a MERV 8 or higher rating and replace filters on a seasonal basis for maximum efficiency.	WELL 05.2.a
	Smoking Prohibited	Smoking is prohibited in the building (including e-cigarettes) and within 25 feet of air intake vents. Smoking is also prohibited on any balconies, rooftops, or any otherwise regularly occupied outdoor spaces. A facility manager is held responsible for enforcing the rules of a smoke-free work environment.	WELL 02.2.a, 02.2.b

Table 13 (continued)

	Operable Windows	Regularly occupied work spaces must have operable windows to provide both fresh air and access to natural lighting. There must be a system in place that notifies occupants of local outdoor air quality conditions; Real-time data must then be used to influence ventilation strategies to maintain the integrity of the indoor air.	WELL, LBC 19.1-19.3, HH.07
Operation & Maintenance	Annual Monitoring of Indoor Environmental Parameters	Particulate Matter: PM2.5 and PM10 must be less than 15µg/m3 and 50µg/m3 over, respectively (24-hr standard).	WELL 01.2.b, 01.2.c
		Ozone levels must be less than 10 ppb.	P4
		Total Volatile Organic Compounds (TVOCs) must be less than 500 µg/m3.	WELL 01.1.b
		Carbon Dioxide (CO2) values do not exceed 800 ppb, as detailed in the Demand Control System criteria.	WELL 03.2.a
		Radon levels must not exceed 2.7 pCi/L in the lowest occupied level of the facility.	P4
		Carbon Monoxide levels must remain below 9 ppb.	WELL 01.2.a
		Formaldehyde levels must be less then 10 ppb.	P4
	Air Data Monitoring Plan	A policy is created that details how monitoring and record-keeping on indoor air pollutants will be tracked, maintained, and recorded. Real time display of continuous indoor temperature, relative humidity, and CO2 levels is a precondition when establishing air monitoring plan.	WELL 18.1-18.3
	Occupant Surveys	To ensure occupant comfort, indoor occupant surveys are distributed once the facility is in full operation, and on a bi-annual basis. These indoor environmental surveys include metrics for thermal (and humidity), lighting, and air quality satisfaction.	WELL 86.1
	Demand Control System	Projects with an occupant density of 25 people per 1000sf must use either a demand control ventilation system or a verified passive design strategy of operable windows to introduce outside air to ensure that CO_2 levels do not exceed 800ppm.	WELL 01.2.a
	Moisture Control	Mechanical systems used for cooling (i.e., window A/C units) must be regularly inspected for mold growth; Additionally, building walls, ceilings, and floors must be regularly inspected for signs of discoloration and mold.	WELL 06.1-06.2
	Steam Systems	Inspect and test steam traps and steel cast iron radiators; repair and replace if leakage is detected.	
	Boilers and Chillers	Boilers and chillers lose between 0.6% and 1% of their efficiency per annum due to mechanical deterioration alone, and as much as 2.4% when standard cleaning is not performed. Notably, HVAC functionality (boilers and chiller systems) as a result of ageing has the greatest impact on overall energy consumption. Boilers and chillers are replaced after their service life is complete, anywhere between 20 - 25 years.	Waddicor, 2016; Facilities Net, 2002
	Established Cleaning Plan	A plan must be established to ensure the proper cleaning and sanitation of the facility. Products that have minimal impacts are detailed by the EPA Safer Choice label; Green cleaning options are at the forefront of the organization.	WELL 09.1
	HEPA Vacuum	Utilize High Efficiency Particulate Air (HEPA) vacuums to limit the resuspension and coagulation of fine particles.	WELL 29.1.c
	No-Idling Zone	No idling zones are established 100 feet from air intake vents; Limit unnecessary idling at loading docks to no more than 5-minutes.	LEED BD+C v4 Pilot Credit
	Office Equipment	Active replacement of existing office equipment with all-in-one or ink jet printers and copiers that off-gas less ozone, VOCs, and particulates.	
	Minimize Air Leakage	Ensure the building has minimum air leakage by performing a blower door test to calculate air changes per hour (ACH). The total outdoor	WELL, ASHRA

Table 13 (continued)

		air supplied and removed from the indoor space can also be determined per the current ASHRAE 62.1-2016 standard which requires 17 cubic feet per minute (CFM) per person of outdoor air.	E 62-1 14.1-14.2

A.4 Indoor Air Quality Survey

PITTSBURGH 2030 DISTRICT

INDOOR AIR QUALITY SURVEY:
2017 PORTFOLIO PERFORMANCE

NAME: ______________________ EMAIL: ______________________

TITLE: ______________________ BUILDING NAME: ______________________

COMPANY: ______________________ BUILDING ADDRESS: ______________________

OPERATIONS & MAINTENANCE

Mats, grilles, grates, and other walk-off systems installed at regularly used entrances, and at least 10 ft long in the primary direction of travel.

1. Does the building have entryway walk-off mats?
   a) None
   b) Some entryways
   c) All entryways
   d) Don't know

Regularly occupied spaces have operable windows that provide access to outdoor air and daylight.

2. Does the building have operable windows?
   a) None
   b) Some windows
   c) All windows
   d) Don't know

3. Are air intakes in an area that prevent intake of common pollutants (e.g., vehicle exhaust and construction dust?)
   a) No
   b) Some intakes
   c) All intakes
   d) Don't Know

Smoking prohibitions include e-cigarettes.

4. What is the building's policy on smoking?
   a) Smoking is allowed without restriction, indoors and outdoors
   b) Smoking is allowed in the following areas (check all that apply):
      - ☐ Certain areas indoors (e.g., bar, smoke shop)
      - ☐ Anywhere outdoors
      - ☐ Outdoors in areas at least 25 ft from entrances
      - ☐ Outdoors in areas at least 25 ft from air intakes
   c) Smoking is prohibited everywhere on the property, indoors and outdoors
   d) Don't know

MERV: Minimum Efficiency Reporting Value is a measure of the effectiveness of the filtration media. Higher MERV ratings are more effective.

5. Does the building filtration have a MERV rating of 8 or higher?
   a) No
   b) Yes, MERV 8-10
   c) Yes, MERV 11-12
   d) Yes, MERV 13+
   e) Not applicable, no mechanical ventilation
   f) Don't know

Green cleaning policies and programs can include equipment, materials, schedules, and employee training.

6. Does the building have an established green cleaning program?
   a) No
   b) Some green cleaning practices, products, equipment, schedules, and/or employee training
   c) All green cleaning practices, products, equipment, schedules, and employee training
   d) Don't know

7. Do all vacuums used in the building have High Efficiency Particulate Air (HEPA) filters?
    a) No
    b) Some
    c) Yes
    d) Not applicable, no vacuuming in building
    e) Don't know

Use signage and operator communications/ education to limit idling.

8. Does the building have clearly marked no idling zones?
    a) No
    b) Yes, outdoors
    c) Yes, indoors (e.g., indoor loading docks)
    d) Yes, indoors and outdoors
    e) Not applicable, no delivery or drop off areas
    f) Don't know

Best practice for printing rooms includes negative pressurization and exhaust strategies.

9. Does your building address pollutants caused by copiers and printers?
    a) No
    b) Yes (check all that apply):
        - ☐ Copiers/printers receive regular preventative maintenance.
        - ☐ Minimizing the number of copiers/printers.
        - ☐ Locating copiers/printers in unoccupied and enclosed rooms.
        - ☐ Sufficiently exhausting air from the copier room so to create negative pressure.
    c) Not applicable, no copiers/printers on site
    d) Don't know

Occupant surveys provide a feedback mechanism for building occupants and can help identify issues.

10. Does your organization administer occupant comfort surveys?
   a) No
   b) Surveys are administered less frequently than annually, covering the following considerations (check all that apply)
      - ☐ Air quality
      - ☐ Lighting
      - ☐ Thermal comfort
      - ☐ Ergonomics
      - ☐ Other: ____________________
   c) Surveys are administered at least annually, covering the following considerations (check all that apply)
      - ☐ Air quality
      - ☐ Lighting
      - ☐ Thermal comfort
      - ☐ Ergonomics
      - ☐ Other: ____________________
   d) Don't know

Demand controlled ventilation provides increased amounts of fresh air in response to the detection of high levels of carbon dioxide (e.g. in a densely occupied conference room).

11. Does the building have a demand control ventilation system?
   a) No
   b) No, but building has operable windows
   c) Yes
   d) Don't know

Cooling coils, ceilings, walls, floors, and water damaged areas should be inspected.

12. Does your building perform regular inspections for moisture, condensation, and mold?
    a) No
    b) Yes (select one)
        - ☐ Annually
        - ☐ Semi-annually
        - ☐ Continuously
    c) Don't know

The policy should include strategies for monitoring and recording keeping, as well as a plan for responding to unacceptable conditions.

13. Does your organization have a policy for monitoring, record-keeping, and remediation related to indoor air pollutants?
    a) No
    b) Yes
    c) Don't know

14. In an effort to minimize air leakage, is the building compliant with ASHRAE 62.1-2016 recommended air changes per hour (ACH) or cubic feet per minute (CFM) per person?
    a) No
    b) No, but compliant with earlier version of ASHRAE 62.1 (YEAR:________)
    c) Yes, compliant with ACH
    d) Yes, compliant with CFM per person
    e) Don't know

Volatile organic compounds (VOCs) include a number of chemicals, some harmful to human health, released as a gas from solid and liquid items including many building products and materials.

15. Does your organization perform testing for common indoor air pollutants?

a) No

b) Yes, but not annually, checking the following levels (check all that apply)

- ☐ Carbon Monoxide
- ☐ CO2
- ☐ Radon
- ☐ PM2.5
- ☐ PM10
- ☐ Ozone
- ☐ TVOCs
- ☐ Formaldehyde

c) Yes, at least annually, checking the following levels (check all that apply)

- ☐ Carbon Monoxide
- ☐ CO2
- ☐ Radon
- ☐ PM2.5
- ☐ PM10
- ☐ Ozone
- ☐ TVOCs
- ☐ Formaldehyde

d) Yes, with continuous monitoring in real time, checking the following levels (check all that apply)

- ☐ Carbon Monoxide
- ☐ CO2
- ☐ Radon
- ☐ PM2.5
- ☐ PM10
- ☐ Ozone
- ☐ TVOCs
- ☐ Formaldehyde

e) Don't Know

RENOVATIONS & CONSTRUCTION

16. Does your building have an erosion & sedimentation control plan in place for construction or renovation projects?
    a) No
    b) Yes
    c) Yes, and it was applied to a construction or renovation project in 2017
    d) Not applicable, no outdoor property

Volatile organic compounds (VOCs) include a number of chemicals, some harmful to human health, released as a gas from solid and liquid items including many building products and materials.

17. Do building materials used in construction and renovations have low or zero VOC content (e.g., paints, adhesives, flooring, insulation, and furniture)?
    a) No
    b) Some materials
    c) Yes, all materials
    d) Don't know

See International Living Future Institute Red List for 22 Red List chemicals and information on the hazards associated with them.

18. Does your building have a materials selection policy that excludes materials containing asbestos, lead, mercury, PCBs, and/or Red List chemicals of concern?
    a) No policy around materials selection
    b) Materials selection policy requiring materials free from (check all that apply)
       - ☐ Asbestos
       - ☐ Lead
       - ☐ Mercury
       - ☐ PCBs
       - ☐ Some Red List chemicals not listed here
       - ☐ All Red List chemicals
    c) Don't know

Sealing ducts protects hard to reach areas and occupied spaces from contamination during construction activities.

19. Does your building have a policy to close off and/ or seal ducts during construction projects?
    a) No
    b) Yes
    c) Yes, and it was followed on a construction or renovation project in 2017
    d) Don't know

Using temporary barriers prevents the contamination of occupied spaces during construction activities.

20. Does your building have a policy to divide construction areas from occupied spaces by sealed media?
    a) No
    b) Yes
    c) Yes, and it was applied on a construction or renovation project in 2017
    d) Don't know

Absorptive materials should be kept dry in order to avoid the potential for microbial growth. These include (but are not limited to) carpets, acoustical ceiling panels, fabric wall coverings, insulation, upholstery, and furnishings).

21. Does your building have a policy to store all materials with absorptive qualities in a safe, dry location?
    a) No
    b) Yes
    c) Yes, and we did so on a construction or renovation project in 2017
    d) Don't know

Air flushing moves large quantities of air through the building in order to remove contaminants introduced during construction.

22. Does your building have a policy to perform an air flush-out after construction and prior to occupancy?
    a) No
    b) Yes
    c) Yes, and we did so on a construction or renovation project in 2017
    d) Don't know

A commissioning agent provides verification that building systems are performing as intended.

23. Does your building utilize a commissioning agent or process (when applicable to the renovation project type)?
   a) No
   b) Some projects
   c) Yes, all projects
   d) Don't know

24. Does your building have a clean construction plan in accordance with the City of Pittsburgh's Clean Construction Diesel Operations Ordinance?
   a) No
   b) Yes (select all that apply)
      - ☐ In compliance with City Ordinance
      - ☐ Meets LEED BD+C Clean Construction pilot credit
      - ☐ We applied it to a construction or renovation project in 2017
   c) Don't know

FUTURE OPPORTUNITIES

25. Will your organization be pursing any of the following in 2018? (circle all that apply)
    a) WELL Building certification (check all that apply):
       - ☐ For one of the buildings covered by this survey
       - ☐ For another building in our portfolio locally
       - ☐ For another building in our portfolio nationally
    b) p4 Air Credit
    c) University project related to indoor air quality
    d) Longitudinal indoor air quality study
    e) I am not pursuing any of the above, but am interested in (check all that apply):
       - ☐ WELL
       - ☐ p4 Air
       - ☐ University IAQ projects
       - ☐ Longitudinal projects

26. Was there anything in this survey we did NOT ask about or that you would like to share?

A.5 Particulate Matter Measurements from On-site and Stationery Monitors

Table 14. Summary of outdoor PM10 concentrations for Pittsburgh

Date	Building	Location	Mean (μg/m^3)	Peak/Max	Week
12/2 – 12/4/14	HB1	On-site	115.8	216.2	11/30 - 12/6/2014
		Flag Plaza	12.1	22.0	
11/3 – 11/5/15	HB2	On-site	108.4	845.3	11/1 - 11/7/2015
		Flag Plaza	21.3	37.8	
		Manchester	19.0	19.0	
3/24 – 3/26/15	HB3	On-site	44.1	77.7	3/22 - 3/28/2015
		Flag Plaza	13.8	24.8	
		Manchester	19.0	19.0	
11/17 – 11/19/15	CB1	On-site	68.6	152.8	11/15 - 11/21/2015
		Flag Plaza	23.6	41.4	
		Manchester	10.0	10.0	
2/24 – 2/26/15	CB2	On-site	34.4	54.9	2/22 - 2/28/2015
		Flag Plaza	24.3	34.8	
		Manchester	18.0	18.0	
11/9 – 11/13/15	CB3	On-site	30.1	60.4	11/8 - 11/14/2015
		Flag Plaza	13.8	22.3	
		Manchester	9.5	12.0	
10/28 - 10/30/14	GB1	On-site	-	-	10/26 - 11/1/2014
		Flag Plaza	17.0	33.0	
2/14 - 2/16/17	GB2	On-site	15.4	56.1	2/12 - 2/18/2017
		Manchester	23.0	16.5	

Appendix B Supporting Information for Environmental Justice and Community-based Research (Chapter 4)

B.1 Targeted Environmental Justice Communities

Geographic Data Analysis (GeoDA) modeling software was used to cluster the spatial dependence of sociodemographic factors in neighborhoods throughout the Pittsburgh region to initially substantiate environmental concern. Ordinary least square estimates positively relate non-white neighborhoods with higher incidents of residents living below the poverty line ($p = 0.00001$) and the housing stock being rated as poor/derelict condition ($p = 0.00009$). Additionally, average annual daily traffic (AADT) count was integrated as a surrogate for exposure to traffic related air pollutants; a set of weighted shapefiles produced by the Pennsylvania Department of Transportation (PENNDOT) were used to identify statistically significant hotspots and assess neighborhoods located in close proximity to high volume roadways. Figure 20 overlays a spatial cluster of low-socioeconomic status neighborhoods, high trafficked roadways, and stack air emissions (TRI facilities). The condensed map uncovers important relationships between social and physical environments in Pittsburgh, pinpointing areas for environmental justice concerns and policy-driven renewal strategies.

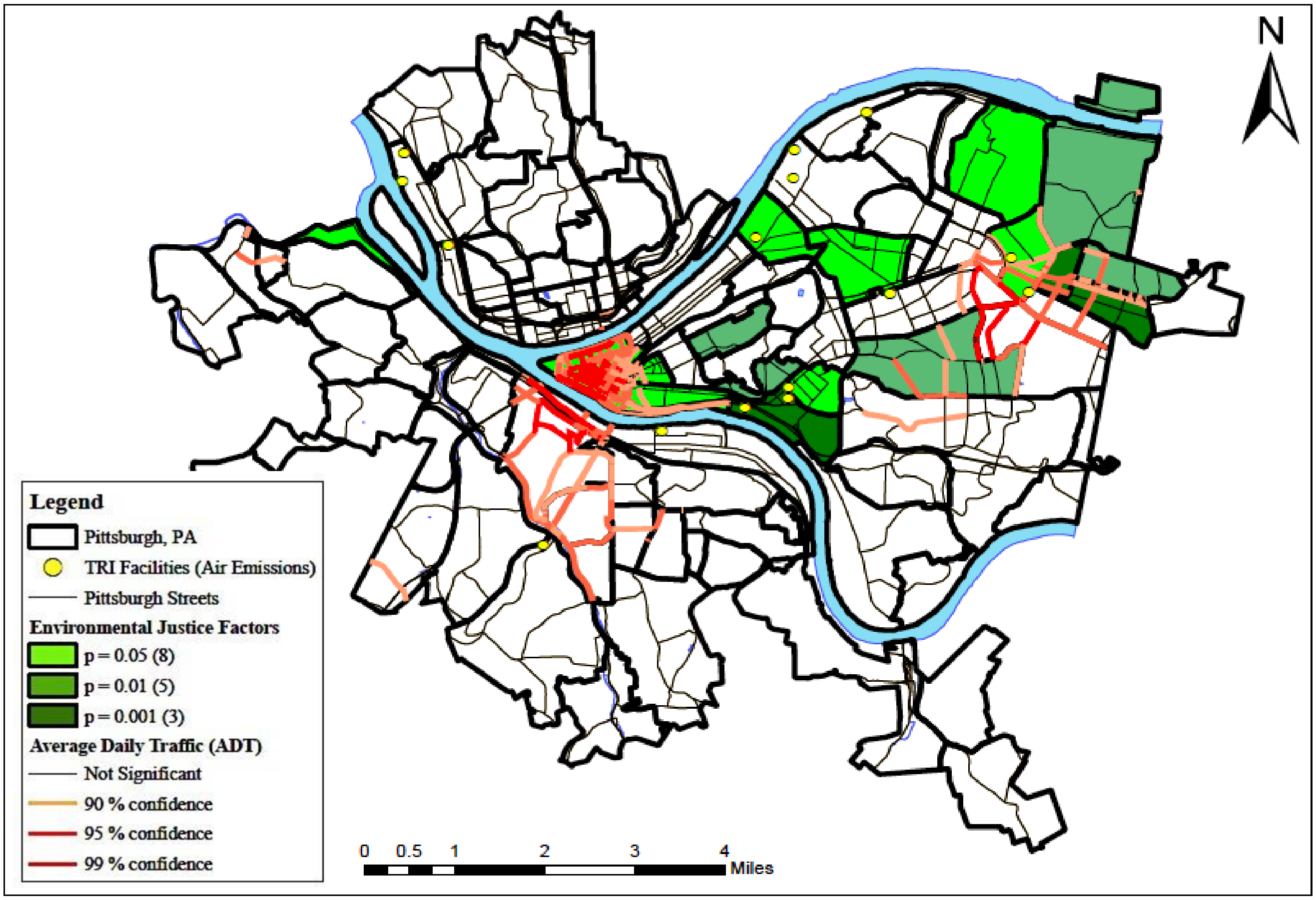

Figure 20. Pittsburgh Environmental Justice Neighborhoods. Combining GIS and spatial analysis to identify air pollution exposure from vehicular traffic and toxic release inventory sites; overlaid broad environmental justice distribution map reflective of non-white residents living below the poverty line and homes rated as poor/derelict condition.

B.2 Community Action Teams (CATs) Pre-survey Questions

Table 15. Community Action teams (CATs) Pre-survey

	Questions
1.	What is a watershed?
2.	Do you know why your/a basement floods?
3.	Do you feel you consume/use too much water in your household?
4.	On average, how much time do you spend indoors?
5.	Poor indoor air quality affects your health in what ways?
6.	How do you think Pittsburgh ranks when compared to other metropolitan cities as it relates to outdoor air quality?
7.	What is your average monthly electricity bill?
8.	Do you feel you use too much electricity in your household?
9.	Do you know ways to reduce your electricity usage?
10.	Are you aware of the EJCAM Project?
11.	Are you familiar with the Larimer Consensus Group (LCG) and the Living Waters of Larimer (LWOL) project?
12.	What neighborhood do you live within Pittsburgh?
13.	What is your age?
14.	What race do you identify with?
15.	What is your current occupation?

B.3 Urban Transition Cities Movement (UTCM) Workshop Evaluations

Table 16. Urban Transition Cities Movement (UTCM) Workshop Evaluation

Questions						
What neighborhood do you live in?						
How did you find out about today's training workshop?	Flyer	E-mail reminder	Website/ Facebook	LCG	Friend/Family	Other:
	-	-	-	-	-	-
If you are unable to attend future CATs training, what most likely is that reason?	Was not aware	No transportation	Weather	Childcare Needed	Topic was not relevant to me	Other:
	-	-	-	-	-	-
Please rate your overall satisfaction with the 4th UTCM Workshop:	Extremely Satisfied	Satisfied	Neutral	Unsatisfied	Extremely Unsatisfied	
Were the topics relevant & relatable?	-	-	-	-	-	
Were the speakers/presenters cohesive?	-	-	-	-	-	
Was the workshop well organized and did it flow?	-	-	-	-	-	
Were your prior expectations met?	-	-	-	-	-	
Did you gain skills that can be translated to your everyday life practices?	-	-	-	-	-	
Rate your overall experience.	-	-	-	-	-	
What topics would you like to see at future UTCM Workshops?						
Additional comments, suggestions, and improvements for UTCM efforts?						

B.4 Mobile Air Quality Monitoring Afternoon and Evening Rush-hour

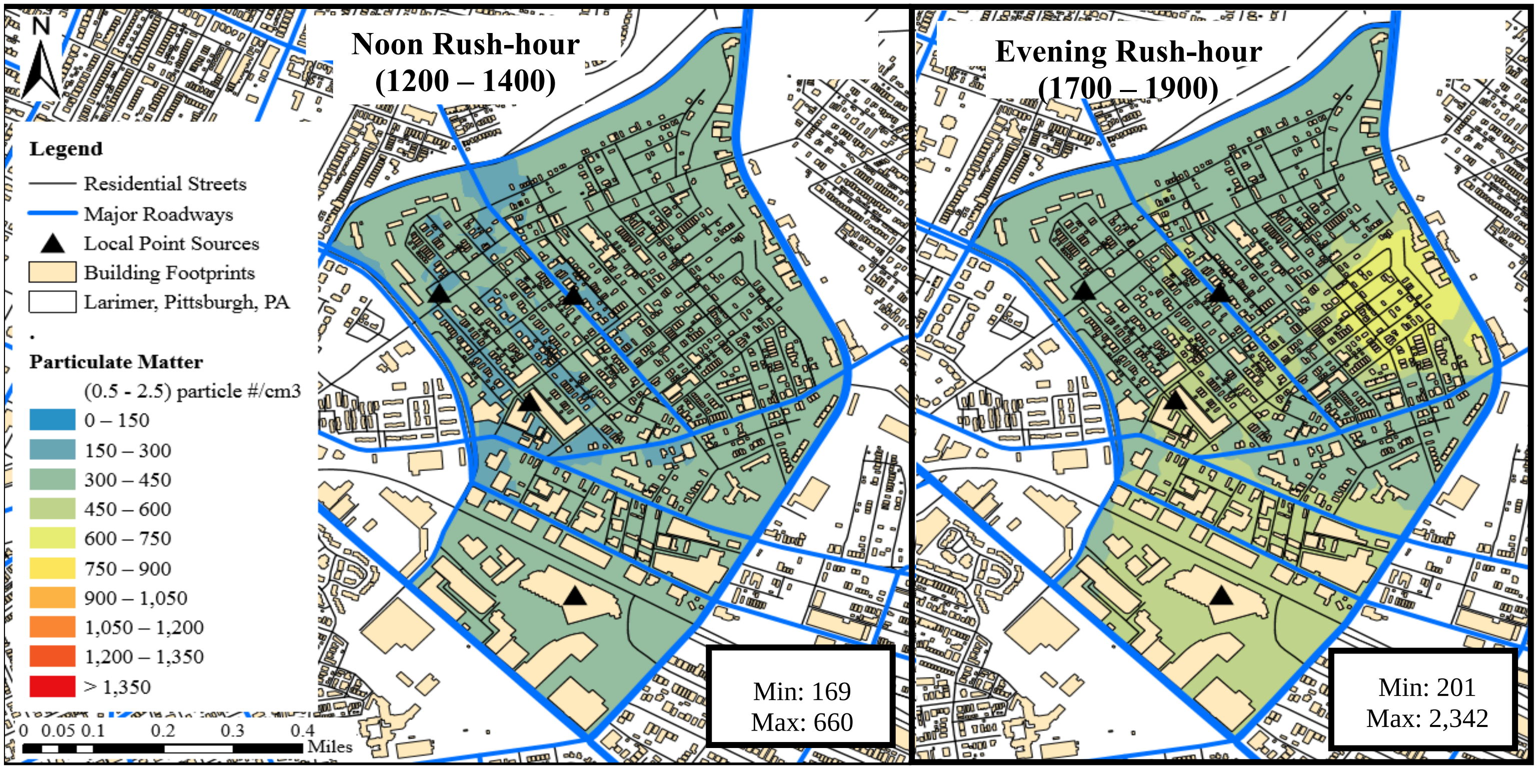

Figure 21. Average Predicted $PM_{2.5}$ Dispersion Map. 853, 318, and 424 particle counts (particle #/cm^3) were recorded during the morning, afternoon, and evening sampling period, respectively.

Appendix C Supporting Information for Indoor Air Quality and Quality of Life (Chapter 5)

C.1 Quality of Life Survey

Dear Resident,

Welcome! This research study is being conducted to understand relationships between resident's perceived Quality of Life (QOL) and Air Quality. We invite your participation; this survey should take approximately 30 minutes.

During the initial homeowner orientation, you previously consented to participate in our research study, which included the completion of this QOL survey. Now that you are officially enrolled in this study, we ask that you assist complete this survey.

This survey asks several questions related to quality of life factors. We will examine factors including **Socio-Economic Development** (household income, unemployment, type of jobs, quality of jobs, cost of living, poverty, and homelessness), **Human Development** (satisfaction of higher and lower order needs), **Sustainability** (resident health, and sustainable ecosystems), and **Personal Utility** (Social life, leisure life, family life, spiritual life, etc., and community conditions and services). **We ask that you think about your life in the last 30 days unless specific instructions define otherwise.** This survey was developed based on questions from the Center for Disease Control and Prevention's Behavioral Risk Factor Surveillance System Questionnaire, and the World Health Organization Quality of Life Instrument [1-2].

Researchers have created this survey to assist in understanding the proposed linkages between Air Quality and QOL. **Be assured that individual responses to the surveys will be kept confidential.** You will receive payment for completion of this research study in the form of a VISA gift card. Full completion of the research study includes: completion of the initial Homeowner Orientation, signed Consent Forms, QOL survey, Home Characterization Checklist, Pre & Post Intervention Evaluation, and two-month Home IAQ Assessment in your home.

This study is being conducted by Dr. Melissa Bilec at 412.648.8075 or mbilec@pitt.edu and Harold Rickenbacker at 803.378.3124 or hjr12@pitt.edu.

Your participation in this study is voluntary. You can skip questions if you wish. You must be 18 or older to participate. Thank you for your time and assistance! We really appreciate your help in taking a step to make our communities more environmentally conscious.

Sincerely,

Dr. Melissa Bilec, Swanson School of Engineering, University of Pittsburgh

Mr. Harold Rickenbacker, Swanson School of Engineering, University of Pittsburgh

1. **What is your age in years?**

    ____

2. **Which one of these groups would you say best represents your race?**

White	Chinese
Black or African American	Filipino
American Indian or Alaska Native	Japanese
	Guamanian or Chamorro
Asian Indian	Samoan

Korean

Native Hawaiian

Vietnamese

Hispanic

Pacific Islander

________________ Other

3. What is the highest grade or year of school you completed?

Never attended school or only attended kindergarten

Grades 1 through 8 (Elementary)

Grades 9 through 11 (Some high school)

Grade 12 or GED (High school graduate)

College 1 year to 3 years (Some college or technical school)

College 4 years or more (College graduate)

4. Are you currently employed?

Employed for wages

Self-employed

Out of work for 1 year or more

Out of work for less than 1 year

A Homemaker

A Student

Retired

Unable to work

Refused

5. What is your annual household income from all sources?

Less than $10,000

Less than $15,000 ($10,000 - $15,000)

Less than $20,000 ($15,000 - $20,000)

Less than $25,000 ($20,000 - $25,000)

Less than $35,000 ($25,000 - $35,000)

Less than $50,000 ($35,000 - $50,000)

Less than $75,000 ($50,000 - $75,000)

$75,000 or more

Don’t Know/Not Sure

Refused

6. What is the zip code where you live?

_______________Zip Code   Don’t Know/Not Sure   Refused

7. Do you own or rent your home?

Own   Rent   Other arrangement   Refused

8. Indicate your sex.

Male Female Transgender Gender Non-Conforming

Refused

9. How many children less than 18 years of age live in your household?

________________Number of children None Refused

If children do not live in the home skip this section.

10. Please list the age of the child/children
____

11. Has a doctor, or other health professional EVER said that the child/children have asthma?

Yes No Don't Know/Not Sure Refused

12. How many times have you been to a doctor, nurse, or other health professional in the past 12 months?

_________Number of Times None Don't Know/Not Sure
Refused

13. Would you say that in general your health is ____________?

Poor Fair Good Excellent

14. Now thinking about your physical health, which includes physical illness and injury, for how many days during the past 30 days was your physical health not good?

1 – 7 | 15 – 21
8 – 14 | 22 – 30

15. Now thinking about your mental health, which includes **stress, depression, and problems with emotions**, for how many days during the past 30 days was your mental health not good?

1 – 7 | 15 – 21
8 – 14 | 22 – 30

16. During the past 30 days, for about how many days have you **felt sad, blue, depressed?**

1 – 7 | 15 – 21
8 – 14 | 22 – 30

17. During the past 30 days, for about how many days have you felt **worried, tense, or anxious?**

1 – 7 | 15 – 21
8 – 14 | 22 – 30

18. During the past 30 days, for about how many days have you felt **very healthy and full of energy?**

1 – 7 | 15 – 21
8 – 14 | 22 – 30

19. During the past month, **other than your regular job**, did you participate in any physical activities or exercises such as running, calisthenics, golf, gardening, or walking for exercise; if yes, how many days?

1 – 7 | 15 – 21
8 – 14 | 22 – 30

20. Do you or someone in your home smoke cigarettes?

Every day Some days Not at all Don’t Know/Not Sure

21. Do you or someone in your home smoke cigarettes INDOORS?

Every day Some days Not at all Don’t Know/Not Sure

22. Has a doctor, nurse, or other health professional EVER told you that you had any of the following? Circle each response.

Heart Attack
Angina or Coronary heart disease
Stroke
Asthma
Cancer; if yes, what kind ___________________
Emphysema
Arthritis
Lupus
Depressive disorder
Diabetes
Chronic bronchitis
Asthma

List any other health related concerns ____

If you do not have Asthma skip this section.

23. During the past 12 months, have you had an episode of asthma or an asthma attack?

Yes No Don’t Know/Not Sure Refused

24. Symptoms of asthma include cough, wheezing, shortness of breath, chest tightness and phlegm production when you don’t have a cold or respiratory infection. **During the past 30 days, how often did you have any symptoms of asthma?** Would you say __________.

Not at any time
Less than once a week
Once or twice a week
More than 2 times a week, but not every day
Every day, but not all the time
Every day, all the time

The following questions ask about how much you have experienced certain things in the last thirty days, for example, positive feelings such as happiness or contentment.

25. Within the past 30 days, have you felt emotionally upset, for example angry, sad, or frustrated, as a result of how you were **treated based on your race**?

Not at all
A moderate amount
Very much
An extreme amount

26. How much are you bothered by fatigue?

Not at all
A moderate amount
Very much
An extreme amount

27. How positive do you feel about the immediate future?

Not at all
A little
A moderate amount
An extreme amount

28. How much do any feelings of sadness or depression interfere with your everyday functioning?

Not at all
A little
A moderate amount
An extreme amount

29. Do you feel you are living in a safe and secure environment? (Neighbor)

Not at all
A little
A moderate amount
An extreme amount

30. How much do you worry about finances?

Not at all
A little
A moderate amount
An extreme amount

31. To what degree does the quality of your home meet your needs? (Physically the home you live in)

Not at all	A moderate amount
A little	An extreme amount

32. How many days out of the week are you able to relax and enjoy yourself?

1	4 - 5
2 - 3	6 or more

33. I fully understand the meaning of the term "sustainability".

Not at all	A moderate amount
A little	An extreme amount

34. Do you think environmental issues directly affect your everyday life?

Not at all	A moderate amount
A little	An extreme amount

35. How willing are you to participate in sustainability activities within your community?

Not at all	A moderate amount
A little	An extreme amount

36. The infrastructure (i.e., roads, buildings, homes) in your community is safe and in good condition.

Not at all	A moderate amount
A little	An extreme amount

37. I have a voice in my community as it relates to decision making and planning.

Not at all	A moderate amount
A little	An extreme amount

38. What aspect of your life worry you most (i.e., finances, work, health, relationships, family); elaborate if possible?

39. I was fully aware and concerned about indoor air pollution before participating in this study.

Not at all
A little
A moderate amount
An extreme amount

40. Being involved in this study has affected my interactions with academic researchers and instilled trust in traditional air quality monitoring.

Not at all
A little
A moderate amount
An extreme amount

41. Being involved in this study has influenced me to develop local action to reduce air pollution exposure and improve public health.

Not at all
A little
A moderate amount
An extreme amount

C.2 Home Characterization Survey

Home Characteristics

1. Contact Information

Numeric Identifier

Monitoring Location Address

City

State

ZIP/Postal Code

* 2. Please list mailing address (If Different from above)

* 3. What are your initials? (Please use 3 Letters)

* 4. What neighborhood is your home in?

5. What year was the house built? (Please enter only numeric value)

* 6. Do you own or rent your house?

If No Answer, Don't Know or Other, please explain.

* 7. Have there been any major additions or renovations?

If yes, What % of floor space was added? and When?

If No Answer or Don't Know, please explain.

* 8. Has the house had significant weatherization/airsealing?

If Yes, please specify.
If No Answer or Don't Know, please explain.

* 9. Do you know the house airtightness from a test?

If Yes, please describe results.
If No Answer or Don't Know, please explain.

* 10. Has the house been tested for Radon?

If Yes, please specify the date and results.
If No Answer or Don't Know, please explain.

* 11. Is the house near the bottom of a river valley or other low-lying area?

If No Answer or Don't Know, please explain.

* 12. What best describes the house location?

If No Answer or Don't Know, please explain.

* 13. Is your house a single, detached house?

If Not, please describe.
If No Answer or Don't Know, please explain.

* 14. What is the foundation type?

☐ Basement

☐ Crawl Space

☐ Slab-on Grade

☐ Other

☐ No Answer

☐ Don't Know

If combination, please specify % of each type.
If No Answer, Other or Don't Know, please explain.

* 15. What is the above-grade floor area? (Answer should be in square feet, enter only numeric value)

* 16. Does the house have a:

	Yes	No
Second Floor	○ Second Floor Yes	○ Second Floor No
Third Floor	○ Third Floor Yes	○ Third Floor No
Fourth Floor	○ Fourth Floor Yes	○ Fourth Floor No

Other (please specify)

* 17. Can the kitchen area, or kitchen/family room area, be closed off with doors?

If No Answer or Don't Know, please explain.

* 18. Does your home have a garage?

Other (please specify)

* 19. How many occupants are in the house at night? (Enter only numeric value)

* 20. How many occupants are in the house during the day Monday-Friday? (Enter only numeric value)

* 21. How many children under 12 live in the house? (Enter only numeric value)

* 22. What percent of the house has hard surface flooring? (Tile, Hardwood, Linoleum, etc.) (Enter only numeric value)

* 23. What percent of the house is carpeted? (Enter only numeric value)

* 24. Is there an odor to the house when you walk in from outside?

If Yes, please specify.
If Occasionally, No Answer or Don't Know, please explain.

HVAC and Ventilation Characterization

25. What is the heating fuel?

- Gas
- Oil
- Electricity
- Wood
- Propane
- No Answer
- Don't Know

If more than one answer applies, please specify % of each.

* 26. What type of heating system do you have?

If Other, No Answer or Don't Know, please specify.

* 27. What is the heat distribution system?

* 28. If the house has a fireplace, woodstove or space heater, what fuel does it use?

- [ ] N/A (No fireplace, woodstove or space heater)
- [ ] Wood
- [ ] Natural Gas
- [ ] Electric
- [ ] Other
- [ ] Don't Know

If Other, No Answer or Don't Know, please specify.

* 29. If the house has a fireplace or woodstove, What is its usage?

- [ ] N/A (No fireplace or woodstove)
- [ ] Daily
- [ ] Weekly
- [ ] Once a Year
- [ ] Other
- [ ] Don't Know

If Other or Don't Know, please specify.

* 30. What type of air-conditioning system do you have?

- ○ N/A (No Air Conditioning)
- ○ Room Air Conditioners
- ○ Ductless Heat Pump
- ○ Central Air Conditioning
- ○ Other

If Other (please specify)

* 31. If you have a forced-air furnace or central air conditioning, is there ducting in an attic, crawl space, or garage?

If Other, No Answer or Don't Know, please specify.

* 32. If there is a forced air furnace or AC, how is the air handler (fan) operated. Note: this is normally controlled at the thermostat.

If Other or Don't Know, please specify.

* 33. If there is a forced-air furnace or AC, what size of furnace filter is being used?

If Other or Don't Know, please specify.

* 34. If there is a forced air furnace or AC, what type of furnace filter is being used?

Other (please specify)

* 35. How many bathrooms have fans?

If Other, No Answer or Don't Know, please specify.

* 36. Does your house have a whole house exhaust?

If Other, No Answer or Don't Know, please specify.

* 37. Does your house have an air exchanger?

If "Yes, Other" or "Don't Know", please specify.

* 38. If there is a ventilation system, how do you operate it?

If Other, No Answer or Don't Know, please specify.

* 39. Do you have a humidifier in use during the monitoring period?

If Other, No Answer or Don't Know, please specify.

* 40. If you have a humidifier, how often is it used?

If Other or Don't Know, please specify.

* 41. Do you anticipate window opening during the monitoring period?

If Yes, please specify number of windows open and estimated schedule.
If Other, No Answer or Don't Know, please specify.

* 42. In the warmer months of the year, what best describes your household?

* 43. Do you have a standalone air cleaner?

If Yes, please specify make and model, location of cleaner(s), and how often it is run.
If Other, No Answer or Don't Know, please specify.

* 44. Are bedroom doors opened or closed during the night?

Please provide additional details, if necessary.

* 45. What type of vacuum cleaner do you have?

* 46. How frequently is your vacuum used?

* 47. Do you have a clothes dryer in the house?

Cooking/Domestic Routines

48. What type of stove do you have?

If Other, No Answer or Don't Know, please specify.

* 49. How frequently do you use the stovetop?

Other (please specify)

* 50. What type of oven do you have?

If Other, No Answer or Don't Know, please specify.

* 51. How often do you use the oven?

Other (please specify)

* 52. If you have a gas stove/oven, what color are the flames?

* 53. Do you have a range hood?

* 54. How often do you use the range hood?

If Other or Don't Know, please specify.

* 55. Which of the following cooking appliances are used in your home?

- [ ] Coffee Maker
- [ ] Toaster
- [ ] Microwave
- [ ] Toaster Oven
- [ ] Slow Cooker (Crock-Pot)
- [ ] Electric Kettle
- [ ] Other
- [ ] None
- [ ] Do not know

If Other (please specify)

* 56. How often in a week do you use a frying pan, griddle, wok, or dutch oven on the stove top? (including sautéing, browning, frying, braising)

Other (please specify)

Particle Re-Suspension and Coagulation

57. Do you have pets?

If Yes, please specify.

If No Answer or Don't Know, please specify.

* 58. How many plants are inside the house?

* 59. Do you burn candles?

If No Answer or Don't Know, please specify.

* 60. Do you burn incense?

If No Answer or Don't Know, please specify.

* 61. Does anyone in the house smoke cigarettes?

If Other, No Answer or Don't Know, please specify.

* 62. Does anyone in the house smoke cigars?

If Other, No Answer or Don't Know, please specify.

* 63. Do you take off outside footwear upon entering the house?

If Other, No Answer or Don't Know, please specify.

* 64. Do you have a FAX/printer/copier in the house?

If Yes, please specify frequency of use.
If Other, No Answer or Don't Know, please specify.

* 65. Are you currently doing any renovation activity?

If Yes, please specify.
If Other, No Answer or Don't Know, please specify.

* 66. Are there any hobbies within the house that could create dust (e.g. woodwork, artwork)?

If Yes or Don't Know, please specify.

* 67. Do you use any cleaning products with a distinctive scent?

If Yes or Don't Know, please specify.

* 68. Do you use commercial “air fresheners”?

If Yes or Don't Know, please specify.

* 69. Are you close to any of the following outdoor sources of particles?

- ☐ Industry (Please specify)
- ☐ Major roads, or a neighborhood road with heavy traffic or congestion
- ☐ Dirt or gravel roads
- ☐ Fracking activity
- ☐ Agricultural fields
- ☐ Neighbor’s woodstove
- ☐ Other (Please specify)

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