THESIS

COMPARISON OF INDOOR AIR QUALITY BETWEEN BUILDING TYPE IN CAMPUS BUILDINGS

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ABSTRACT

COMPARISON OF INDOOR AIR QUALITY BETWEEN BUILDING TYPE IN CAMPUS BUILDINGS

The average American spends an estimated 90% of their time indoors on any given day. Rapid urbanization is also sweeping the country leading to ever increasing time spent in the built environment. Human exposure to the surrounding environment accounts for 90% of all disease. The air we breathe represents a major component of that exposure and becomes increasingly relevant as more time is spent indoors. Many studies have set out to characterize and improve indoor air quality in various settings from the workplace to schools. However, few have investigated higher education and its shift toward green, sustainable buildings. The objective of this research was to evaluate the effects of building type and occupancy on indoor air quality in higher education buildings. We measured LEED certified, retrofitted, and conventional building types on a college campus for particulate matter, formaldehyde, carbon dioxide, and nitrogen oxides. For each building type, we conducted multi-zonal, 48 hour measurements during times when the buildings were occupied and unoccupied. Statistically significant differences in two size fractions of particulate matter were observed between building types. Carbon dioxide and particulate matter concentrations were significantly higher during occupied sampling when compared to unoccupied. Results from this study suggest that occupancy status has a larger impact on indoor air quality in campus buildings than building type.

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1. INTRODUCTION

Human exposure to the surrounding environment can be summarized by the air we breathe, water we drink, food we eat, and the contact with our surroundings.[1] Due to increasing urbanization (63% to 84% from 1950 to 2015), our surrounding environment is quickly changing.[2] The EPA estimates that the average American spends 85 to 90% of their time indoors with another 3-6% spent in various forms of transit.[1, 3] Therefore, the air we breathe in the indoor environment is a major exposure pathway in everyday life. Indoor air is composed of biological, chemical, and particulate constituents that can have a significant impact on human health, comfort, and productivity.[4] The quality of indoor air or indoor air quality (IAQ) of a building is influenced by three factors: pollutants generated inside the building, pollutants generated outside the building, and any mitigating building systems or conditions.[4] In situations where one factor is lacking, there is a potential for poor indoor air quality. Exposure to poor IAQ environments is linked to multiple adverse health effects, particularly in populations with chronic exposures or susceptibilities.[5-9]

Higher education represents a significant fraction of the population across the country. Each year and estimated 20 million students enroll at nearly 4,600 college level institutions staffed by 4 million faculty and employees.[10, 11] The sheer scale of students and faculty in campus building environments demonstrates the need to understand higher education environments. Little information exists detailing the conditions of college campus buildings, but construction data provides some insight. Estimates show a shift toward new building projects with new projects receiving significantly more funding then renovation projects on existing buildings.[12] This is indicative of the nationwide shift to newer high efficiency, low emitting buildings. However, this shift has led to a drop in allocation of funds to repair existing buildings and HVAC systems. Consequently, poorly functioning HVAC systems and low ventilation rates have been linked to poor air quality.

A number of state courts and congress have recognized that a high-quality learning environment is essential to educating the nation's children.[13] Campus buildings should be no different, as students still receive information through a classroom setting and are tested on their ability to perform cognitive tasks. Studies conducted in elementary and office settings have indicated a decrease in cognitive function or ability to complete performance based tasks when exposed to poor IAQ environments.[8, 9, 14, 15] While no such studies have been conducted in college settings, it is anticipated that the effect would be similar in college students.

The nationwide shift towards green buildings on makes characterization all the more important as little is known about their IAQ. The most widely used green building certification in the world is LEED, with an estimated 92,000 projects comprising 19.3 billion square feet.[16] The Colorado State University campus utilized in this study has nearly one third of its buildings certified under LEED requirements. A study investigating perceived air quality between LEED buildings and conventional buildings indicated better perceived IAQ in LEED certified buildings. However, no research has investigated quantitative IAQ measurements between building types.

Although indoor air quality has been heavily researched in school settings and green buildings, there is little information involving higher education and comparisons between building types. Therefore, the characterization of exposures to higher education students, and subsequent impact building type has on exposures, has yet to be explored. This objective of this research was the test if IAQ metrics have a direct association with building type and what impact occupancy status may have on this relationship. We hypothesize that newly constructed LEED certified buildings will exhibit the lowest level of contaminants, followed by retrofitted buildings, and traditional buildings, and all buildings will exhibit higher levels of IAQ contaminants when occupied than unoccupied.

2. REVIEW OF LITERATURE

2.1. The Indoor Environment and Indoor Air Quality

The total of human exposure to environmental contaminants can be summarized by the air we breathe, the water we drink, the food we eat, and the contact we have with our surroundings.[1] These environmental exposures account for about 90% of all human disease, with only 10% due to genetics.[17] Globally, people are spending more time than ever indoors, increasing the risk for chronic exposures to indoor pollutants.[18] Current estimates demonstrate that the average American spends 85-90% of their time indoors with an additional 3-6% being spent in vehicles or other means of transit.[1, 3] This growing time spent indoors, compounded with a rapid increase in urbanization (64% to 83% from 1950 to 2015), is making characterization of the indoor environment increasingly relevant.[2]

Inhalation is a major route of exposure to the environment around us, so it's essential that indoor air and its effects on human health are understood. Indoor air quality (IAQ) is a term used to describe the biological, chemical, and particulate constituents that make up indoor air and how those constituents impact human health, comfort, and productivity [4]. Examples of indoor air quality constituents include: inhalable and respirable dust particles, volatile organic compounds, nitrogen oxides, carbon dioxide, carbon monoxide, mold, and many more. Three primary factors influence the IAQ of a building: pollutants generated inside the building, pollutants generated outside the building, and any mitigating building systems or conditions[4]. Poor IAQ has been linked to various adverse health effects, particularly in susceptible populations and those with chronic exposures.[6, 8, 9, 18] Schools are an environment where both chronic exposures and susceptible populations exist.

A snapshot of higher education illustrates its massive scale and growing presence. Each year more than 20 million students apply and enroll at 4,599 college institutions in the United States alone.[10, 11] In order to educate students and operate all these colleges, an estimated

4 million staff and faculty are employed by higher education institutions.[11] In total, around 24 million people occupy campuses across the United States on any given day. The sheer scale of students and employees exposed to campus building environments demonstrate the need to understand them. Little data exists detailing the condition and state of university buildings. However, university construction data allows for speculation into the state of campus buildings. A 2014 university construction report estimates more than $12 billion was put into university construction.[12] Of that $12 billion, 78.8% was put into new buildings (the highest since 1995), 9% into additions, and 12.2% into retrofits.[12] Conversely, a lack of funding for renovations could contribute to deteriorating quality of existing buildings. Among retrofits, HVAC repair/replacement accounted for 50% of all money spent. HVAC and ventilation rates have been shown in primary and secondary education settings to be a contributing factor to poor air quality.[14, 19, 20] Therefore, reduced allocation of funding to retrofit construction could have negative impacts on HVAC operation and indoor air quality.

College campus buildings also represent a major concern for potentially poor indoor air quality due to the populations that occupy them and the duration of occupancy. A number of state courts and congress have recognized that a high-quality learning environment is essential to educating the nation's children.[13] While college undergraduates are young adults, their brains are still in the final stages of development.[21] College students also receive information through a classroom setting and are tested on their ability to perform cognitive tasks. Multiple studies have shown a decrease in cognitive function or ability to complete performance based tasks in K-12 students and adults working in poor IAQ settings.[8, 9, 14, 15] No such studies have been completed among college age participants. However, considering indoor air quality affects adults and younger students, it's fair to hypothesize the same will hold true for college age students. These factors make college students an important population to protect from

poor IAQ. Regardless of the susceptibility of college students, the WHO has issued a document attesting that access to healthy indoor air is a human right.[22] Therefore, it is important to characterize IAQ and its pollutants in higher education environments.

2.2. Indoor Air Contaminants

IAQ is determined based on the presence or lack of contaminants in indoor air. Indoor air is comprised mostly of oxygen and nitrogen, but may also contain a diverse mixture of contaminants present at varying concentration (typically on the order of several parts per billion (ppb) to hundreds of parts per million (ppm)). Depending on the concentrations of individual pollutants, the resulting indoor air pollution may adversely affect health in adults and children. Examples of air pollutants commonly measured indoors include formaldehyde, particulate matter, carbon dioxide, and nitrogen oxides. The indoor concentrations of these pollutants, and others are a function of multiple factors.

2.2.1. Formaldehyde

2.2.1.1. Properties

Formaldehyde is a colorless, flammable, highly reactive compound at room temperature that quickly photo-oxidizes in carbon dioxide and reacts with hydroxyl radicals to produce formic acid.[18] Formaldehyde also exhibits a characteristic odor. Possible exposure routes are inhalation, ingestion, and dermal absorption with inhalation being the most common.

2.1.1.2. Health effects

Acute exposure to formaldehyde can lead to sensory irritation to the eyes and upper respiratory system, eczema, asthma, and allergy.[5, 6, 23] According to a recent controlled exposure study on human participants, subjective sensory irritation begins at 0.38mg/m^3 for the eyes and 0.63mg/m^3 for the nose.[24]

Chronic exposure to formaldehyde has been linked with the development of cancer. Specifically, the International Agency for Research on Cancer (IARC) concluded that there is sufficient evidence for the carcinogenicity of formaldehyde, based on its association with nasopharyngeal cancer.[25]

2.2.1.3. Sources and levels

Formaldehyde is frequently found in the environment around us because it is emitted from both natural sources and man-made products. Environmental and anthropogenic sources include biomass combustion or decomposition.[18] Daily and annual formaldehyde concentrations measured in outdoor air are, on average less than 0.01mg/m^3 but average concentrations in highly urbanized or industrial areas can reach 0.02mg/m^3.[18, 25] Major indoor sources of formaldehyde include building materials (e.g. furniture, wood products containing formaldehyde containing resins, ceiling foams, insulating materials, wallpapers) and consumer products (e.g. glues, adhesives, paper products, electronic equipment, and even cosmetics) .[18, 23, 25-27] Long-term, indoor concentrations of formaldehyde are also dependent on the age of the source and the special density of sources in a given environment.[27] Correspondingly, higher education buildings may have elevated levels of formaldehyde relative to residences, due to high density of furniture and building materials in lecture halls. Mean exposure concentrations of formaldehyde in indoor settings range from 0.005 to 0.15mg/m^3 based on aggregate data compiled by World Health Organization and IARC.[18, 25] One study conducted on a campus in Northwestern China found concentrations of 0.0009 to 0.0722mg/m^3.[28] The Office of Environmental Health Hazard Assessments (OEHHA) recommended 9ug/m^3 exposure level and the less protective 1mg/m^3 guideline proposed by WHO are potentially exceeded confirming the plausibility of overexposure in campus environments.[29].[5] However, the American Conference for Governmental Industrial Hygienists (ACGIH) occupational exposure limit of 0.75ppm (0.92 mg/m^3) is not included in either observed ranges, but is far less protective than WHO or OEHHA.

The possibility of overexposure to formaldehyde combined with the lack of information on concentrations in higher education buildings illustrates the importance of further research.

2.2.2. Particulate Matter

2.2.2.1. Properties

Every day, we as humans inhale billions of particles suspended in the air.[30] Depending on the size, shape, composition, density, and charge and surface area, particles can be deposited in different parts of the respiratory tract.[30, 31] The respiratory system can be broken down into three different sections: the head airways, the lung airways, and the pulmonary region.[31] The diameter of particulate matter or particle size can range anywhere from 0.005 to 100 micrometers.[31, 32] Particle size is an important characteristic in determining health effects. Particles with more than a 10 micron diameter will generally deposit in the upper airways by impaction with a significant amount of ultrafine particles also being deposited.[31, 33, 34] Particles with a diameter range of 0.5µm to 10µm will more likely be deposited in the lower respiratory tract/tracheobronchial region primarily through impaction and some settling.[31, 33-35] Sub micrometer sized particles also have enhanced deposition in the tracheobronchial region due to Brownian motion.[31] Deposition in the alveolar region is largely composed of particles smaller than 10µm, with 3µm particles accounting for the greatest deposition of all sizes.[31] Sub micrometer particles are also retained in this part of the respiratory system about 10-20%.[31] Particles deposited in the lower respiratory tract are difficult to clear and can be retained within the alveolar region for decades resulting in extended exposure beyond the time of inhalation.[36] Chemical composition of particulate matter varies greatly and is dependent on combustion sources, climate, season, and industrial pollution present during formation.[32] Particles can be made up of volatile species, transition metals, reactive gases, carbonaceous material, biologics, and minerals.[32] The variability of substances that make up particulate matter make it much more difficult to determine health effects and mechanisms of toxicity.

2.2.2.2. Health effects

Acute exposure to $PM_{2.5}$ causes adverse respiratory effects such as inflammation and exacerbated allergic responses through generation of reactive oxygen species and the upregulation of pro-inflammatory cytokines. Causal relationships have also been found between particulate matter and cardiovascular effects ranging from increased heart rate variability to mortality.[35, 37, 38] A review of epidemiologic, exposure, and toxicological studies indicate a possible causal relationship between $PM_{10-2.5}$ and cardiovascular effects.[35] A study focused on healthy college age students found an association between $PM_{2.5}$ exposure and decreased lung function.[39]

Long term $PM_{2.5}$ exposure increases risk of cardiovascular symptoms and mortality.[33, 35, 37] There is also suggestive evidence of reproductive, developmental, and cancerous/mutagenic health effects from chronic exposure.[35]

Due to its lack of ability to penetrate as deep as particles less than 2.5 micrometers, the coarse fraction ($PM_{2.5-100}$) is believed to be less harmful. However, emerging research suggests coarse PM could also be associated with negative cardiovascular and respiratory effects.[35, 40-42] Additionally, according to the EPA, suggestive evidence exists between short term exposure to $PM_{10-2.5}$ and cardiovascular effects, respiratory irritation, and mortality.[35] Recent studies have also indicated a link between inhalable particulate and occupational allergic rhinitis.[41, 42] However, there is much more uncertainty in regard to the association between larger particles and the above health effects due to limited evidence, variability in composition, and lack of defined mechanisms.[35]

2.2.2.3. Sources and levels

Particulate matter is formed either by condensation of gases in the air or mechanical generation from combustion and other processes.[33] Larger particles in the PM_{10} to PM_{100} range are created through uncontrolled combustion and mechanical fragmentation of soil and other materials. Fine particles in the $PM_{2.5}$ diameter range are produced through engine

emission, manufacturing processes, and burning biofuels.[33] A review of epidemiologic studies investigating indoor concentrations found average $PM_{2.5}$ concentrations of 6.1 to 16.8ug/m^3 and $PM_{2.5-10}$ concentrations of 5.6 to 33.2ug/m^3 indicating that particulate are generated outside and infiltrate indoor environments.[35] Multiple international studies investigating indoor $PM_{2.5}$ levels, specifically in higher education buildings found concentrations of 25 to 151ug/m^3.[34, 38] Those same studies found PM_{10} concentrations between 32 and 220 ug/m^3.[34, 38] The WHO air quality guideline for mean concentration during a 24hr period is 25µg/m^3 for $PM_{2.5}$ and 50µg/m^3 for PM_{10} indicating overexposure in both studies.[5] It is important to note that both studies were performed on campuses where indoor smoking is still prevalent. Regardless, this data lends credence to the possibility of overexposure in college classrooms, highlighting the importance of additional research classifying particulate levels in higher education. From a regulatory perspective, observed $PM_{2.5}$ and PM_{10} concentrations are well below the established respirable OSHA permissible exposure limits of 5mg/m^3 and 10mg/m^3 by an order of magnitude. However, it is important to note that OSHA uses PM_4 to represent the respirable size fraction and these studies measured $PM_{2.5}$.

2.2.3. Carbon Dioxide (CO_2)

2.2.3.1. Properties

Carbon dioxide is a colorless, odorless gas formed during combustion as well as the respiratory cycle. Primary exposure routes are inhalation and dermal. CO_2 targets the respiratory and cardiovascular systems.[43]

2.2.3.2. Health effects

Acute exposure to high levels of CO_2 causes headache, dizziness, restlessness, paresthesia, difficulty breathing, sweating, increased heart rate, asphyxia, convulsions, and death in extreme exposures.[43] Possible health effects such as decreased performance and decision making ability have been presented at lower exposures.[8, 9, 14, 15]

2.2.3.3. Sources and levels

Carbon dioxide is abundant in both the indoor and outdoor environment. Natural CO_2 sources account for the largest portion released into the atmosphere. Major natural sources are the ocean, animal respiration, forest fires, and volcanic eruptions. On a much smaller scale, there are also anthropogenic sources of CO_2 such as: power generation, chemical production, agricultural practices, and petroleum production. Most of these sources can be attributed to the burning of fossil fuels.[44] Typical outdoor levels of CO_2 are around 380 parts per million (PPM) but can reach up to 500 ppm in urban areas.[45] However, in indoor environments, occupants are the primary source of CO_2 through respiration.[20] Because humans produce and exhale CO_2, concentrations in occupied indoor spaces exceed concentrations outdoors.[9] Indoor CO_2 concentrations encountered in normal indoor environments range from 350 ppm to 2,500 ppm.[20] An intervention study performed in college computer rooms reported indoor concentrations between 470 ppm and 1020 ppm.[19] With regard to regulatory compliance, the levels presented above are well below the OSHA permissible exposure limit and the ACGIH threshold limit value (5000 ppm). However, these limits are designed to protect against more obvious health effects like narcosis and asphyxiation. No widely adopted limit value has been identified for performance and cognitive based health effects that occur at lower concentrations.

Occupancy in college lecture halls can exceed 200 students. A recent article on the University of Colorado, Boulder campus indicated over 33 courses with more than 400 students enrolled.[46] Efforts to break up large courses into sections only lower that number into the low hundreds.[46] Occupancy levels this high are rarely seen in any industry or business outside of academia, highlighting the risk for high levels of CO_2 when air handling requirements are not met.

2.2.4. Nitrogen Oxides (NO_x)

2.2.4.1. Sources

Nitrogen Oxides are a group of compounds including nitrogen dioxide (NO_2) and nitric oxide. NO_x compounds are a byproduct of high temperature combustion in air.[7, 47, 48] Nitrogen dioxide is a gas with a reddish-brown color, strong oxidant properties, and a characteristic pungent odor.[23] In ambient conditions, nitric oxide is rapidly oxidized in air to form nitrogen dioxide by available oxidants, such as ozone.[18]

2.2.4.2. Health effects

Nitrogen dioxide enters the airways and penetrates into the respiratory system where it generates secondary oxidative species. [7, 18] These oxidative species can lead to symptoms of acute exposure, including inflammation, irritation, oxidative stress, and allergic responses in asthmatics. In non-asthmatic children and adults, oxidative products of NO_2 can lead to development of asthma. [7, 18] There is also suggestive evidence that short term exposure to high concentrations of NO_2 can cause cardiovascular disease and death.[7, 18]

Long-term exposure to nitrogen dioxide is associated with the same respiratory and cardiovascular effects seen in short term exposure. Additionally, there is suggestive evidence of a causal relationship with diabetes and cancer.[7] Due to the mechanism in which it works NO_2 has been shown to affect cellular and humoral systems which can weaken immune defenses and increase susceptibility to infection and disease.[7, 47]

2.2.4.3. Sources and levels

Since NO_x compounds are generally a byproduct of high temperature combustion, anthropogenic sources are most common. The largest source of NO_x emission is highway vehicles followed closely by off-highway vehicles (e.g. construction).[7, 48] Other common sources are combustion utilities.[7, 47] Nationally, vehicles and stationary fuel consumption accounts for over 90% of total estimated emissions.[48] The Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU (INDEX) project reported NO_2

concentrations in the range of 13 to 62ug/m^3 indoors and 24 to 61ug/m^3 outdoors.[23] Another study comparing nitrogen dioxide levels between 18 different countries found indoor levels of 10.35 to 120ug/m^3 indoors.[49] The WHO determined a guideline of 200ug/m^3 for a 1 hour average concentration and 40ug/m^3 as an annual average concentration guideline.[18] Based on above average concentrations and the guidelines set by WHO, there is a risk of overexposure in college students. From an occupational standpoint, expected concentrations should fall well below the OSHA permissible exposure limit of 9mg/m^3.

2.3. "Green" Buildings

University campuses are very diverse and unique when it comes to their buildings and facilities. Campuses include buildings ranging from 200-year-old brick structures to newly built, environmentally friendly buildings. With the development of organizations such as the U.S. Green Building Council, Energy Star program, and Leadership in Energy and Environmental Design (LEED), construction of sustainable "green" buildings has become increasingly common.[50] The EPA defines green building as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle".[50] To achieve green building status a building must meet requirements set by a building rating system, which can include LEED, but would also include other rating systems such as (Energy Star, Green Globes, Green Seal, etc.). Building rating systems vary in the metric in which they grade buildings upon, although the underlying principles of the rating systems share similar characteristics: a performance evaluation based on design parameters, according to criteria in areas such as water and energy consumption, use of natural resources, and indoor environmental quality.[4]

LEED is the most widely used green building rating system in the world with over 2.2 million square feet certified every day. [16] Since the LEED building certification system was founded in 2000, there have been an estimated 92,000 projects comprising over 19.3 billion

square feet.[16] Specifically, at Colorado State University, the location of this study, 26 LEED certified buildings have been constructed since 2008, with all but one building being built in the last eight years (2010 to 2018). LEED utilizes a building rating system comprised of four levels of certification: Certified, Silver, Gold, and Platinum.[51] Each level of certification is achieved by exceeding a point threshold associated with that level. Points are awarded prior to occupancy based on criteria in several categories including: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials, and resources, indoor environmental quality, innovation, and regional priority.[51] Indoor air quality is included in the indoor environmental quality category.[51]

A study investigating indoor air quality between LEED certification levels found a positive relationship between certification level and occupants perceived IAQ.[52] However, the points earned from IAQ criteria were not related to the level of worker satisfaction in that area.[52] The average contribution of IAQ to American green building certifications is 9.4% and contributes 8.2 to 9.1% in LEED certifications.[53] Conversely, builders may choose to pursue higher scores in the other categories and only meet prerequisites for IAQ lessening the impact of IAQ on the overall score. For example, it is possible to achieve LEED Platinum certification without receiving any points from the IEQ category.[52] Therefore, parody exists between LEED certified buildings regarding IAQ depending on the priorities of the builder, which creates a question as to whether green buildings have better IAQ.

2.4. Green vs. Conventional vs. Retrofitted

Buildings are typically categorized based on the materials used in their construction as well as the efficiency performance metrics to which they are designed to operate. This approach to classification has led to three building types: newly constructed “green” buildings, conventional buildings, and retrofitted buildings.

Green buildings are constructed using environmentally friendly practices, low emitting materials, and energy-saving mechanisms according to a rating system. Conventional buildings

are constructed with an approach focused on minimizing cost, not maximizing efficiency. Retrofitted buildings are constructed in the same way a conventional building would be but are retroactively upgraded with high efficiency HVAC systems or building materials. Most research that has investigated IAQ among different building types has focused on the broader category of IEQ and perception of IAQ.[54-57] Each study reported higher perceived and environmental quality among green buildings compared to conventional buildings. However, there has been little formal exploration into IAQ specific metrics comparing green buildings to retrofit and conventional buildings.

2.5. Objective of this Research

Although indoor air quality has been widely studied in school settings and green buildings, there is little information involving higher education and differences between building types. Therefore, the characterization of exposures to higher education students, and subsequent impact building type has on exposures, has yet to be explored. This study sought to test if IAQ metrics have a direct association with building type and what impact occupancy status will have on this relationship. We hypothesize that newly constructed green buildings will exhibit the lowest level of contaminants as compared to, followed by retrofitted and, traditional buildings (which will have the highest levels). Further, we hypothesize that all buildings will exhibit higher levels of IAQ contaminants when occupied compared to times when the same buildings are unoccupied.

3. METHODS

3.1. Sample Collection

Three representative buildings were selected from approximately 100 buildings on the main campus of Colorado State University (CSU). A Newly constructed 'green', retrofitted, and conventional building was selected to account for the range of construction and design on campus. Newly constructed buildings were defined as a recently constructed building, built to LEED certified gold status for new construction. Retrofitted buildings were defined as traditional buildings that had received updates to the building air handling systems and building materials in the last ten years. Traditional buildings were defined as those that had not been updated within the past 20 years and were not constructed with any green building certifications in mind.

Indoor air samples and environmental conditions were collected during six distinct sampling campaigns over three seasons: fall, winter, and spring. In each season, one sampling campaign occurred when the building was occupied and the other when the building was unoccupied. Occupied samples were collected during normal building and classroom operations. Unoccupied samples were collected during campus shutdowns such as breaks and holidays. During each sampling campaign, air samples were collected in the following four different locations: two classrooms, one common area, and one outside. The three indoor locations represented areas where students spend a majority of their time inside, where there is heavy traffic between classes, and where infiltration of outdoor pollutants were likely to occur. The outdoor location was selected to give an estimate of ambient pollutant levels directly outside the building.

Samples were collected using specialized air sampling stations consisting of a pump/instrument housing and an elevated platform for samplers (Figure 1). A range of indoor air pollutant measurements were collected over 48 hours using co-located active and passive

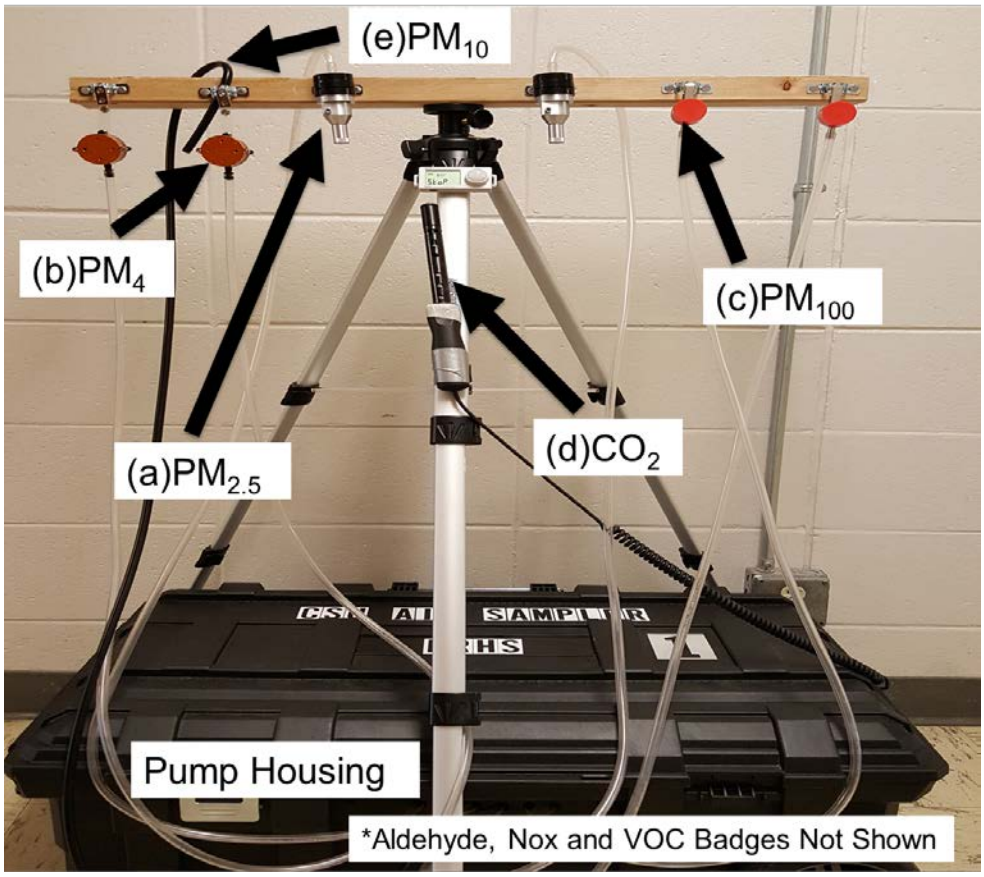

Figure 1: Air sampling station. Pumps and equipment were housed in the box with samplers and probes attached to the tripod and 2x4 above.

samplers; outdoor samples were collected over one eight hour period during the second day of sampling. 48-hour sampling periods were selected as a representative sampling period that could adequately account for potential day-to-day variability. A 48-hour sampling period, at the specific flowrate (below) was also sufficient to collect enough particulate matter for later quantitative analysis. The 8-hour outdoor sample period was selected due to equipment constraints in regard to weather. Each sampling station included a total of six samplers (including replicates) for measuring PM_{100}, PM_4, and $PM_{2.5}$ using two SKC Buttons (SKC Inc. Eighty-four, PA), two SKC aluminum parallel particle impactors (PPI), and two BGI KTL aluminum cyclones (Mesa Labs). The samplers were loaded with 5 µm pore size polyvinyl chloride filters and calibrated. To produce the desired flowrate, each sample was attached to individual pumps that were calibrated to a flowrate of 4 liters per minute (L/min) before each

campaign using a primary flow standard. Samplers flow rates were measured following sample collection to verify pump performance. Differences of less than 5% between pre- and post-measurements were considered acceptable. Samplers were positioned approximately 1.5 meters off the ground in each location using the air sampling station.

In addition to collecting particulate matter, each sampling station was equipped with passive samplers to measure: aldehydes and nitric oxides. UMEx 100 samplers (SKC, Inc.) were used to measure formaldehyde and acetaldehyde. These samplers were positioned to limit the effect of airflow produced by adjacent active samplers. During the fall and winter sampling campaigns, three samplers were deployed at each sampling location to collect an 8, 24, and 48-hour sample. However, during the spring sampling campaigns an additional UMEx 100 sampler was added to each sampling station to collect a second 24-hour sample to quantitatively evaluate the 48-hour sample and determine the relative contribution of aldehydes from each sampling day (this data is not presented). Outdoor sampling stations were outfitted with one UMEx sampler to collect an 8 hour sample. Locations of the four badges on sampling stations remained constant throughout all sampling campaigns.

To measure nitric oxides, an Ogawa passive sampler was affixed to each air sampling station. Samplers were loaded with 14.5 mm triethanolamine pre-coated filters to capture the following compounds: NO_x, NO, and NO_2. Filters were stored at freezing temperatures (<32°F) prior to and after sampling until analysis was performed. Ogawa samplers were not included in fall sampling campaigns, but were implemented during the winter and spring campaigns. The position of the Ogawa sampler (as with the Umex 100 sampler) remained constant across all campaigns. One Ogawa sampler was used at each sampling location inside and outside each building for the 48-hour and 8-hour sampling periods, respectively.

Each sampling station also included two direct reading instruments: the SidePak aerosol monitor (AM510, TSI, Inc., Shoreview, MN) and the Q-Trak (7575, TSI, Inc., Shoreview, MN). Both instruments logged data at 1-minute intervals over the 48-hour and 8-hour sampling

periods. The SidePak measured real-time aerosol concentrations (mg/m^3) using a 10 µm impactor to provide time-resolved measurements that complement the data from the filter based samplers (data not presented). Employing nonconductive Tygon tubing the SidePak was placed in the pump housing with the tube inlet hanging from the tripod unblocked. The Q-Trak was deployed to characterize real-time environmental conditions, including carbon monoxide, carbon dioxide, temperature, and relative humidity measurements. The Q-TRAK probe was extended outside the pump housing and positioned near the PM samplers.

3.2. Sample analysis

3.2.1. Gravimetric

The total mass of PM collected was determined by weighing a filter using a Mettler MT5 balance (Mettler-Toledo, Inc.) alongside an anti-static bar. Filter samples were desiccated for a minimum of 24 hours before tare and gross weighing was conducted. Filters were weighed in duplicate, and the average of two measurements was used to compute the difference between pre- and post-sampling mass of each filter. Concentrations were calculated by dividing the mass of particulate matter on each filter by the volume of air sampled (Equation 1). Filter samples were subsequently archived at -80°C for future analyses to determine the biological and chemical composition of the different aerosol fractions.

$$(1)\ \text{Concentration } (\mu g/m^3) = \frac{mass\ (ug)}{sampling\ rate(m^3/min)\ x\ sampling\ time(min)}$$

3.2.2. High performance liquid chromatography

Analysis of UMEx 100 samplers was performed in accordance to the EPA IP-6C method as previously described.[58] Each sampler was opened to remove the filter, which was extracted in 3 ml of acetonitrile with mechanical agitation via shaker table. Subsequently, 100 µl aliquots were pipetted into 2 ml HPLC vials compatible with the auto sampler. Calibration standards were produced by mixing DNPH-formaldehyde and DNPH-acetaldehyde powder purchased from AccuStandard with acetonitrile. Subsequent dilutions of the stock were

performed using acetonitrile to produce the following: 25ng/ml, 50ng/ml, 100ng/ml, 250ng/ml, 500ng/ml, and 750ng/ml standards. A new set of working standards was created prior to each round of analysis to ensure accuracy. Due to extenuating circumstances two HPLCs were utilized across all sampling campaigns; a Waters 2690 separations module with a 2487 absorbance detector and an Agilent 1290 Infinity. All precautions were taken to maintain consistency across both instruments, including transfer of the chromatography column and sample run parameters. The column used was a Zorbax Eclipse Plus C18 (2.1mm x 100mm, 3.5um) column. Additional parameters include a 10 µl sample injection volume, acetonitrile and water mobile phase, and a 9 minute run time with 4 minute cool down. During the sample run solvent concentrations gradually changed from 75%:25% (water: acetonitrile) to 20%:80% (water: acetonitrile) and back quickly at the end utilizing the gradient elution function of the instrument. UV detection was set to 365nm and subsequently produced chromatograms. A calibration curve was then generated from the analytical standards, and using the curve, samples were integrated and quantitated in terms of DNPH-formaldehyde concentration. The concentration of DNPH-formaldehyde was then converted to its concentration in formaldehyde using equation (2).

(2) Formaldehyde(ug/ml) = [DNPH-Formaldehyde(ug/ml) x 30.03] / 210.21

Next the concentration of the blank filter was subtracted from the sample concentration. Using the blank corrected concentration total mass was calculated with equation (3).

(3) Total mass(ug) = Concentration(ug/ml) x Desorption volume(ml)

Volume of air pulled through the sampler was then calculated using equation (4).

(4) Volume of air(L) = [Time(min) x Sampling rate(ml/min)] / 1000(ml/L)

Using the products from equation 3 and 4 the concentration of formaldehyde and acetaldehyde in the air was calculated according to equation (5).

(5) Concentration(ug/m^3) = [Total mass(ug) / Volume of air sampled(L)] / 1000(L/m^3)

3.2.3. Spectrophotometry

Analysis of NO_x compounds was completed through spectrophotometry on a BioTek Synergy HTX multi-mode reader. Filters were removed and extracted in 50 ml Falcon tubes containing 8 ml of HPLC grade water. Tubes were mechanically agitated for 30 minutes then cooled in a refrigerator for 30 minutes. 2 milliliters of color producing agent was added to the sample solution. Vials were then shaken for a couple minutes before cooling for an additional 30 minutes. Samples were then allowed to equilibrate to room temperature before 125µl aliquots were pipetted into a 96 well plate for spectrophotometry. Standards were created by diluting a previously prepared nitrite stock solution to generate 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 µg/ml standards. Next, standards were cooled and color-producing reagent was added. Standards were then added to the 96 well plate along with three NO_x filter blanks and three NO_2 filter blanks. The 96 well plate was then run through the spectrophotometer at 545 nm wavelength using Gen 5 software. With the standard concentrations as well as their respective absorbance, a standard curve slope was calculated with equation (6). X is the defined as the standard concentration, y is the absorbance of the standard, y^o is the blank absorbance, and x^2 is the standard concentration squared.

(6) $\frac{\sum x(y-y^\circ)}{\sum x^2}$= Standard Curve Slope

After the curve slope is determined samples are blank corrected to control for contamination. Next, the solution concentration of NO_x and NO_2 samples are calculated with equation (7).

(7) Solution Concentration = Blank corrected absorbance / Standard curve slope

The NO_x and NO_2 total collected weight is then calculated with equation (8).

(8) Total Collected Weight (ng) = Solution Concentration x abstract amount (8ml) x 1000

Using their respective total collected weight, concentration conversion coefficient, and exposure time NO_2 and NO concentrations are calculated with equation (9). The NO total collected weight used is determined by subtracting the NO_2 total weight from the NO_x total weight.

(9) Concentration (ppb) = (Collected weight x Conversion coefficient) / Exposure time

Finally, the concentration of NO_x is calculated by adding the NO and NO_2 concentrations.

3.3. Statistical Analysis

Data were organized into groups based on building type, occupancy status, sampling station location, and analyte, resulting in 38 statistical analyses. Descriptive statistics were completed for all groups to determine averages and variation among the groups listed above. Data was then log transformed to test for a log normal distribution typically found in air quality measurements. Subsequent qqplots and levene tests were done on groups being compared to test assumptions for normality of residuals and equality of variances respectively. In cases where assumptions were met, ANOVA multiple comparison tests were conducted (alpha = 0.05). In situations where either normality of residuals or equality of variance were not confirmed, a less powerful, but appropriate, non-parametric Kruskal-Wallis tests was performed (alpha = 0.05). The following comparisons were tested: concentration by building type, concentration by occupancy by building type, and concentration by sample location. When significance was observed in ANOVA or Kruskal-Wallis tests, subsequent pairwise comparisons were done to determine where differences between groups existed. Pairwise comparisons on significant ANOVA results were done with Fisher's least significant difference test while significant Kruskal-Wallis results were tested for pairwise significance with Dunn's test. Additional two sample t-tests were used for comparisons between two groups and also employed an alpha of 0.05. This test was used to test for differences in mean concentrations by occupancy status. All statistical analysis was done with R software (R3.4.0) operating within the R Studio program.

4. RESULTS AND DISCUSSION

Samples were collected from six sampling campaigns, spanning fall, winter, and spring, in three building types. Indoor samples were integrated over 48 hours while outdoor samples were integrated over 8 hours. Much shorter outdoor sample times were due to inclement weather during sampling campaigns. Averaged across all measurements collected, PM arithmetic mean concentrations were 10.79µg/m^3, 7.61 µg/m^3, and 2.72 µg/m^3 for PM_{100}, PM_4, and $PM_{2.5}$ respectively (n=400). Formaldehyde samples collected had an average concentration of 9.21 µg/m^3 (n=45). Carbon dioxide samples had an average concentration of 514ppm (N=61). Each carbon dioxide sample represents an average of one minute readings taken during the sampling period. Descriptive statistics across PM_{100}, PM_4, $PM_{2.5}$, formaldehyde, carbon dioxide, and nitrogen oxide samples are presented in Table 1.

Table 1. Descriptive statistics for each indoor air pollutant. Minimum, first quartile, median, mean, third quartile, and max concentration values for carbon dioxide, formaldehyde, PM_{100}, PM_4, and $PM_{2.5}$.

Analyte	n	Min	Q1	Median	Mean	Q3	Max
CO_2 (ppm)	61	271	404	479	515	612	986
Formaldehyde (µg/m^3)	45	0.75	4.23	7.52	9.21	13.61	34.25
PM_{100} (µg/m^3)	130	0.90	4.10	6.05	10.79	12.38	60.50
PM_4 (µg/m^3)	137	0.90	3.00	4.50	7.61	7.60	51.50
$PM_{2.5}$ (µg/m^3)	133	0.40	0.90	1.40	2.72	3.60	17.20
NO_x (ppb)	35	<LOQ	<LOQ	<LOQ	<LOQ	<LOQ	36.31

4.1. Particulate Matter

A Kruskal-Wallis test indicated a significant difference in PM_{100} concentration among building types (*p*-value <0.001). Subsequent pairwise testing using the Dunn test indicated no significance, meaning there is a difference among mean concentrations between building types,

but the specific difference cannot be found. The retro-fitted building type had the lowest average concentration of PM_{100} (7.9 µg/m^3) followed by the conventional building type (9.7 µg/m^3), and newly constructed LEED building type (14.7 µg/m^3). A Kruskal-Wallis test on $PM_{2.5}$ indicated that there was a significant difference in observed concentration between building types (p-value < 0.05). Again, no significant results were observed from Dunn pairwise tests meaning the source of the difference couldn't be identified. The concentration of $PM_{2.5}$ was lowest in the retrofit building (2.1 µg/m^3), while the conventional and LEED buildings exhibited higher concentrations of 2.7 µg/m^3 and 3.3 µg/m^3 respectively. PM_4 concentrations by building type differed from other size fractions in that the retrofitted building had the lowest average concentration followed by the newly constructed building and conventional building type. However, an ANOVA test on PM_4 by building type was not statistically significant (p-value = 0.29).

We anticipated that concentrations in the LEED building would be the lowest. Instead, data from two of the three cut points (PM_{100} and $PM_{2.5}$) indicate that the newly constructed green building had higher particulate levels than the other two buildings. These findings may be attributed to (1) a larger number of occupants in the green building during sampling and/or (2) interior negative pressure within the building, likely resulting from blocked ventilation ducts (During sampling periods, we observed ventilation blockages in the LEED certified building that were attributable to occupant interferences). Higher occupancy provides greater opportunity for resuspension of particulate matter from carpeting and surfaces. Observed blockage of ventilation ducts within classrooms and offices potentially affect air change rates and may lead to contaminant levels in some managed indoor spaces. Additionally, blocking vents creates a negative pressure environment which limits the ability of building envelope to keep outdoor PM out of the building.

The effect of occupancy status on indoor particulate levels was analyzed across all three size fractions. Unoccupied arithmetic mean concentrations were 2.5 $\mu g/m^3$, 7.5 $\mu g/m^3$, and 9.1 $\mu g/m^3$ for $PM_{2.5}$, PM_4, and PM_{100} respectively; compared to 2.9 $\mu g/m^3$, 7.6 $\mu g/m^3$, and 12.5 $\mu g/m^3$. As hypothesized, a statistically significant increase in PM_{100} (p <0.001), PM_4 (p <0.001), and $PM_{2.5}$ (p <0.04) was observed in occupied campaigns when compared to unoccupied samples.

It is important to note that these results exclude building type and instead pool all three buildings data into size fractions, potentially overlooking an important variable. In order to better understand the effect of occupancy status on particulate concentration across building types, the data were also analyzed in sub-groups by building type and occupancy status. Concentrations separated by building type and occupancy status are presented in Figure 2 below.

After stratifying building type by occupancy status, the data demonstrate that occupancy has varying degrees of impact on particulate concentration levels. Most notably, a large increase in concentration across all three size fractions occurred in the LEED building. Statistically significant increases from unoccupied concentrations to occupied concentrations were observed at all size fractions [PM_{100}(p-value<0.001), PM_4(p-value<0.001), $PM_{2.5}$(p-value<0.002). The retrofitted building type also experienced increased concentrations when occupied at all three size fractions. However, significant differences were only observed at the 100 micron cut point (p-value<0.001). The conventional building had increases in particulate matter concentrations from unoccupied to occupied at two of the three size fractions and saw a significant difference for PM_4 (p-value<0.03).

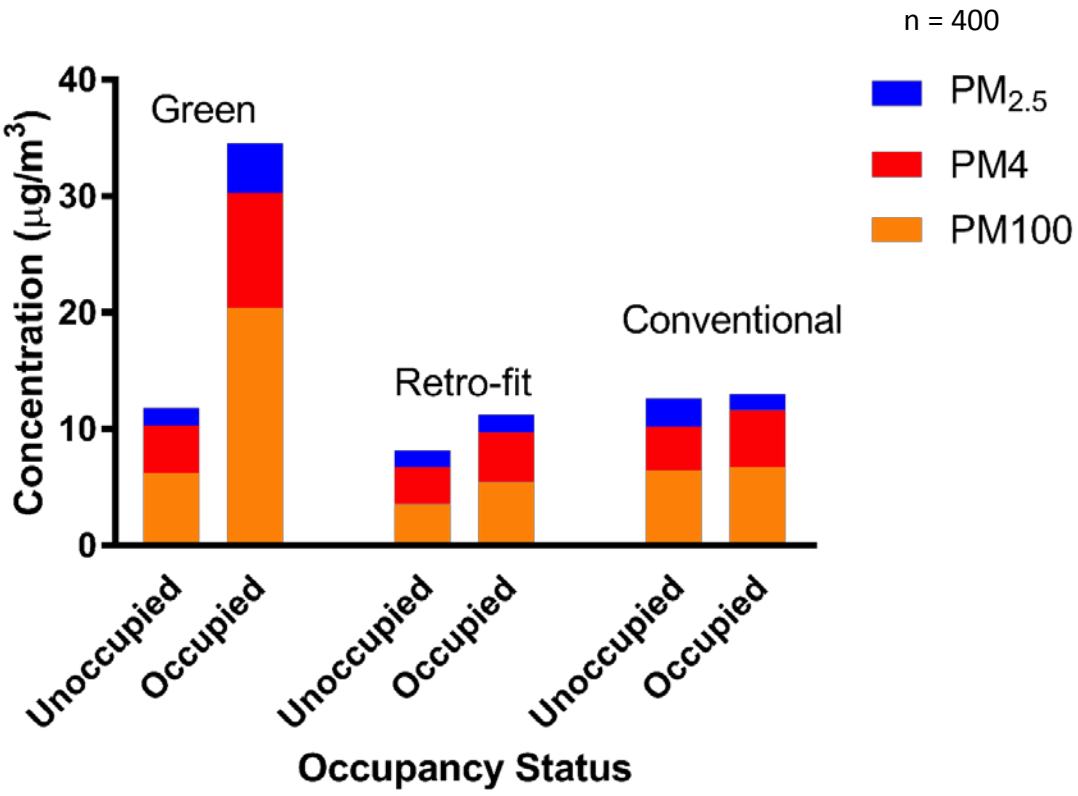

Figure 2: Building particulate levels. Stacked bar graph of PM_{100}, PM_4, and $PM_{2.5}$ concentrations stratified by building type and occupancy status illustrating the differences among unoccupied and occupied samples.

At the smallest size fraction, the conventional building experienced higher levels while unoccupied than occupied contrary to the hypothesis. However, this anomaly is primarily due to an outlier sample that exists in the unoccupied data set that is much higher than all other values in the comparison. This sample was averaged over a much shorter sampling period due to a pump fault after 4 hours. Additionally, this result was not significant (*p*-value = 0.19).

PM concentrations were significantly higher when the buildings were occupied as compared to unoccupied. Still, each building exhibited varying levels of impact associated with occupancy status. The LEED building concentrations increased across all size fractions, the retrofitted building had increases to a much smaller extent, and the conventional building had even smaller differences evidenced by significance at only one size fraction. An explanation for

this can be inferred from the level of occupancy each building experiences. The newly constructed building was observed experiencing a much higher influx of occupants during an average sampling day followed by the retrofitted and conventional buildings. Knowing that, it makes sense that the newly constructed building was impacted to a higher degree by occupancy than the conventional building. Moreover, the reports of occupants covering vents with cardboard and objects within the building only strengthen the impact of occupancy in the newly constructed building.

The concentrations of PM also varied by sampling locations within each building. Outdoor, classroom, and common area particulate matter concentrations are presented in Table 2.

Table 2: Particulate descriptive statistics by sample location. Particulate matter arithmetic average concentrations and standard deviations for PM_{100}, PM_4, and $PM_{2.5}$ for each sampling location across all building types.

Cut Point	**Common Area** **Mean(Std. Dev.)**	**Classroom** **Mean(Std. Dev.)**	**Outdoor** **Mean(Std. Dev.)**
PM_{100} µg/m^3	5.8(3.9)	9.5(9.8)	28.1(16.6)
PM_4 µg/m^3	5.1(3.4)	5.3(5.1)	21.6(13.8)
$PM_{2.5}$ µg/m^3	1.6(1.1)	2.4(2.7)	6.1(3.4)

As referenced in the methodology section, four sampling locations were selected within each building type: two classrooms, one common area, and one outdoor. The impact of each sampling location was tested by pooling data across all building types into the three location categories as seen in Figure d below. ANOVA testing indicated significant difference between sampling location was observed at all three size fractions [PM_{100}(p-value<0.001), PM_4(p-value<0.001), $PM_{2.5}$(p-value<0.001). Based on subsequent pairwise comparisons, outdoor PM_{100} concentrations were found to be significantly higher than concentrations observed in the classroom and common areas.

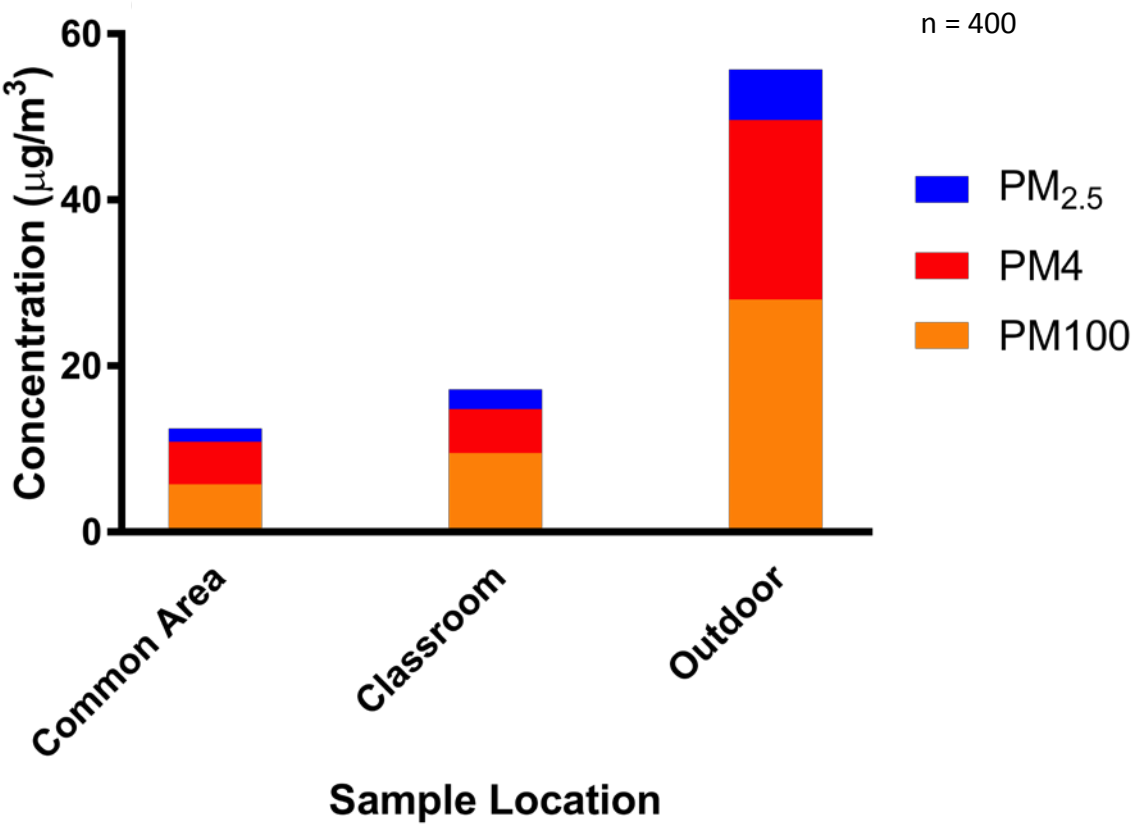

Figure 3: Location particulate levels. Stacked bar graph of unoccupied and occupied PM_{100}, PM_4, and $PM_{2.5}$ concentrations by sample location. Outdoor concentrations at PM_{100} (bottom bar), PM_4 (middle bar), and $PM_{2.5}$ (top bar) were significantly higher than concentrations in the other two sample locations.

Further, classroom levels were significantly higher than common area. While outdoor PM_{100}, PM_4, and $PM_{2.5}$ concentrations were significantly higher than the other two locations, no significant differences were observed between classroom and common area.

Particulate matter levels between sampling locations were highest among outdoor sampling locations followed by classrooms and common areas. High outdoor levels relative to indoor concentrations are to be expected due to a lack of major indoor combustion sources within the building, maintained ventilation systems, and low occupant activity levels (primarily students seated in class). However, higher levels seen in classrooms when compared to common areas was unexpected. Common areas have a higher activity level than classrooms

(walking vs sitting) and should have a higher infiltration rate as they were directly connected to entrances. A possible explanation is the classrooms are heavily occupied for a larger percentage of the day than common areas. For example, aside from periodic passing periods the number of occupants in the common areas were generally low while classrooms were occupied and full excluding passing periods. So it is possible that the level of occupancy is having a greater impact than activity level and infiltration, leading to higher concentrations in classrooms.

4.2. Formaldehyde

Formaldehyde concentrations were highest among the retrofitted building (10.6 $\mu g/m^3$), followed by the newly constructed green building (10.0 $\mu g/m^3$), and the conventional building type (7.0 $\mu g/m^3$). These concentrations fall within the range of indoor concentrations reported in previous research.[18, 25, 28] Additionally, observed concentrations fall well below the WHO guideline and ACGIH limit value. Concentrations by building type can also be visualized in figure 4 below.

Due to small sample size (n=45) and high variability, there were no statistically significant differences in concentration between building type. While there were no significant differences, it is worth noting that the average concentrations between buildings does not support the initial hypothesis, which was the following: the newly constructed green building was built with low emitting building materials and would be expected to have lower levels than the other buildings that didn't follow LEED requirements. However, emission decay was not considered when the hypothesis was proposed. A typical source of formaldehyde indoors is building materials, and the emission source strength of these materials is anticipated to decline with time, resulting in lower indoor formaldehyde levels.

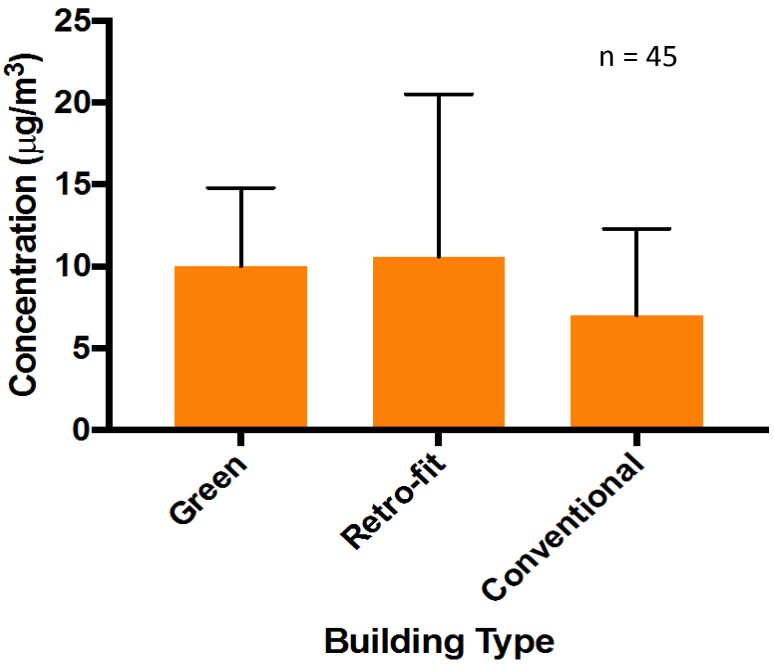

Figure 4: Formaldehyde concentrations by building type. Mean concentrations between building types were not significant. All concentrations are below occupational limits and near background concentrations.

A study on particleboards, a building material containing formaldehyde, found an average half-life of 216 days across 16 products.[59] Considering the age of the conventional building type, it can be assumed that the formaldehyde available for emission from the high emitting building materials used during construction have been depleted over time. Conversely, the retrofitted and newly constructed green buildings have had much less time to off gas any volatiles present in their building materials. Had all three buildings been constructed at the same time, the original hypothesis would theoretically hold true but it seems time has had a major impact on formaldehyde concentrations across building type.

The effect of occupancy status on formaldehyde concentration was analyzed across all 48 hour samples excluding building type. No statistically significant differences were observed (*p*-value = 0.31). Indoor formaldehyde concentrations are primarily produced by furniture, wood products, and building material emissions. Therefore, this result was expected.

Formaldehyde concentrations were compared between classrooms and common areas. Outdoor measurements were excluded from analysis as no representative 48 hour outdoor samples were taken during the study due to aforementioned outdoor sampling constraints. Concentrations in common areas (10.4 µg/m^3) were similar to those measured in classrooms (6.8 µg/m^3). No significant differences were observed between the two locations. It is possible that the classrooms sampled were constructed with lower emitting materials, but without additional information about specific materials utilized little can be inferred from these results.

4.3. Carbon Dioxide (CO_2)

The newly constructed green building had the highest mean CO_2 concentrations (540ppm), followed by the retrofitted building at (539ppm), and conventional building with (467ppm). ANOVA statistical testing produced no significant difference between building types (*p*-value = 0.29) While no significant differences were observed slightly higher concentrations were noted in the LEED and retrofitted buildings, which can be related to higher occupancy.

With regard to occupancy status, higher CO_2 concentrations were found in occupied samples (603ppm) compared to unoccupied samples (423ppm). Additionally, occupied concentrations were found to be significantly higher than unoccupied values (p-value<0.0001). This result is expected because in buildings without a large combustion source, humans are the primary contributor to increased levels of carbon dioxide.[20] Also, levels of carbon dioxide during unoccupied conditions in all three building types and location types were near ambient conditions (402ppm) referenced by the National Oceanic and Atmospheric Administrations, which is anticipated in empty buildings.

A further comparison of carbon dioxide levels under different occupancy conditions and different building type are presented in Figure 5 below.

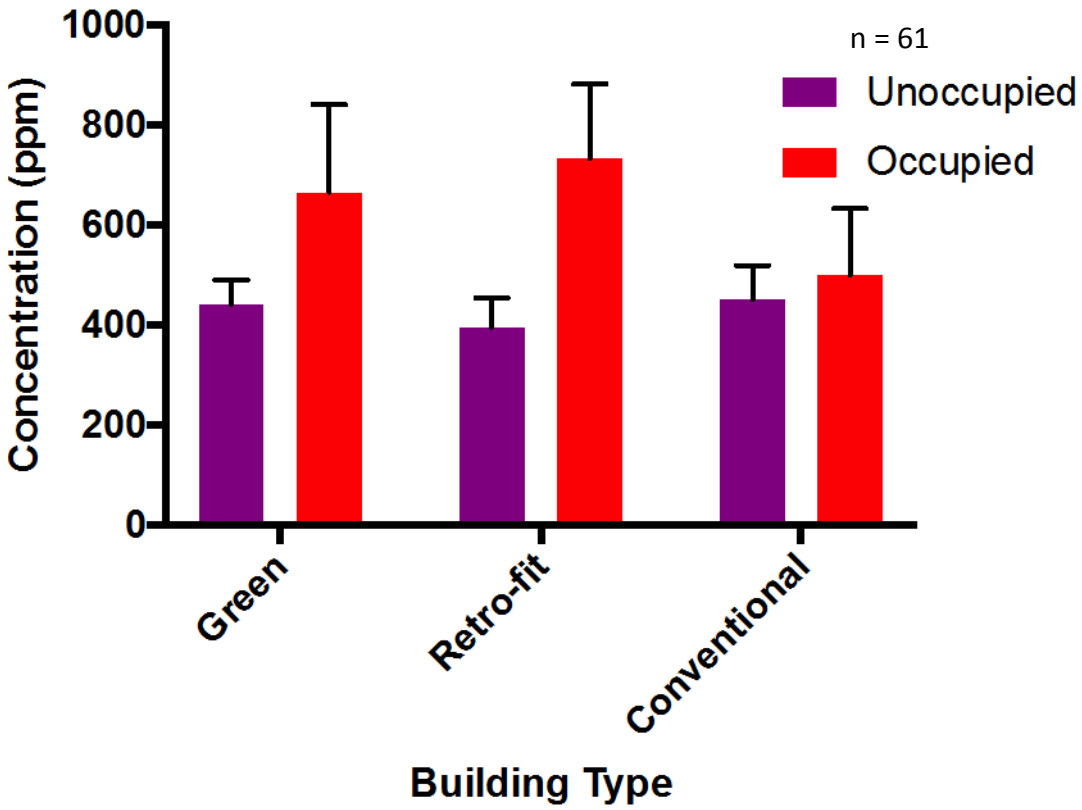

Figure 5: CO_2 concentrations by building type. Larger increases from unoccupied to occupied CO_2 concentrations was observed in the LEED and retrofit building types compared to the conventional building.

Separated by building type, Figure 5 illustrates an increase in CO_2 concentration from unoccupied to occupied in each building. ANOVA statistical analysis confirms a significant difference between occupied and unoccupied conditions for the newly constructed green and retrofitted building types with p-values of 0.01 and <0.0001 respectively. No significant difference was found in the conventional building type.

Concurrent with particulate matter results, occupied settings were associated with an increase in CO_2 concentrations. Moreover, the newly constructed building and retrofitted building saw a larger difference in mean concentration between occupancy conditions than the conventional building. Again, this increase in CO_2 among all three buildings can be explained by the level of occupancy each building experienced under the assumption that occupants are the main source of indoor CO_2. The conventional building was observed with a small number of

occupants during a given sampling period and therefore would be expected to have a smaller difference between occupancy statuses. A larger number of occupants were observed in both the retrofitted and green buildings lending to a greater difference between occupancy statuses. Concentrations differences seen in the green building could also be partly attributed to occupants tampering with the ventilation during occupied sampling. Blocking of air vents observed in the LEED building could have limited air flow concentrating CO_2 within the building.

Classrooms CO_2 levels were highest (540ppm), common areas saw the second highest concentrations (512ppm), and outdoor had the lowest levels (433ppm). No significant difference was seen between the three locations. Using CO_2 as an indicator for occupancy, it is understandable that classrooms that are occupied a majority of the day have higher levels than common areas that are only full during passing periods.

4.4. Nitrogen Oxides (NO_x)

Due to the method and equipment selected for analysis of nitrogen oxides the limit of quantitation (30ppb) was above all but one sample concentration. Additionally, only 13 of 70 samples exceeded the limit of detection (9ppb), meaning that while 12 samples were detected we were unable to report their concentrations confidently. Therefore, no statistical analyses were done on either nitrogen dioxide or nitrogen monoxide. This outcome is not surprising, as expected indoor NO_2 concentrations fall right around the limit of quantitation for our equipment.[23, 49] Concentrations in this study were also expected to be low as major NO_x sources like vehicles and other combustion activities are not present in an indoor setting.[7, 48] This data will be analyzed categorically and added to a statistical model in a future manuscript.

5. CONCLUSIONS

Substantial amounts of time are being spent indoors as urbanization continues to rise in the United States. Therefore, it is essential to understand the indoor environment and potential harmful exposures found within it. Inhalation is a major route of exposure to environmental pollutants indoors, and indoor environmental exposures have been associated with various negative health outcomes. Characterizations of indoor air pollutants and their subsequent health outcomes have been conducted in elementary schools and office settings. However, limited information is known about the indoor environment at institutes of higher education. Recent transitions to more efficient and sustainable campus buildings and extended durations of student exposures illustrate the need to quantify indoor air quality in higher education. Using campus buildings, we characterized indoor air quality across three different higher education building types. Three size fractions of particulate matter, formaldehyde, carbon dioxide, and nitrogen oxides were compared across building types, occupancy status, and sample location. While building type did have a significant impact on indoor air quality performance, a far more pronounced impact was observed from occupancy status. Additionally, LEED certification was found to have no positive impact on air quality contrary to the hypothesis. Instead it seems that while being built with efficiency and sustainability in mind, air quality measurements were higher in the LEED building type. This study will provide a reference for future research into higher education and more broadly the implications of recent shifts toward a green building environment.

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APPENDIX

Supplemental pairwise tests

Table 3: Pairwise comparison tests and associated P-values.

Comparison	P-value
$PM_{2.5}$ Conventional – Retrofitted	0.103
$PM_{2.5}$ Conventional – LEED	0.628
$PM_{2.5}$ Retrofitted – LEED	0.059
PM_{100} Conventional – Retrofitted	0.051
PM_{100} Conventional – LEED	0.198
PM_{100} Retrofitted – LEED	0.058
$PM_{2.5}$ Common – Class	0.135
$PM_{2.5}$ Common – Outdoor	<0.001
$PM_{2.5}$ Class – Outdoor	<0.001
PM_{4} Common – Class	0.8711
PM_{4} Common – Outdoor	<0.001
PM_{4} Class – Outdoor	<0.001
PM_{100} Common – Class	0.057
PM_{100} Common – Outdoor	<0.001
PM_{100} Class – Outdoor	<0.001
CO_2 Conventional – Retrofitted	0.398
CO_2 Conventional – LEED	0.634
CO_2 Retrofitted - LEED	0.869