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INVESTIGATING THE TOLUENE REMOVAL OF A BOTANICAL AIR FILTER WITH A LOOSE-PACKED GROWTH MEDIA FOR POTENTIAL ENERGY SAVINGS

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By Osama Saad Alraddadi

Entitled
INVESTIGATING THE TOLUENE REMOVAL OF A BOTANICAL AIR FILTER WITH A LOOSE-PACKED GROWTH MEDIA FOR POTENTIAL ENERGY

For the degree of Master of Science

Is approved by the final examining committee:

William J. Hutzel
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Brandon Boor
Mark Shaurette

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Approved by Major Professor(s): William J. Hutzel

Approved by: Duane Dunlap 04/11/2016

Head of the Departmental Graduate Program Date
INVESTIGATING THE TOLUENE REMOVAL OF A BOTANICAL AIR FILTER WITH A LOOSE-PACKED GROWTH MEDIA FOR POTENTIAL ENERGY SAVINGS

A Thesis
Submitted to the Faculty
of
Purdue University
by
Osama S. Alraddadi

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science

May 2016

Purdue University
West Lafayette, Indiana
For my mother Zahra Al-Ahmadi who sacrificed her welfare to the nurture, education, and wellbeing of my sisters, my brother, and myself.

إلى أمي الغالية: زهرة الأحمدي
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ABSTRACT


The research of this thesis developed experiments inside a sealed environmental chamber to examine the effectiveness of a botanical air filter with an assisting fan and a loose-packed growth media (i.e., Biowall) in removing toluene from air. Through injecting a known amount of toluene and continuously monitoring its decay inside the environmental chamber, five different toluene decay rates were quantified: the natural decay rate (empty chamber), the decay rates with the presence of the Biowall for two different fan speeds, and the decay rates with the presence of growth media without the plants for dry and wet conditions. The clean air delivery rates for the Biowall with both fan speeds and the growth media with both conditions were then found through the mass conservation of contaminates equation with respect to the natural decay rate and the chamber’s volume. Additionally, with the reference to ASHRAE 62.2 standard for acceptable ventilation rates for residential buildings, weather data, and typical home sizes, the thesis estimated preliminary potential energy savings in ventilation for different climate zones based on the clean air delivery rates of the Biowall.
CHAPTER 1. INTRODUCTION

This chapter introduces the indoor air quality problems and their significance. The chapter also defines the scope of the research, and addresses the research question of this thesis. Definitions, limitations, delimitations and assumptions are also discussed at the end of this chapter.

1.1 Problem Statement

The current movement toward energy-efficient buildings, especially residential buildings, poor indoor air quality (IAQ) became an increasing problem. Air sealing the building is one of the approaches to save energy in air conditioning. The absence of proper ventilation, the airtightness and the very low infiltration of air in such buildings cause poor IAQ. Harmful chemicals and particles inside buildings become a part of the indoor air environment that can be two to five times more polluted than outdoors according the U.S. Environmental Protection Agency (EPA) (EPA, 1989). Volatile organic compounds (VOCs), for example, are typically present in indoor air as these compounds emit from a wide variety of sources (e.g., adhesives, paint and cleaning products). The presence of VOCs, and other chemicals creates poor IAQ that leads to serious health issues. Sick building syndrome, asthma, and other respiratory illnesses can be caused by the poor IAQ, which costs the U.S. over $70 billion dollars annually (Fisk, 2000).
Between improving the IAQ and saving energy, the problem comes to revolve around ventilation. Using proper natural ventilation, for instance, will certainly improve the IAQ but it will definitely increase cost of air conditioning in return, and it may introduce outdoor pollutants. Energy recovery ventilators, in which supply and exhaust air exchanges heat, are some of the approaches to maintain acceptable IAQ without a high cost of energy. Energy recovery systems can have a high efficiency, but higher efficiency comes with a higher capital cost plus their operating cost. Air cleaning devices and systems such as carbon filters, ultraviolet lights, and botanical air-filtration are other types of technologies but they are not typically incorporated into ventilation systems. The integration of air cleaning systems and devices with the ventilation systems needs to be thoroughly studied and evaluated to provide a sustainable solution to the poor IAQ issue.

1.2 Research Question

Can a botanical air filter with a loose-packed growth media improve the removal of toluene from air to provide potential energy-savings?

1.3 Scope

The study in this thesis aims to quantify the cleaning ability of a botanical air filter to remediate VOCs from air. The botanical air filter in this study consists of different plant species that are placed in a loose-packed mixture of a growth medium. As previous literature, which are discussed in the next chapter, showed the significance of plants in remediating VOCs from air, especially at the root-zone (i.e., rhizosphere), the air is forced to pass through the growth media of the botanical air filter. In a controlled
environment, the botanical air filter will be evaluated for its air cleaning ability and performance as an active filter.

The botanical air filter is studied as sustainable alternative for other ventilation systems. Using botanical air filter to reduce VOCs concentrations may reduce the amount of circulated outside air to the inside of homes. The botanical filter, therefore, could highly contribute to the energy saving of residential homes. To investigate whether the botanical air filter is a sustainable system, its potential energy savings will be evaluated in this research.

1.4 Significance

The high concentrations of VOCs in homes IAQ present substantial problems, and practical solutions are needed. According to Fisk (2000), the poor IAQ is a major cause of respiratory diseases, and sick building syndrome, which some of its symptoms are nausea, fatigue, and throat and eye irritations. In poor IAQ, these diseases pose a threat on occupants’ health, especially the elderly and young. The economical cost associated with the problem, on the other hand, is enormous, and, in fact, the cost is suggestively higher when the lost of productivity is taken into account (Fisk, 2000). The existing problems can keep growing unless solutions are implemented. Botanical air filtration systems have already shown potential in improving IAQ, and especially in cleaning air from VOCs such as formaldehyde, toluene, and benzene (Wolverton, 2010; Wang, 2011). Botanical air filters might be one of the next affordable and applicable systems that will assist in solving the poor IAQ problems in residential homes.
Botanical air filtration is a sustainable system with a possibly positive impact on one of the global challenges—Energy. Botanical air filters, in contrast to other ventilation technologies, do not necessarily require any energy input for operating (e.g., fan power), nor do they need any periodical replacement. Majority of the botanical filter components are naturally available resources (e.g., plants and growth media) that form a sustainable system. With the system ability to improve IAQ, botanical air filters can reduce ventilation rates of a building envelope. Consequently, the energy consumption of heating and cooling will also be reduced. Since heating, ventilation, and air-conditioning (HVAC) systems consume the majority of energy in residential buildings, which was around 48% in 2009 according to a survey by the U.S. Energy Information Administration (2013), botanical air filters can be a contributor in minimizing the HVAC systems’ usage of energy in residential buildings. In such manner, the botanical air filters will assist in moving toward sustainability and energy efficiency.

1.5 Definitions

Biofilter – “a bioreactor where a contaminated air or water stream is actively passed through a region with a high biological activity where the contaminants are neutralized by biological processes” (Soreanu, Dixon, & Darlington, 2013, p. 2)

Biowall—“The “Biowall” is envisioned as an integral part of the heating and cooling system for a home or small commercial building; where it will remove airborne contaminants by leveraging the natural ability of plants to metabolize harmful volatile organic compounds.” (Newkirk, 2014)

Botanical biofiltration – “a hybrid of biofiltration and phytoremediation” (Soreanu, Dixon, & Darlington, 2013, p. 2)
Clean Air Delivery Rate (CADR) – “The CADR is a measure of a portable air cleaner’s delivery of contaminant-free air, expressed in cubic feet per minute.” (EPA, 2008, p.9)

Phytoremediation – “using plants for cleaning large contaminated areas of soil and water in the outdoor environment, especially with heavy metals, fertilizers (nitrate, ammonium), oil spills and solvents”(Soreanu, Dixon, & Darlington, 2013, p. 2)

Rhizosphere – “Hiltner [German agronomist and plant physiologist Lorenz Hiltner] described the rhizosphere as the area around a plant root that is inhabited by a unique population of microorganisms influenced, he postulated, by the chemicals released from plant roots.” (McNear Jr., 2013, p.1)

1.6 Assumptions

The assumptions for this research are:

• The environmental chamber represents an airtight room.
• The adsorption of toluene on the plant’s leaf is neglected.
• The air is well-mixed inside the environmental chamber.
• The only source of VOC in the chamber is from the test injection.
• Toluene is distributed equally in the chamber by the mixing fan.
• The plants’ microbial community is the major contributor in remediating VOCs from the chamber indoor air.
• The plants consume the absorbed toluene by the growth media, especially activated carbon pellets medium.
1.7 Limitations

The limitations for this research are:

- Toluene is the only VOC that is generated and monitored during the experiment of this research.
- The Photoionization Detector (PID) is limited in accuracy with a minimum reading of 0.1-ppm.
- Longer-term performance of the Biowall cannot be evaluated in this research.
- The environmental chamber has a known air leakage.
- Commercial grade sensors are controlling and monitoring the HVAC system of the chamber, only.
- The data collection may not be continuous but it is collected on specific time intervals.
- Moisture content in the growth media cannot be controlled.

1.8 Delimitations

The delimitations for this research are:

- The energy analysis, if any, does not investigate any type of buildings but energy-efficient residences.
- Only the decay of air containments is measured in this research.
- The mechanism of removing containments by plants is not investigated in this research.
1.9 Chapter Summary

This chapter stated the problem, the significance and the scope of this research. Besides defining the scientific and technical terms, assumptions, limitations and delimitations were addressed.
CHAPTER 2. REVIEW OF LITERATURE

The literature review of this thesis will discuss three main areas. First, the indoor air quality problem and the regulations associated with it. The second part is the history of biofiltration and phytoremediation. The third part will study the prior work of using biofiltration in energy efficient buildings.

2.1 Indoor Air Quality

This section will discuss two main points. The problem of indoor air quality and its origin will be the first topic. The review will go further to point out the regulations that were taken by U.S. government and international organizations.

2.1.1 Problem of Indoor Air Quality

After the oil embargo in 1973, the future of energy became more important in the United States. The National Energy Act of 1978 is an example of a legislative response at the federal level, besides several other legislative actions. The U.S. congress actions led to significant changes in the national use of energy and the public awareness of the problem. Along with many of the prominent changes, construction of buildings was among the top transformers toward energy efficiency. Reducing the energy consumption of heating, ventilation and air-conditioning (HVAC) systems was a top priority for its
excessive energy use in buildings. Improving HVAC efficiency was not the only approach; sealing buildings to reduce heat transfer was another way that created what is known today as energy-efficient buildings or net-zero buildings. As a result of the movement towards energy-efficiency in buildings, ventilation systems were altered and consequently raised problems with indoor air quality (IAQ), health and productivity (Spengler & Chen, 2000).

Professor John Spengler of Harvard University and Professor Qingyan Chen of Massachusetts Institute of Technology (2000) at that time examined a critical question: “Are healthy buildings a subset of green buildings?” In their study, people, buildings and outside environment are stated as the main sources of contamination. High airtightness of new buildings, which almost isolates the outside air from the inside, provides poor IAQ inside the building. Using a variable air volume (VAV) in the HVAC system instead of a constant volume that lowers the supply air is another cause of maintaining poor IAQ in buildings (Spengler & Chen, 2000).

The source of air containments, on the other hand, is the volatile organic compound (VOC) emissions from a wide range of household products as well as from the home occupants. Furnishing, adhesives, finishing, painting, tobacco smoke, cleaning products, wires and many other items inside buildings are source of pollutant gaseous and VOC such as formaldehyde, toluene, benzene and xylenes. The existence of VOCs in the indoor air caused an increase in the number of building-related illnesses (Spengler & Chen, 2000). Other sources of VOCs inside home is the breath of occupants, their clothes and their personal products according to Jill Fenske and Suzanne Paulson of the University of California of Los Angeles (Fenske & Paulson, 1999).
Noted in 1989, the U.S. Environmental Protection Agency (EPA) in their report to the congress identified the IAQ threat. The EPA report showed that around 90% of people spend most of their time indoors than outdoors. As a result of the time spent indoors and the rising concentration of VOCs from chemical products, Sick Building Syndrome (SBS) became a phenomena. Allergies and low productivity were also related issues to poor IAQ. Elderly, according to the report, are at a higher risk from building-related illnesses, in general, due to lack of awareness. Children and those who are immunocompromised, similarly, are another threatened by the poor IAQ and resulting diseases. Beside the EPA’s actions to solve the problem and the suggestions that they provided to the government, they also listed several research needs such as control techniques for indoor air pollutants as well as the sources of these pollutants (U.S. Environmental Protection Agency, 1989). The EPA was not the only agency that took action. The Occupational Health and Safety Administration (OSHA) and the World Health Organization were also involved and developed regulations and guidelines for acceptable VOC levels in buildings and workplace (Spengler & Chen, 2000).

2.1.2 Regulations and Standards

In 1973, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) developed the first standards (i.e., ASHRAE standards 62) that noted “acceptable ventilation rates”. ASHRAE standard 62-1973 required a ventilation of 20 cfm (cubic feet per minute) for each occupant. In 1981, the name of the standards changed to “Ventilation for Acceptable Indoor Air Quality,” and the required ventilation rate drastically fell to 5 cfm per person. In 1989, the ventilation rate went back up to 15
cfm per person or 0.35 ACH (air change per hour), whichever was higher. ASHRAE 62 standards were updated six times after 1989. Since 2004, ventilation rates are specified based on both area and occupant basis. The most current standards for IAQ are divided into two sub-standards: ASHRAE standards 62.1-2013 – Ventilation for Acceptable Indoor Air Quality and ASHRAE standards 62.2-2013 – Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. ASHRAE is trying extensively to balance between IAQ and energy consumption. As ventilation rates are directly proportional to energy cost, any increase in the ventilation rate corresponds with an increased energy cost (ASHRAE, 2013a; ASHRAE, 2013b; Aydogan 2012; Jansen 1999; Spengler & Chen, 2000).

Briefly, this section of the literature review revealed a few major points on the formation of today’s required ventilation rates. As buildings moved towards energy-efficiency after the 1973 energy crisis, IAQ issues appeared due to the high airtightness, low ventilation and VOC emissions in buildings. Regulations such as ASHRAE and the EPA made efforts to provide solutions for improving IAQ without comprising energy. Maybe healthy buildings are not yet a subset of green buildings, but the improvements are still ongoing. Infants, children, pregnant women, asthma patients are at a higher risk when they are exposed to VOCs.

2.2 Biofiltration

In this subchapter, the origin of biofiltration to remove VOCs from air is discussed. The pioneering work in the area of botanical air filtration is also overviewed. Dr. Bill Wolverton, a pioneer in biofiltration, was the main reference of this section.
2.2.1 Can Plants Remove VOCs from air?

At the John C. Stennis Space Center in Mississippi, NASA researchers were the first to scientifically show the ability of plants to remove VOCs in a sealed environment. The findings indicated that VOCs (i.e., formaldehyde, benzene and trichloroethylene) were remediated at various removal capacities for each of 12 different indoor plant species. NASA, subsequently, built a living test chamber called Biohome for additional research. Synthetic materials for building and furnishings were used in creating the sealed environment where VOCs would present. Foliage plants were placed in a fan-assisted planter-box. The fan was used to pull air through the growing medium, which was a mixture of soil and activated carbon, to evaluate the plant ability in removing VOCs. A mass spectrometer analysis showed that the setup of this type of filter could remove VOCs from the air with the same efficiency of 15 commonly known potted plants. The researchers, in addition, found that there were no SBS symptoms (e.g., burning eyes and throat problems) in contrast to their experience prior placing the plants inside the Biohome. The research went further where a student lived in the house for a summer and he gave positive feedback in regards to IAQ (Wolverton, 2010).

2.2.2 Can Plants Remove a Continuous off-gassing of VOCs?

During the 1990s, the study of plants’ ability to remove VOCs from a sealed environment focused on the mechanism and possible applications. “Phytoremediation” is the term for the process in which plants and their root microbes are employed to clean either air or water. Wolverton Environmental Services, which was founded by Dr. Bill Wolverton, a pioneer researcher in phytoremediation, continued the research to find out
whether plants can remove VOCs when they were continuously introduced to a sealed environment. Scientists from Wolverton Environmental Services constructed two sealed test chambers for the experiment. A lady palm (*Rhapis excelsa*) was placed in one chamber and the other control chamber was left empty. Urea-formaldehyde was placed in both chambers and a water container was placed in the control chamber to create a humid environment as in the plant chamber. After testing, the formaldehyde level did not change in the plant-free chamber but around 75% formaldehyde removal was achieved in the first 12 hours of the test in the plant chamber and continued to decay for the rest of the 60 hours of the test. Also, the test revealed that the increase in temperature assisted in removing the formaldehyde faster. Another finding was that around 60% of the phytoremediation was removed in rhizosphere. Nevertheless, removing the plant from the soil reduced the removal rate of the rhizosphere (Wolverton, 2010).

### 2.2.3 Is Phytoremediation a Clean and Reliable Process?

Using phytoremediation as a filter for air pollutants showed some advantages that are not provided by commercial air filtration devices such as activated carbon air filters. The available air filters in the consumer market require periodical replacement because after a certain time, the air pollutants accumulate in the filter. The acclamation of containments over time may clog the filter and cause high concentrated pollutants that could potentially return back into the indoor environment. Biofilters, on the other hand, do not need to be changed periodically because the plants use the VOCs as food and energy sources. WES also did an experiment that compared a new biofilter versus a two years old biofilter. The results showed that the ability of both biofilters, in removing
formaldehyde, were almost the same. The biofilters that WES used are called EcoPlanter; they are patented by Dr. Wolverton and commercially licensed to Actree Corporation in Japan. Beside the minimal maintenance requirement and cost savings, the biofilters are environmentally friendly and they do not require special disposal such that required by activated carbon filters (Wolverton, 2010).

2.2.4 The Removal of VOC by Different Parts of the Plant

From the National Horticultural Research of South Korea, in 2008, Kwang Jin Kim et al. investigated the contribution of the root zone and the aerial parts of the plants for their ability to remove Formaldehyde. Weeping Fig (Ficus benjamina) and Paperplant (Fatsia japonica) plants were chosen since they both have a single stem that helped in the separation process of the aerial parts from the rest of the plant. In a 1m³ airtight chamber, the aerial part, the root zone and the entire plant were each tested for five hours during the daytime and five hours during the nighttime. The plants were potted in a mixture of Mix #4 (i.e., around 60% peatmoss, perlite, dolomitic lime, gypsum, and wetting agent), bark-humus, and sand with a ratio of 5:1:1. The aerial part of the plant was tested by sealing the lower portion with a Teflon bag, while the root zone was tested by removing the foliage of the plants. The tests were conducted at around 23°C and a relative humidity of approximately 40%. The initial concentration of the formaldehyde inside the chamber was around 2.00ppm, which was more than 10 times higher than the acceptable amount of formaldehyde in new houses in South Korea. The concentration of the formaldehyde inside the chamber was measured every 1-hour by using a sampling tube (Kim et al., 2008).
Figure 2.1, which was taken from Kim’s publication, shows the results of the described test. The upper portion of the figure shows the removal of the entire plant, which was effective during the day and night times. The middle portion shows how the aerial parts of the plant are significantly more effective during the daytime than during the nighttime. Lastly, the lower portion shows that the roots are effective in both times, but they are more efficient during the nighttime. The results showed how the root zone has an important role in the air-cleaning process of the plants (Kim et al., 2008).

Figure 2.1 Formaldehyde Removal of Various Parts of the Plants during Day and Night (Kim et al., 2008)
To summarize, this section discussed the beginning of using plants in cleaning air from VOCs. NASA started the research and found significant results of the plants’ ability to remove VOCs formaldehyde, benzene and trichloroethylene. Dr. Wolverton continued the research on the mechanism of how plants remediated VOCs from air. The research also confirmed commercial validity of biofilters and the plants ability to remove VOCs in real world settings. Kim et al. also investigated different parts of the plant and they found that the root zone has a significant impact in increasing the clean air delivery.

2.3 Biofiltration in Green Buildings

This section will discuss the applications of biofilters in buildings and their potential energy savings. In 1990s, Dr. Alan Darlington was the first to integrate botanical air filters into an HVAC system. In the 21st century, further studies were applied at Syracuse University, Rensselaer Polytechnic Institute, and Purdue University. This section will try to cover most of the significant findings by the four different studies.

2.3.1 Living Wall Biofilters

Dr. Alan Darlington from the University of Guelph (Ontario, Canada) and his team presented (2000) a different biofiltration approach. Instead of using a standalone biofilter like Wolverton’s EcoPlanter, Dr. Darlington’s team integrated a living wall of plants into an independent HVAC unit. The vertical-10 m² (108 ft²) living wall consisted of 150 different indoor plant species with a 3,500-liter (124 ft³) aquarium in its base. The living wall was constructed in a 160 m² (1,722 ft²) airtight room at Canada Life Assurance Co. headquarters building. Their goal of this particular study was to examine
the possibility of replacing the traditional ventilation systems with a living wall of plants in order to improve IAQ without spending energy in circulating outside air to the inside. The team also studied whether biofiltration had any negative impact on IAQ. The IAQ measures were the levels of formaldehyde, total VOC (TVOC) and aerial spore counts. In this experiment, the VOCs were not introduced to challenge the plants’ cleaning ability but to compare the performance of the living wall against other similar spaces that used traditional ventilation systems. The room of the living wall, which was naturally lighted, was maintained at an average temperature of 20°C (68 °F) and relative humidity levels between 40 to 70%. The face velocity of air passing the living wall was around 0.01 m/s (0.03 ft/s) (Darlington, Chan, Malloch, Pilger & Dixon, 2000).

After one year of collecting and sampling data, various results were obtained using two-way ANOVA analysis. Knowing that the living wall room was around 25 times less ventilated than the traditionally ventilated room in this comparison, the TVOC and formaldehyde level were almost similar and less in some cases. In other words, the living wall was able to maintain acceptable IAQ levels for VOCs with 25 times less circulation of outside air. On the other hand, the spore counts in the living wall room were insignificantly higher than other rooms in the comparison that Dr. Darlington et al. made on their study. The irrigation system used in the living wall was the reason for the higher spore counts as the observation was made during the irrigation cycles. Nevertheless, the study concluded that the living wall did not show any significant negative impacts on IAQ (Darlington, Chan, Malloch, Pilger & Dixon, 2000).

Dr. Darlington published (2004) further results for potential energy savings based on installed living walls at various locations. The results in the study were Based on
ASHRAE standards 62-1989 where three to six air changes per hour per person was required for acceptable ventilation and IAQ. Under normal operation of an HVAC system, according to Dr. Darlington, up to 20% of the building energy could be consumed in maintaining acceptable IAQ. The energy consumption of ventilation may vary based on the outside temperature and relative humidity conditions. However, based on Dr. Darlington’s study, a biofilter could bring 60% of the IAQ requirements that could save around 0.3KW/occupant in the summer and 0.58KW/occupant in the winter. In other words, using a botanical air filtration could save up to 60% of the energy use in ventilation based on Darlington’s study (Darlington, 2004).

Gabriela Soreanu, Michael Dixon and Alan Darlington published (2013) a ‘mini-review’ on botanical biofiltration that discussed various aspects including, but not limited to, limitations, challenges and benefits. The review was written based on various botanical biofiltration studies in addition to the authors’ research experience in phytoremediation for more than a decade. The article suggested a thorough selecting process of plants in biofilters because, up to the date of the article, it was not proven whether long-term exposure of plants to containments is toxic to the plant. Another challenge is the increase of relative humidity as previous research showed around 20% increase in relative humidity when using botanical air filtration systems. The acceptable relative humidity levels in indoors environment is usually below 65%. Some of the benefits, on the other hand, could be in improving the psychological disposition and the occupant wellbeing. Integrating the botanical biofiltration system into the rising zero-emission green buildings could be beneficial for energy conservation and sustainability. The review also listed future research needs for biofiltration systems. Studying the
acceptance and the impact of biofiltration in a real setting, the relation between VOC and energy performance of a building, the control of relative humidity and carbon dioxide and maintenance of such systems needs to be further investigated (Soreanu, Dixon & Darlington, 2013).

### 2.3.2 Dynamic Botanical Air Filtration

In 2010, Jensen Zhang, Zhiqiang Wang and Dacheng Ren from Syracuse University revealed the performance of their dynamic botanical air filtration system (DBAF). DBAF, compared to the living wall of Darlington, was smaller in size but had a higher face velocity of air passing through the root bed (i.e., up to 0.26 m/s (0.85 ft/s)). The system had a pressure drop of 97 Pascal (0.38 in w.c.) across 50% activated carbon and 50% pebbles growth media with a thickness of 0.15m (0.49 ft). The system was 1.08 m$^2$ (11.62 ft$^2$) in area with a maximum air delivery of 1010 m$^3$/h (594 cfm). The DBAF system was tested inside a 55 m$^3$ (1,942 ft$^3$) environmental chamber as a stand-alone system for a short-term study, and it was also integrated into an HVAC system inside a 96.8 m$^2$ (1042 ft$^2$) office for a long-term study. DBAF used eight Golden Pothos (Epipremnum aureum) plants for their low maintenance requirements and high microbial community in the rhizosphere, as the researchers stated. An auto-irrigation system was used to maintain an average moisture level of 0.1 to 0.3 ft$^3$-water/ft$^3$ of bed volume. The VOC source for this test was a wood-based product while the measurement parameters were formaldehyde and TVOC. During the test of DBAF, the relative humidity was maintained at 30% and the temperature at 22°C (71.6°F) (Zhang, Wang & Ren, 2010).

The results of the DBAF system were given as a short-time performance and a long-term performance. By using a proton transfer-mass spectrometer, formaldehyde,
toluene, xylene and other VOCs were found and monitored in a real-time basis. In the short-term, the equivalent clean air delivery rate (CADR) for DBAF system was around 475m$^3$/h (280 cfm) based on formaldehyde removal. Beside the DBAF, there was an outside ventilation rate of 5% so that both DBAF and the outside ventilation could potentially provide up to 25% toluene removal. Based on the given removal rate, this could result in 15% energy savings according to the study. For the long-term study, the DBAF was operating for around 10 months and the concentration of formaldehyde and toluene were 17 ppb and 2 ppb respectively. After 10 days, the system roughly removed 41% of the formaldehyde and 50% of the toluene. Single pass efficiency for formaldehyde removal was found to be 60% according to the long-term performance test of DBAF. On the other hand, the researchers noted that there was an increase in relative humidity with an average of 11% in the chamber and 17% in the office. The temperature decreased by 1°C (1.8°F) in the chamber and increased by 0.5°C (0.9°F) in the office. They also concluded that DBAF could replace 20% of the ventilated outside air and save energy up to 15% per year. The energy simulation was based on the weather of the Syracuse, NY climate and it may not apply elsewhere (Wang & Zhang, 2010; Zhang, Wang & Ren, 2010).

In a more recent study, Zhiqiang Wang, Jingjing Pei and Jensen S. Zhang (2014) performed a series of tests to understand the removal mechanisms in the DBAF. The tests were divided into three groups: (1) static potted plant, (2) dynamic microbial community, and (3) DBAF system. The first group test was conducted to study the effect of the leaf versus a total potted-plant in a 5.1m$^3$ stainless steel chamber at 23°C±0.6C and relative humidity of 50%±3%. The second group was to investigate the microbial community
effect in both single injection and multiple injections of formaldehyde. The second group was tested in a 50 liters stainless steel chamber at 23C±0.6C and relative humidity of 90%±3%. The third group was tested to study the effect of adsorption by dry sorbent and by moisture in wet bed and the effect of relative humidity on DBAF at different levels (i.e., 50% to 92%, ±3%). The third group was tested in the same chamber as the first group at 23C±0.6C. The thickness of growth media for all tests was 0.15m and the source of the formaldehyde source was a para-formaldehyde powder that was heated and then delivered to the chambers (Wang, Pei & Zhang, 2014).

The first test, which had one to two potted Golden Pothos (Epipremnum aureum) in a soil without air passing through the root zone, was conducted without any ventilation. The results showed a CADR of 0.2 m$^3$/h per potted plant, or 5.1 m$^3$/h per m$^2$ bed. To meet with ASHRAE 62.1-2010 standards for the given CADR, around 900 plants per 100 m$^2$ are required. Although using static plants is unpractical, the results confirmed the ability of the plant and its foliage contributes to the air cleaning process (Wang, Pei & Zhang, 2014).

The second test for evaluating the microbial community showed a significantly higher CADR. A. aurescens TC1, which had the best removal capacity of formaldehyde out of other seven bacterial species, was extracted from the root zone of the plant and cultured in a laboratory. The relative humidity for this test was as high as 90%±3% to keep microbes alive. With a face velocity of 0.25m/s, the microbial community showed a CADR up to 1050 m$^3$/h per m$^2$ bed. Additionally, a clean air was passed through a wet bed and a wet bed with microbes for 12-hours to investigate any desorption of formaldehyde. After the concentrations was measured downstream the two beds, the wet
bed (without microbes) showed a peak concentration of 0.30ppm while the wet bed with microbes showed a peak concentration of 0.20ppm. The results confirmed the major role of microorganism in the cleaning process of air from VOCs (Wang, Pei & Zhang, 2014).

The third test results for quantifying the CADR for the DBAF at different relative humidity levels showed the effect of the latter in the air-cleaning process. At around 55%, 75%, 92% relative humidity levels, the associated VWCs in the root bed were 3.4%, 7.8%, and 13.7%, respectively. The tests were conducted with a face velocity of 0.25m/s across the root zone of the DBAF. The CADRs were 142, 175 and 233 m$^3$/h per m$^2$ bed for 55%, 75% and 92% relative humidity levels, respectively. The results showed that higher VWCs and relative humidity levels provided higher CADR. Up to 15% increase in ambient relative humidity was observed. The researchers noted that the increase of relative humidity in the given range is acceptable and it can help in humidifying the air, especially in winter seasons. Two other tests were conducted without the plants at 50% relative humidity and 2.7% VWC (dry bed without plants), and 92% relative humidity and 13.7% VWC (wet bed without plants). The CADRs were 21 and 121 m$^3$/h per m$^2$ bed for the dry bed without plants and wet bed without plants, respectively. Using Henry’s law for abruption by water film and first order kinetics for degradation by microbial community, the researchers calculated the CADR for microbial activity to be around 108 m$^3$/h per m$^2$ bed with a bio-degradation rate of 0.071h$^{-1}$. According to the researchers, a further study is needed to quantify the CADR for the adsorption by water and microbial degradation individually to identify the major contributor to the air-cleaning mechanism (Wang, Pei & Zhang, 2014).
2.3.3 Building-Integrated Active Modular Phytoremediation System

At the Center of Architecture Science and Ecology (CASE) in Rensselaer Polytechnic Institute (RPI), Ahu Aydogan examined a Building-Integrated Active Modular Phytoremediation System (BI-AMPS) in her PhD dissertation. BI-AMPS research had a similar goal as the precedent systems, which is improving IAQ and conserving energy, but this system was developed with more focus on the architectural morphology and how it relates to the air cleaning capacity. One of Aydogan’s objectives was to significantly increase the air cleaning capacity of the BI-AMPS through the root environments with respect to scalability, modularity, adaptability, recyclability and other architectural and ecological measures for the system. Other objectives were to examine the cleaning capacity of various growing medium, and to optimize the system performance (e.g., pressure drop across the growing medium) in order to find how the system can be incorporated into buildings. The research also aimed to maximize the surface area and minimize the materials in order to maximize the cleaning capacity and minimize the structure of BI-AMPS, respectively (Aydogan, 2012).

The scope of Aydogan dissertation was testing and optimizing a laboratory prototype of BI-AMPS, and then scale up the prototype to a mockup building. The prototype, which is the only part reviewed by this literature review, was evaluated by its ability to remove formaldehyde in a single-pass. As formaldehyde was the chosen pollutant for testing the air cleaning capacity, various plants were individually tested and then selected based on their ability to remediate air from formaldehyde. The aerial plant part of the plant, root zone and the entire plant were all tested for their removal capacities in a similar approach to Kim et al. study, which was reviewed in subchapter 2.2.4.
Similarly for the growth media of the plants, Aydogan tested various mixtures of growstone, expanded clay and a layer of activated carbon for air porosity, water holding capacity and adsorption of formaldehyde. A drip irrigation system was chosen for its low maintenance and its efficiency in irrigation in various types of growing medium and for different plant species. LED lights were used to deliver necessary light for plants, and UV lights were also used to kill any bacteria, viruses, and harmful microorganisms. Each modular of the BI-AMPS had a plant with their own irrigation lines, LED light, UV light and growing media (Aydogan, 2012).

The removal of formaldehyde was tested on the following four plants: H. helix, C. morifolium, D. compacta and E. aurenum. In 5-hours period and with an average initial concentration of 2000µg/m³ formaldehyde, each of the root zones, the aerial parts and the entire plants were able to remove between 81% and 96% of the formaldehyde, for the four mentioned plants. The entire plants were able to remove two thirds of the initial concentrations of formaldehyde just in between 23mins and 56mins. The removal capacities varied within the given range for each part of each plant but they all showed significance in their contribution to the air-cleaning process, which agreed with Kim’s study in 2008 (Aydogan, 2012).

The growing mediums were also tested for their uptake of formaldehyde in three conditions: growing medium alone, dry medium in a pot, and a wet medium in a pot. Each growing medium was tested for 10-hours period with an average initial concentration of 2000µg/m³ of gaseous formaldehyde. Activated carbon alone showed a 97.6% reduction, 94.1% reduction when it was in a dry pot, and 88.9% reduction when it was in a wet pot. The expanded clay showed a reduction of 26.4% alone, 47.5% in a dry
pot, and 62.6% in a wet pot. Lastly, the growstone reduced the concentration by 17.4% alone, 39.3% in a dry pot and 62.3% in a wet pot. Although the test was carried in 10-hours period, the activated carbon was able to reduce two-thirds of the initial concentration just in 6 minutes, while expanded clay and growstone (in a wet-pot) reduced two-thirds of the initial concentration in 58mins and 53mins, respectively.

Taking air porosity and water holding capacity into account alongside with the removal capacities of each growing medium, the BI-AMPS used a mixture of 62% growstone, 20% expanded clay and 18% activated carbon as the final growth media mixture (Aydogan, 2012).

Additional tests were conducted for formaldehyde removal capacity for one module of the BI-AMPS. Inside a 1.0m$^3$ airtight chamber, a cassette with a cross-sectional area of 0.11m$^2$ was placed in the middle of the chamber to split it into two halves. The cassette contained the growth media of 62% growstone, 20% expanded clay and 18% layer of activated carbon. Three tests were conducted: dry growing medium, wet growing medium, and a wet-growing medium with a Golden pothos plant. The formaldehyde was introduced to one side of the chamber, and the air was pulled through the cassette to the other side of the chamber in the three tests. Figure 2.2 shows the results of the tests for 9 days period. As the graph shows that the peak concentration of the dry medium was 80% higher than the peak concentration with the plant (Aydogan, 2012).
Further analysis by Aydogan showed a CADR of 470m$^3$ per hour for the BI-AMPS based nine modules calculations. With the mentioned CADR, a potential reeducation of outside air by up to 72% could be achieved when using the BI-AMPS for ventilation according to Aydogan. Up to 60% energy savings in the summer and 50% energy savings in the winter could be achieved by the BI-AMPS if the system was used on Sheikh Khalifa Medical Center in the United Arab Emirates, according to Aydogan’s model (Aydogan, 2012).

2.3.4 Biowall

The last biofilter to be reviewed in this literature is the Biowall at Purdue University that is the same project of this research. The initiative of the Biowall was during Purdue’s involvement in an international competition for net-zero homes that was called the Solar Decathlon-2011. Purdue’s team built a house a net-zero house but the
IAQ was a challenge due to the high airtightness. The team decided to install a wall of plants that was integrated into the central air conditioning unit of the house. The goal of the team was to provide acceptable IAQ levels and reduce energy use by minimizing the circulation of outside air to the inside. As the competition had a fast-paced environment, the Biowall performance was not efficient enough for a long-term application. Therefore, after Purdue’s team won the second place in the competition, the Biowall was returned to the lab for further investigation on its performance, ability to remove VOC from air and capability to conserve energy (Newkirk, 2014).

Daniel Newkirk at Purdue University conducted the most recent research on the Biowall for IAQ and energy conservation. Newkirk’s research was focusing on the ability of Biowall to remove air containments as well as to conserve energy without the need of outside air circulation in energy-efficient residences. The Biowall was designed with 12 ft² surface area and was placed inside an 800 ft³ environmental chamber. Twelve different species of plants were used on the Biowall, and they were treated as a “black box” where the mechanism of VOC removal was not a part of the study. In contrast to previous systems, the plants were perpendicularly placed on a vertical wall of a felt-type material (i.e., without a growing medium). 50% of the air was forced to pass through the filter and the ‘hanging’ roots, while the other 50% was bypassed from the sides to minimize the pressure drop across the filter. The Biowall used a spray irrigation system to provide water and LED lights to maintain plant growth. Both the irrigation and lighting systems were automated by timers and their energy consumption was monitored.

Newkirk performed a ‘pull-down’ test method, where a known amount of Toluene was introduced to the chamber and its decay was monitored over time. The ‘pull-down’ test
was implemented to quantify the natural decay on the chamber without the presence of the Biowall, and then another test was done to measure the decay with the presence of the Biowall. Both relative humidity levels and temperature were monitored during the test. A matched-pair t-test and a thermodynamic model were applied to analyze the significance the Biowall’s removal capacity and the potential energy savings (Newkirk, 2014).

Newkirk’s study showed potential results for the Biowall in improving IAQ and saving energy. According to Newkirk, the Biowall showed the ability to clean the chamber from Toluene (P<0.01) when compared to the natural decay. The test had 150 samples that were taken in one-minute interval. Figure 2.3 shows the difference between the two exponential decays, where the green area is the filtration factor of the Biowall (Newkirk, 2014; Newkirk et al., 2014).

Based on Newkirk’s thermodynamic model, additionally, the Biowall showed a potential energy savings that could be up to 30% if the Biowall was installed in an energy

![Figure 2.3 The Biowall Cleaning Ability (Newkirk et al., 2014)](image-url)
efficient residence. Figure 2.4 shows the contribution of the Biowall to the energy efficiency based on different climates and in comparison to alternative technologies. From the diagram, the Biowall would be more effective in cold climate since the watering of plants assist in humidifying the indoor air, and thus contribute in saving more energy. The assistance of botanical air filter in air humidification was also concluded by Wang and Zhang based on Syracuse, NY climate, which has a cold climate (Newkirk, 2014; Wang & Zhang, 2010).

![Figure 2.4 Potential Energy Savings of the Biowall (Newkirk, 2014)](image)

Similar to both Syracuse and Darlington systems, the Biowall did not show any negative impact on the indoor environment. According to Newkirk observations, the plants maintained a good health throughout the test. Newkirk recommended further improvements on the design of the Biowall such growth media, plant selection and irrigation system (Newkirk, 2014).
To conclude this section, four biofiltration systems were reviewed. All the system confirmed the significance of the plants’ ability to remediate air from VOCs, and their potential to save energy. Further analysis by Wang and Zhang showed the major role of the microbial community in the air cleaning process, especially at elevated relative humidity levels. Aydogan from RPI analyzed the uptake of formaldehyde by the different type of growing mediums and different part of the plants that confirmed the importance of a careful selection for both the growth media, and the plants. The Biowall of Purdue University showed promising results for integrating the Biowall into energy efficient residences. None of the four systems confirmed any negative impacts of the botanical air filters. An increase in relative humidity levels, on the other hand, was observed on the four systems, which was claimed to be useful in winter climate to humidify indoor air.

2.3.5 The New Generation of the Biowall

One of next major steps of the Biowall project is to re-install the biofilter in ReNEWW (Retrofit Net Zero: Energy. Water. Waste.) house in West Lafayette, IN by January 2016. The ReNEWW house is a net-zero energy house that was retrofitted collaboratively by Purdue University and Whirlpool Corporation in 2013 for energy and environmental research purposes. The 2,900-ft² house has three bedrooms, two bathrooms and a basement where temperature, relative humidity, and energy consumption are closely monitored. The house is a living laboratory where graduate students are living and conducting research. A score of 1 HERS (Home Energy Rating System) index with an energy cost of less than $150 annually was achieved by the house (Green Builder, 2015). In order to prepare the Biowall for the ReNEWW house, several
development projects were taken between 2014 and up to date that will be discussed in this section.

2.3.5.1 Growth Media

Reinhard Mietusch, a visiting scholar to Purdue University from Dresden University of Technology in Germany, studied the mixture of growing media for the Biowall. The goal of Mietusch study was to experimentally optimize the growing media to provide a maximum water holding capacity and maximum air porosity with respect to the plants’ health and the pressure drop across the media (i.e., below 0.1 in w.c.). For the study, Growstone was chosen as the air porous component to minimize the air resistance. Since the air outlet of the Biowall will be connected to the return duct of the HVAC system, minimizing the air resistance is vital to reduce the load on the fan HVAC’s fan. Coco coir, in contrast, was chosen for its water holding capacity to maintain acceptable environment for the plants. Activated carbon was also added to the mixture for its ability to adsorb VOCs.

To perform the study, a test apparatus was built and placed inside the same environmental chamber discussed in subsection 2.3.4. The test apparatus had a surface area of 26.5” x 26.5” and a depth of approximately 6.5”. An axial fan was used to pull the air through the mixture of the growing media. Differential pressure measurements were taken across the growing media, in addition to temperature, relative humidity, and air velocity (Mietusch, 2015). The apparatus is shown in figure 2.5 in the following page.

Mietusch conducted several tests on various mixtures of growing media with a thickness of 10 cm (3.9”) at different face velocities and constant volumetric water
content (VWC). The pressure drop across the different combination of growing medium was measured at different face velocities that ranged between 0.025 and 0.150 m/s (4.92 and 29.53 fpm) with an increment of 0.025 m/s (4.92 fpm) for each test.

![Figure 2.5 The Apparatus Used to Test the Growth Media Mixture inside the Environmental Chamber with a Circulated Fan (Yellow in Color) and the Growth Media on Top.](image)

The activated carbon content was fixed at 18% per volume for all tests as recommended by other studies according to Mietusch. The coco-coir content was tested at 0% and up to 60% per volume with 10% increment in each test. The growstone, in each test, was the remaining to complete 100% volume. For example, the first test was 0% coco coir, 82% growstone, and 18% activated carbon, the second test was 10% coco coir, 72% growstone and 18% activated carbon, and so on. For all the previously mentioned tests, the VWC was 20%, which was in the recommended range by Syracuse study.
(Wang & Ren, 2010). After the tests were repeated for different mixtures at different face velocities, linear regression was used to model the relationships between face velocity and pressure drop at 20% VWC for the different set of mixtures (Mietusch, 2015).

Based on Mietusch results, the 0.1 m/s (19.69 fpm) face velocity was chosen since the pressure drop did not exceed 25-Pa (0.1 in w.c.) for all the mixtures. Mietusch suggested a growing media mixture for the Biowall that have 50% coco coir, 32% growstone and 18% activated carbon. The suggested mixture can have a water holding capacity up to 46.3% per volume. In addition, Mietusch placed 10 plants to the apparatus to investigate the pressure drop difference. The pressure drop was doubled with the existence of the plants but it was still under the upper limit of 0.1 in w.c. for the given mixture. Similar to the previous studies, an increase in relative humidity and a decrease in temperature were observed during the tests (Mietusch, 2015).

2.3.5.2 Plants

For the new Biowall, three different plant species will be used. Golden Pothos (Epipremnum aureum), Spider Plant (Chlorophytum comosum), and Philodendron (hederaceum) are the chosen plant species. These plants were specifically selected for their ability to survive in a droughty environment as well as their high removal capacity for VOCs (Wolverton, 1999). The drought environment was a factor in the selection process because forced air will be passing through the plants root zone in the Biowall. The plants will be irrigated through the use of pressurized soaker hoses that will be buried inside the growth media. LED grow lights are used to provide necessary lightings
for the plants. The technical details of both irrigation system and lightings will be provided on the methodology chapter.

2.3.5.3 Challenge Gas

A senior-design team (2015) from the school of Engineering Technology at Purdue University designed and assembled a gas dispersal system (GDS) to introduce Toluene in the environmental chamber. The GDS is a syringe pump with an atomization nozzle that is used to introduce Toluene as a vapor inside the environmental chamber. The goal of the GDS was to introduce Toluene in the chamber accurately and repeatedly at a constant rate. The system is controlled through LabVIEW software from outside the chamber and the Toluene reading is provided by a MultiRAE gas monitor, which is calibrated for toluene. Further technical details will be discussed in the methodology chapter of this thesis.

Toluene was chosen as the challenge gas for this research for few reasons. Safety was the main concern for choosing toluene over other VOCs. The Applied Energy Lab (AEL) at Purdue University, where the environmental chamber for the Biowall is located, is not prepared to handle very hazardous chemicals at very low concentrations such as formaldehyde. According to the Occupational Safety and Health Administration (OSHA) database for chemicals, the formaldehyde permissible exposure limit at a workplace is 0.75 ppm as time weighted average, whereas the limit for toluene is 200 ppm (OSHA, 2015). Even though the challenge gas will be introduced inside a sealed chamber, toluene is safer and easier to handle than formaldehyde. On the other hand, toluene was
recommended as a challenge gas by ASHRAE standards 145.1 that was developed for testing the performance of a gas-phase air-cleaning systems. According to the standards, Toluene, which is used in adhesives and paint, is the most common contaminant in the indoor air environment (ASHRAE, 2015).

### 2.3.5.4 Testing

The goal of this research is to test the CADR for the new Biowall after all the previously mentioned development and changes. In contrast to Newkirk research, the new Biowall has a growth medium where the entire roots are contained. The activated carbon and the wet bed of the growth media will help in adsorbing and absorbing the containments, respectively, as suggested by the reviewed literature. The assumption is that the adsorbed and absorbed VOCs in the growth media will be metabolized as a food and energy by the plants as found by Wolverton (Wolverton, 2010). This research will investigate whether the developments and assumptions actually will assist in increasing the CADR of the new Biowall in comparison to the old one.

Another practice this research will follow is the adherence to testing standards. Even though there are not any particular standards for testing the CADR for botanical air filters, the test will follow the guidelines and principles of currently available standards. ASHRAE 145.1, which was developed to test the performance of gas-phase air-cleaning systems of loose granular media, will be taken into consideration in the testing. ASTM D6670 standard, which was developed for testing VOCs emissions from materials in full-scale chamber, will be also followed, especially in the preparation of the chamber for
testing. Both of the mentioned standards, and other standards, will be specifically referred in the methodology chapter whenever they are applied.

In short, the new design of the Biowall has changed notably than the previous Biowall in Newkirk’s (2014) experiment. The growth medium was studied to provide a high water holding capacity with a very low air resistance. The plants were selected carefully to survive in droughty conditions and provide high air cleaning capacities. Spray irrigation system was replaced by soaker hose irrigation. A reliable introduction of the challenge gas was developed. Finally, this research will quantify the CADR of the new Biowall before it is installed in the ReNEWW house in 2016.

2.4 Chapter Summary

This chapter reviewed three major areas that are potential for this research. The IAQ problems and the regulations associated with them. The origin of biofiltration, as a solution for VOC removal, was then reviewed. Lastly, the modern development of botanical air filtration systems and their integration to HVAC systems were analyzed based on their potential for both IAQ improvements and energy conservations.
CHAPTER 3. RESEARCH METHODOLOGY

The main objective of this research is to understand the ability of remediating toluene from air by a newly designed and improved version of Purdue’s botanical air filter (Biowall). Purdue’s Biowall team specifically designed the Biowall to be installed in the living room of the ReNEWW house, and to be connected into the house’s return duct in early 2016. Prior to installing the Biowall in the house, this research aims to quantify the Biowall’s clean air delivery rate (CADR), and to evaluate its performance in a laboratory environment.

Chapter three explains the methodology of the thesis and its related topics. The new design of the Biowall will be presented. The experiment’s setup, procedure and protocols will be explained. The data collection and their analysis and threats to validity will be described as well.

3.1 The New Biowall

The Biowall was designed as a modular system inside a large plenum. The plenum has a place for a supporting fan at the rear, and four trays to contain the plants at the front. The front of the plenum has rectangular shape (75” x 23.5”), which extends in depth for 18” until the end of the trays, and then it converges to the supporting fan. The converging part of the plenum has an access side-door to the empty space space for maintenance and sensor placement purposes. Figure 3.2 shows a 3D model of the
Biowall’s plenum and its trays, which were made of stainless steel at Purdue’s shop for Sheet Metal and Welding.

Figure 3.1 The new Biowall inside the Environmental Chamber.

The trays were designed to fit inside the plenum with easy assembly and disassembly for maintenance and plants replacement purposes. Each tray has a volume of 18 “ in length, 22” in width and 4” in depth. The trays’ bottoms are perforated with diameters starting from 1.15” at the closer end to circulating fan, and up to 2.00 “ holes at furthest point from the fan with respect to the horizontal plane. The perforated holes were
designed with different diameters, based on the distance from the fan, to ensure uniform plenum and the trays (see Appendix B for the 2D schematic). Underneath each tray, on the other hand, there is an inclined surface leads to a water sink and a 17” by 3.5” adjustable air-path opening. Each opening will be fixed once prior the testing by measuring the airflow rate across each tray to ensure its uniformity (Leuner, 2016).

![Biowall Design Concept](image)

Figure 3.2 Biowall Design Concept (Leuner, 2016).

Each tray will have three to six plants in a fixed mixture of a growth media. The plants that the Biowall is using are: Golden Pothos (*Epipremnum aureum*), Spider Plant (*Chlorophytum comosum*), and Philodendron (*hederaceum*). The plants were propagated
in a green house with the assistance of the Horticultural Department at Purdue University. After the plans were well rooted, they were transferred into a growth media mixture of 50% growstone and 50% coconut coir at the same green house. The plants were then transferred to the Biowall after more than 4 weeks at the green house. The growth media for each tray of the Biowall, on the other hand, has a mixture of 40% coco coir, 40% growstone, and 20% activated carbon pellets per the volume of tray. The growstone will assist in providing the air porosity, the coconut coir will increase the water holding capacity (WHC) of the growth media, and the activated carbon will assist in adsorbing the VOC (Mietusch, 2015; Wolverton, 2010).

Soaker hoses and LED growth lights are used to provide adequate living conditions for the Biowall’s plants. Inside each tray, there will be a soaker hose that is spirally placed from the side of the tray to its center (i.e., inside the growth media) as shown in figure 3.3. The hose has a diameter of 0.625”. A solenoid valve and a timer will control the water supply to the soaker house. The hose is connected to one side of the tray by quick-connect hydraulic couplers to an outside water supply, and it’s plugged on the other end, which is in the center of the tray. Each tray, on the other hand, will have overhead LED lights that will provide a minimum photon-flux of 50 µmol/s.m². The lights are blue LED lights coated with red and green phosphor to provide a white color for the naked eye. A timer will be programmed to turn on the lights for 12 hours per day. The LED lights are used because the environmental chamber does not have an access to natural lights, and they are shown in figure 3.3.
3.2 Experimental Setup

The experiment for testing the decay of toluene for the new Biowall took a place in the environmental chamber. An external hydronics system was used for conditioning the chamber. Instrumentation, data acquisition system, and safety protocols are also discussed under the experimental setup.

3.2.1 Environmental Chamber

The environmental chamber, which is located at the Applied Energy Lab (AEL) in Knoy hall of Technology at Purdue University, will be used to conduct the experiment of this research. The sealed chamber has a volume of approximately 800 ft\(^3\) (22.6 m\(^3\)). The chamber has one access door that will remain close during all tests. Besides the new Biowall, sensors, mixing fan, a table, a tripod, and overhead lights will be also placed inside the environmental chamber. The wires from inside to outside the chamber, or vice versa, pass through a wiring box (inside the chamber) that is packed with a glass wool. An additional baffle and brush seal are placed outside the chamber to avoid any leakage.

Figure 3.3 Growth lights (A), Water Connection Point (B), and Placement of Soaker Hose (right) (Leuner, 2016).
from the wiring path. An aluminum tape and ‘trash bags’ were used to cover any vents that are located inside the chamber,

The following subsections will discuss various topics related to the environmental chamber and testing. The hydronic system of the chamber, the chamber conditions, chamber’s leak test and the chamber’s cleaning technique will be all explained.

3.2.1.1 Hydronic System of the Chamber

The environmental chamber has an external hydronic system for cooling and heating with building automation system (i.e., WebCTRL). The hydronic system uses a mix of 50% glycol and 50% water that passes through radiators inside the chamber. The system will provide the desired air temperature. WebCTRL will automatically control the operation of the hydronic system operations based on defined set-points The WebCTRL system has its own temperature and relative humidity sensors inside the environmental chamber that will be used as feedback to maintain the test specified conditions inside the chamber.

3.2.1.2 Chamber Test Conditions and Variables

The test conditions inside the chamber will follow the parameters of ASHRAE standards 145.1. The air temperature, according to the standards, should be kept at 73°F±4°F (23°C±2°C), while maintaining a relative humidity of 50%±5% (ASHRAE, 2015). Even though the hydronic system can control the temperature adequately. The relative humidity levels cannot be controlled due to the humidification process from the Biowall inside the sealed chamber, which could increase the relative humidity up to 80%.
Nevertheless, both temperature and relative humidity levels are monitored and recorded during the all tests.

There are three types of variables in the experiment. First, the controlled variables, which are held constant during testing, are temperature, toluene concentrations, growth lights. Second, the independent variable in the experiment is the airflow rate. Lastly, the dependent variable of the experiment is the toluene decay, and relative humidity, and moisture content. The moisture content is a dependent variable since the water in the growth media evaporates due to the airflow through the media. Nevertheless, every 48 hours the plants are watered by approximately 4-Liters of water per tray, which is 15% of the tray’s volume. Each of the variables will be discussed in further details in the following sections.

3.2.1.3 Leak Test of the Environmental Chamber

Prior to testing, the chamber will be investigated for any air leakages to ensure its airtightness. Around 36g of CO\textsubscript{2} cartridges will be used as a tracer gas to provide a concentration of approximately 2,000-ppm inside the environmental chamber with a mixing fan. The decay of the CO\textsubscript{2} will be recorded over time by using Fluke AirMeter 971 for three different tests. According to ASTM E741-11 standards for “Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution,” the following equation (1) is adopted:

\[
ACH = - \frac{\ln C_1 - \ln C_2}{\Delta t}
\]

equation (1)

ACH is air exchanges per hour (h\textsuperscript{-1}), \(C_1\) is Tracer Gas Concentration at start of test, \(C_2\) is the Tracer Gas Concentration at end of test, and \(\Delta t\) is the change of time in hours (ASTM,
2011). The equation will be applied to all the data points to establish the best curve fit in which the leak rate is found (i.e., slope of the curve fit).

The significance of the leak rate will be determined according to ANSI/AHAM standard AC-1, “Test Method for Rating Performance of Portable Room Air Cleaners.” According to the AC-1 standards, the leak rate of the testing chamber is neglected as long as it is below 0.03 ACH. If the leakage rate is above 0.03 ACH, then the air exchanges should be included in the CADR calculations, which will be discussed in more details in the data analysis section of this chapter (ANSI/AHAM, 2002).

3.2.1.4 Chamber Cleaning

In addition to the previous set up and testing, the chamber will be cleaned before each test for accurate toluene decay rates measurements. The cleaning technique of the chamber is adopted from ASTM D6670-13 standards, “Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products.” According to ASTM (2013):

“Clean the chamber by scrubbing its interior surfaces with a sponge mop and a solution of laboratory ionic detergent that contains phosphate as the water softener and rinsing several times with clean water, followed by a final rinse with filtered deionized water. (p. 11)”

Sparkleen from Fisher Scientific in Pittsburgh, PA is the selected ionic detergent with phosphate, and Type II Deionized Water from ChemWorld in Kennesaw, GA is used for the final rinse according to the quote above. Both products are shown in figure 3.4. The cleaning of the chamber’s surfaces is performed to avoid the possibilities of toluene being desorbed back to the chamber from its own surfaces. Similarly, the Biowall’s plenum and
other objects’ with large surfaces, which are located inside the chamber, will be also cleaned according to the ASTM D6670-13 standards.

Figure 3.4 Ionic Detergent with Phosphate (Left) and Deionized Water (Right)

The previous four points discussed the preparation of the chamber for testing. The hydronic system will be controlled by a building automation system to provide ambient conditions that adheres to ASHRAE standards 145.1. The chamber will be tested for leakage according to ASTM standards E741-11. Finally, all the surfaces inside the chamber will be cleaned before each test according to ASTM standard D6670-13.
3.2.2 Data Acquisition System

The main data for this research will be acquired by using two different portable systems. The two systems are totally independent from the building automation system of the chamber that was discussed earlier. The first portable meter is Fluke AirMeter 975 that will measure CO$_2$ concentrations (2.75%±75 ppm), ambient relative humidity levels (±1.00%), and ambient temperature (±1.00°F). The second system is a photo-ionization detector (PID) called MultiRAE gas detector (model: PGM-6628) by RAE systems (see Appendix A for specifications). The MultiRAE detector is calibrated to measure concentration from 0.1 ppm and up to 5,000 ppm. The toluene concentration will be measured as a bulk concentration for the entire chamber. Both sensors have their own data loggers that will record readings on a specified time intervals. After each test, data will be uploaded to a computer, saved and given a unique name and description beside the date and time.

Additional sensors will be installed on the Biowall apparatus to obtain temperatures, relative humidity, and pressure drop readings. The three measurements will be taken across the Biowall. The sensors will be connected to a WebCTRL that will collect data during all the tests periods. These sensors are used to perform the energy analysis, as it will be explained in the analysis section. Table 3.1 shows all the sensors’ specifications. Sensor (1) will measure the zone temperature and relative humidity inside the chamber. Sensor (2) will measure the temperature and relative humidity inside the Biowall’s duct. Sensor (3) will measure the pressure drop across the Biowall, which is the difference between ambient pressure of the chamber and the pressure inside the duct (before the fan). Appendix B has a schematic that shows the placement of sensors.
Table 3.1 Data Acquisition Sensors for WebCTRL System

<table>
<thead>
<tr>
<th>#</th>
<th>Target Measurement</th>
<th>Sensor</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature</td>
<td>BAPI BA/1K[375]-H200-R Wall mount sensor</td>
<td>0 - 100 °F</td>
<td>±0.065 °F</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
<td></td>
<td>0 - 100 %</td>
<td>±2 %</td>
</tr>
<tr>
<td>2</td>
<td>Temperature</td>
<td>BA/T1K [20TO120F]- H200-D-BB In-duct sensor</td>
<td>20 - 120 °F</td>
<td>±0.065 °F</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
<td></td>
<td>0 - 100 %</td>
<td>±2 %</td>
</tr>
<tr>
<td>3</td>
<td>Pressure Drop</td>
<td>ZPT-LR-BB-NT-D differential pressure sensor</td>
<td>0 - 0.25 in w.c.</td>
<td>±0.5%</td>
</tr>
</tbody>
</table>

3.2.3 Gas Dispersal System

The challenge gas (toluene) will be introduced to the chamber through a gas dispersal system (GDS) that uses a syringe-pump and atomizer. The GDS uses a syringe-pump made by New Era (Model: NE-1010) with a 25mL syringe. The pump, which is controlled by a LabVIEW program, is capable of introducing specified amounts of toluene with flow rates between 0.35-µL/h and up to 4591-mL/h. An atomizing nozzle is attached to the syringe’s luer through an adapter to disperse the liquid toluene as a gas (more details are available in Appendix A). Undergraduate students designed the syringe pump as a senior design project in 2015 (Newcomer, Williamson & White, 2015). Figure 3.5 shows the syringe pump, a syringe filled with toluene and the atomizing nozzle.

The syringe pump was tested for repeatability by injecting different volumes of toluene with a flow rate of 15-mL/min. The flow rate was chosen based on the syringe specification (25-mL syringe manufactured by SGE analytics, Australia). A 5-mL injection of toluene provided a peak concentration of approximately 45-ppm ± 5-ppm inside the sealed environmental chamber. 1-mL injection of toluene had approximate concentrations of 11-ppm ± 1-ppm. Lastly, a 0.2-mL injection of toluene had peak concentration was around 1.6-ppm ± 0.2-ppm.
To confirm the results, the toluene physical property and the size of the chamber were used to estimate the ideal concentration. At 68 °F (20 °C), toluene has a density of 0.87 g/mL and a conversion factor from ppm to mg/m$^3$ of 3.77 mg/m$^3$ for each 1-ppm according to Toluene information on the Air Toxic Website of the U.S. Environmental Protection Agency (EPA, 2012). The chamber has an approximate volume of 22.6-m$^3$. For example, the mass of 5-mL is approximately 4,350 mg based on the toluene density. Dividing the mass of 5-mL injection by the chamber volume, the concentration should be about 192 mg/m$^3$ (i.e., 50-ppm). During the tests of 5-mL injections, the concentration of toluene varied inside the chamber varied between 40-ppm to 50-ppm, and thus the accuracy of the 5-mL injection test was 45-ppm ± 5-ppm. The same approach was used to confirm the other injections amounts, and to ensure the syringe pump system was functional in dispersing toluene to air.
3.2.4 Safety Protocols

One of the main components of this research is the adherence to safety protocols and requirements by both Purdue University and OSHA. As the test will be carried in the AEL, which have regular presence of graduate and undergraduate researchers, proper signs will be posted at the chamber’s door. During the preparation of each test, personal protective equipment such as goggles, laboratory coats and gloves are used. Emergency contacts and first aid procedure and location are also posted at the AEL’s door. For safety concerns, toluene levels inside the chamber will be always kept under the OSHA limits for permissible exposure in working space, which is 200 ppm as time weighted average (OSHA, 2015).

3.3 Experiment Procedure

Section 3.3 starts by a brief explanation of the ‘pull-down’ test, its procedure and the calculation of decay constants as well as the CADR. Each test will then be explained in more details for its own objectives and parameters.

The National Center for Energy Management and Building Technologies final report for reduced energy use through reducing indoor contamination in residential buildings included details for the ‘pull-down’ test method and CADR calculations (Chen et al., 2006). The ‘Pull-down’ method is defined as a method in which a known amount of toluene is introduced to the environmental chamber and its decay is monitored over time. To calculate the CADR, the exponential decay rate constant in the testing chamber without the filter needs to be found, in addition to the exponential decay rate constant for in the testing chamber with the Biowall and the volume of the chamber (Chen et. al,
The equations of the CADR will be shown in the data analysis section of this chapter.

3.3.1 Testing

For this thesis project, five different tests will be performed to find the toluene decay inside the chamber. All the tests followed a ‘pull-down’ test method, when possible, to measure the decay of toluene inside the chamber in different scenarios. The first tests were to quantify the natural decay of toluene inside the environmental chamber without the presence of the plants, but the plenum and its trays were kept inside the chamber. The second and third tests were designed to measure the decay of toluene with the presence of the plants (entire Biowall) for two different airflow rates. The fourth and fifth tests were for testing the toluene decay with growth media (without the plants) in both dry and wet conditions. The growth media was new and was not in contact with plants before the test.

Each of the four series of tests was examined for different injections of toluene. The natural decay was tested for 5-mL and 1-mL toluene injections. The Biowall was tested for 5-mL, 1-mL, and 0.2-mL injections of toluene in addition to multi-injections of 5-mL of toluene. The dry and wet growth media were tested for 5-mL injections and a multi-injection of 5-mL of toluene. Each of the tests was repeated for three times. The following paragraphs explain the general testing procedure and any special procedure for the mentioned tests.

There was a general testing procedure that was followed for all the tests. First, the chamber was cleaned and prepared as explained in 3.2.1 before performing any of the tests. Second, the hydronic system was run before testing until the temperature was
around 73°F±4°F (22°C±2°C). The MultiRAE gas detector (PID) was placed as close as possible to the center of the chamber, which can be seen in the earlier figure 3.1 at the center of the Biowall, and also as seen in the 2D schematic in Appendix B. A mixing fan was placed inside the chamber, and it was running during the entire period of any test. Once the sensors were setup and the chamber’s door was closed, the GDS system introduced a specified amount of toluene as required by each test. To allow the dispersed toluene to mix in the entire chamber, the Biowall fan in the plenum was turned on after 3 minutes from the time of the injection. The data was recorded and monitored for the entire period of each test. The sampling rates were one sample per second for the PID, and one sample per minute for the temperatures, relative humidity levels and pressure drop.

Each type of toluene injection had different time periods and a slightly different procedure. For the single injection of toluene (i.e., 5-mL, 1-mL, and 0.2-mL), the time of the test was 12-hours. After each test, the chamber doors were left open for at least 12-hours to fresh air to enter the chamber prior the following test. For the multi-injection tests (i.e., 4 x 5-mL injection), the tests were running for 48-hours. The first injection was introduced at the beginning of the test, and each subsequent injection was introduced after 12-hours from the previous injection. During any injection of the multi-injection test, the fan was also turned off for 3-minutes, and the door was closed for the entire testing period.

In short, there was five different testing series. The natural decay was examined for two injection amounts of toluene (5-mL and 1-mL). The Biowall with high fan speed (105 cfm) and low fan speed (65 cfm) were tested for all the type of injections. The dry
and wet growth media were tested with a high fan speed (105 cfm) for a 5-mL injection and a multi-injection of toluene. The following table 3.2 presents a brief summary of all the five tests discussed above.

**Table 3.2 Summary of Tests**

<table>
<thead>
<tr>
<th>Target Test</th>
<th>Fan Speed (cfm) [m³/hour]</th>
<th>Injection amount [peak concentration in ppm]</th>
<th>Inside the Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Decay</td>
<td>N/A</td>
<td>Yes Yes No No</td>
<td>Plenum and trays only</td>
</tr>
<tr>
<td>Biowall</td>
<td>105 [180]</td>
<td>Yes Yes Yes Yes</td>
<td>Entire Biowall</td>
</tr>
<tr>
<td></td>
<td>65 [110]</td>
<td>Yes Yes Yes Yes</td>
<td>Entire Biowall</td>
</tr>
<tr>
<td>Growth Media</td>
<td>Dry 105 [180]</td>
<td>Yes No No Yes</td>
<td>Entire Biowall without plants</td>
</tr>
<tr>
<td></td>
<td>Wet 105 [180]</td>
<td>Yes No No Yes</td>
<td></td>
</tr>
</tbody>
</table>

**3.4 Threat to Validity**

The validity of this experiment could be affected by three factors: possible leakage, adsorption effect, and emission of other VOCs. Possible leakage in the environmental chamber is the first factor. The leakage might be a factor in toluene decay inside the environmental chamber. To minimize the effect, the environmental chamber is tested for the leakage rate prior to testing as explained earlier. Adsorption of toluene to surfaces inside the environmental chamber is another factor. Although most of the surfaces are cleaned prior to testing, the adsorption of toluene to activated carbon, especially, was not controlled nor was it quantified. Since activated carbon pellets were
designed to be an efficient absorbent, toluene might be absorbed until some of the pellets were saturated, which might be an impact on the toluene decay rates. On the other hand, the premade assumption, based on the literature, suggested that the plants would consume the adsorbed toluene on the activated carbon pellets as food and energy source. Absorption effect in water, in contrast, was neglected since toluene is insoluble in water. Finally, the emission of other VOCs inside the chamber from other sources might be a threat as well. Therefore, the air inside the chamber was sampled three times to investigate the presence of any other VOCs, and the results from the samples presented in the next chapter.

3.5 Data Analysis

The data in this experiment were analyzed to quantify the CADR of the Biowall and its performance. Each of the mentioned analyses will be described in this section.

The first analysis of the data will quantify the CADR of the Biowall. In order to find the CADR of the Biowall, the exponential decays of the test A, test B, and test C will be calculated. To calculate the CADR, the following equations, from Chen et al. (2006) report, will be used:

\[ V \frac{dC_{at}}{dt} = -(k_n \cdot V + CADR) \cdot C = -k_f V \cdot C, C = C_0 \text{ at } t = 0 \quad \text{equation (2)} \]

Therefore,

\[ \text{CADR} = V(k_f - k_n) \quad \text{equation (3)} \]

Where CADR is the clean air delivery rate in (m³/hour), V is the volume of the chamber (m³); \( k_f \) is the exponential decay rate of toluene with the Biowall (h⁻¹); and \( k_n \) is the exponential natural decay rate of toluene (h⁻¹) (i.e., without the Biowall); \( C \) is the concentration at time \( t \) (ppm), and \( C_0 \) is concentration at \( t=0 \) seconds (ppm). The decay
constants in equations (2) and (3) are found by using the least square method optimization, the CADRs for the Biowall with both fan speeds and the growth media with both conditions are found and presented in the Results chapter.

3.6 Chapter Summary

Chapter three discussed the methodology of the research topic. The experimental design and the test procedure were identified. Threat to validity and the data analysis were also explained in this chapter.
CHAPTER 4. RESULTS

Chapter four focuses on the results of the experimental testing and analysis. The testing conditions section discusses the background contaminants, leakage testing, and the condition of the air. The toluene removal results for the Biowall in different setting as well as the removal of toluene by the growth media are also shown and described. The results and analysis of the clean air delivery rates (CADR) are then explained.

4.1 Testing Conditions

Section 4.1 discusses three main topics. The first subsection shows the background contaminants of the chamber after cleaning the surfaces as explained in 3.2.1.4 of the methodology chapter of this thesis. The second subsection contains information about the air leakage of the chamber, and the natural decay of toluene to the chamber surfaces. The last subsection has information about the temperature and relative humidity for the ambient air of the chamber and for the air after the filter in addition to information about the pressure drop across the filter.

4.1.1 Background VOCs

The air inside the chamber was sampled to investigate the presence of any volatile organic compounds (VOCs) that were emitting from other sources. Each sample was collected for 24-hours in a 1-liter sampling canister from Galson Laboratories in East Syracuse, NY. Galson also conducted the analysis on the collected samples according to
OSHA PV2120/EPA TO15 method, which uses a GC-MS technique (i.e., gas chromatography-mass spectrometry technique) to determine the concentrations of different VOCs. Each sample, its purpose, and its results are explained.

Two air samples were taken to examine the effectiveness of the cleaning method of this experiment. The first sample was taken after the chamber was cleaned according to ASTM-D6670, which was explained in the methodology chapter. The second sample was taken after wiping the chamber’s surfaces with deionized water only, which was after a natural decay test with a 5-mL injection of toluene.

Figure 4.1 shows the detected VOCs for the first sample of the testing. The vertical axis indicates the concentration as parts per billion by volume (ppbv), while the horizontal axis has the names of the detected compounds. There were 13 different compounds that were found by Galson Labs analysis in their library search test. Freon-11, which had a concentration of 380 ppbv, is likely present because it was used as a blowing agent for the insulation in the walls of the chamber. Toluene, on the other hand, had a concentration of 25-ppbv, and it was expected to be present in the chamber since multiple tests were conducted in the past using toluene as a challenge gas. Acetone also appeared with a concentration of 28-ppbv.

The rest of the compounds in Figure 4.1 were below 25-ppbv, and they did not appear in the future sampling.

The second sample detected only three compounds. Toluene was present in a higher concentration (i.e., 710-ppbv). The higher concentration might be due to desorption of toluene from the chamber’s surfaces after the natural decay test was conducted. Freon-11 was still present with a concentration of 410-ppbv, which was 30-
ppbv higher than the first sample’s result. Acetone, on the other hand, had a concentration of 16-ppbv with a 12-ppbv below the first sample.

The overall results of this test demonstrate that the background VOC levels were well below the level measured during a decay tests. This indicates that the test results were not effected by ambient VOC levels.

Figure 4.1 The Estimated Concentration Levels of Various VOCs inside the Environmental Chamber from the First Air Sample.
4.1.2 Leakage Rate

The leakage rate of the chamber in air changes per hour was tested to determine its significance to the testing. The leakage test, as described in subdivision 3.2.1.3 in the methodology chapter, was repeated three times for each test. Applying a first order exponential regression to the decay curve of CO₂ concentration against the time, the leakage rate was computed. The average leakage rate of three tests was approximately 0.016 air exchanges per hour (ACH). Both the average and the maximum leakage rates were below the specified limit by AHAM/ANSI standard AC-1 (i.e., 0.03 ACH). Therefore, the leakage rate of the chamber was within the acceptable limits to be negligible in the future calculations.

4.1.3 Natural Decay

A natural decay test for VOC’s was also repeated three times to understand how toluene decayed without the presence of the Biowall inside the chamber. Similar to the leakage rate, a first order exponential regression was applied to the change in concentration with respect to time. The natural decay rate inside the chamber was determined to be -0.038 h⁻¹ as an average of three tests in which the minimum rate was around -0.025 h⁻¹, and the maximum rate was of -0.045 h⁻¹. The average natural decay rate is used in the future calculations and determination of the clean air delivery rate (CADR).

4.1.4 Air Conditions

In this subsection, three different topics are discussed. The zone temperature of the chamber, and the temperature at the Biowall’s duct are covered in the first point. The relative humidity in the zone and the duct are then shown. The last point focuses on the
pressure drop across the filter (i.e., the Biowall) and the growth media (without the plants) in different settings.

4.1.4.1 Temperature

The chamber’s zone temperature was one of the monitored and controlled variables inside the chamber. The hydronic system was set up to provide an air temperature of 73°F±4°F inside the chamber. Throughout all the tests, the temperature was adequately within the range, and it did not exceed 77°F, nor did the temperature go below 69°F. During the tests, where the Biowall’s fan was running on a high speed (i.e., 105 cfm), the average zone temperature was approximately 71°F. During the Biowall’s tests with the low fan speed (i.e., 65 cfm), the average temperature was approximately 74°F.

The temperature between the filter bed and the Biowall’s fan (i.e., in the Biowall’s duct) was also monitored during all the tests. Figure 4.2 shows an example of both (a) the chamber’s zone temperature profile at the Biowall, and (b) the Biowall’s duct temperature. The vertical axis has the temperature in degrees Fahrenheit, and the horizontal axis has the time in hours, where 0-hours is a reference to the time when the Biowall’s fan was turned on.
As figure 4.2 shows, in the first two hours, or three hours, of each test, the temperature inside the Biowall’s duct was notably lower than the chamber’s zone temperature. A lower air temperature after the filter was expected due to evaporative cooling, and it was also observed in previous Biowall testing in which the chamber’s conditions were controlled by a forced air system instead of a hydroponic system with sealed vents (Leuner, 2016). After approximately three hours, on the other hand, the difference in temperature drops to 1°F, or less because less evaporative cooling occurred. Due to the airtightness in the chamber and the introduction of new fresh air, the change in temperature was not consistent in comparison to the testing with the forced air system.
4.1.4.2 Relative Humidity

The relative humidity inside the chamber was also monitored in this experiment. In general, the relative humidity inside the chamber significantly increased from below 40% to above 60%, and as high as 80% in some cases due to the evaporative cooling effect. The increase in relative humidity was also expected since the air passes through a wet filter as was shown in previous Biowall tests. For instance, Figure 4.3 shows the relative humidity from test that was used in the temperature example. The top graph shows a test in which the fan was operating on a high speed (105 cfm), while the bottom graph shows a test when the fan was operating on a low speed (65 cfm). In all tests the relative humidity increase up until the air was saturated with moisture.

Figure 4.3 Relative humidity profile for (a) high fan speed, and (b) for low fan speed
As seen in Figure 4.3, each graph has two curves. The first curve in blue is for the zone relative humidity inside the environmental chamber. From the time of the fan’s operation (i.e., 0-hours) to the first hour, or to the second hour, the relative humidity was increasing in an exponential fashion, and then became almost constant, or oscillating within a specific range. The relative humidity in the Biowall’s duct, on the other hand, had a slight increase during the first hour of both tests, and then it was almost constant for the rest of the tests. In contrary to the expectation, the relative humidity in the Biowall’s duct was low despite the closeness to the wet filter. The low relative humidity downstream the Biowall could be due to the turbulence at the Biowall’s duct as observed in previous research (Leuner, 2016).

4.1.4.3 Pressure Drop Across the Biowall

The pressure drop data was collected for the Biowall with a high fan speed, Biowall with low fan speed, dry growth media (without plants) with a high fan speed, and wet growth media (without plants) with a high fan speed. Depending on the moisture content, which was not monitored, the Biowall with a high fan speed had a pressure drop between 0.130 to 0.150 inches of water column (in w.c.). The Biowall with a low fan speed had a pressure drop between 0.07 and 0.09 in w.c., and the values were also based on the moisture content. The dry growth media, on the other hand, had a very consistent pressure drop around approximately 0.105 in w.c.. The addition of water to the growth media without the plants caused the pressure drop to increase to somewhere between 0.120 to 0.140 in w.c., which was also dependent on the amount of water.
Figure 4.4 has the pressure drop readings over the testing period of time for all the four mentioned scenarios. Similar to the previous graphs, the 0-hours indicates the time at which the fan started running. The vertical axis is the pressure drop was measured in inches of water column, and the horizontal axis has the time in hours. For the Biowall with high and low fan speeds, the data are from the same tests that were used as an example for the temperature and relative humidity.

Figure 4.4 Pressure Drop across the Biowall for the High Fan Speed (105 cfm), and the Low Fan Speed (65 cfm) as well as the Growth Media (GM) without Plants in Dry, and Wet Setting with a High Fan Speed (105 cfm).

Figure 4.4 shows, for all the four different tests, that the pressure was almost consistent throughout the testing period. The expectations were that the pressure drop
would decrease overtime since the water was either consumed by the plants, or evaporated into the air. The curve in purple, for the wet growth media, shows the expected trend in which the pressure drop after 10-hours was slightly lower than the beginning of the test. For the two Biowall curves in figure 4.4, the pressure drop was oscillating constantly within the same range. The dry growth media, on the other hand, had a constant pressure without any oscillations.

To summarize the air conditions, several observations can be stated. The temperature and relative humidity downstream the Biowall may not represent a realistic case due to the high airtightness of the chamber. The increase in relative humidity could be overcome when using a forced air system. The addition of water and plants, when operating on a high fan speed, could add up to 0.05 in w.c. of pressure drop. The low fan speed operation of the Biowall is almost half the pressure drop of the high fan speed.

4.2 Toluene Removal by the Biowall

For subsection 4.2, the results for the toluene removal by the Biowall are presented based on the amount of toluene injection. The first results are for the 5-mL injection of toluene, which provided a peak concentration of approximately 45-ppm ± 5-ppm inside the environmental chamber. The second results are for the 1-mL injection test in which the peak concentration was about 11-ppm ± 1-ppm. The third results are for a 0.2-mL injection, where the peak concentration was around 1.6-ppm ± 0.2-ppm. The fourth results of this subsection are for the multi-injection test of 5-mL of toluene every 12 hours for 48 hours (i.e., total of four injections). Each setting was tested for the Biowall with its high fan speed and its low fan speed.
4.2.1 5-mL Injection Results

The first series of tests for the Biowall were conducted with a 5-mL injection (4.35 grams) of toluene inside the environmental chamber. The experiments were run for the Biowall with a high speed, and the Biowall with a low speed. Although the water content in the growth media was not monitored for these tests, an alternative approach was followed to observe any difference caused by the water content to the decay rates of toluene. In the first tests, for each fan speed, the plants were watered prior to the injection. The second set of tests, for each fan speed as well, were performed 24-hours after the first set of tests without any additional watering to the plants. Therefore, the second set of tests should have less water content per tray than the first set of tests.

Figure 4.5 contains five different decay curves for the 5-mL injection test series. The first curve is the natural decay rate without the presence of the Biowall in the chamber. The second (BWH-a) and third (BWH-b) curves are for the Biowall with a high fan speed, where BWH-a was the first test, in which plants were watered, and the BWH-b was the second test after 24-hours without the addition of water. The fourth (BWL-a) and fifth (BWL-b) curves were for the Biowall with a low fan speed. Similarly, BWL-a was the first test, where the plants were watered, and BWL-b was the second test after 24-hours without adding any water to the growth media. The vertical axis of the graph has a normalized toluene concentration, while the horizontal axis has the time of the test in hours. The beginning of the time axis (i.e., 0-hours) indicates the time at which the fan started operated.
There are three main observations that can be visually noted from Figure 4.5. First, the Biowall with both fan speeds was able to remove up to 50% of the toluene from the chamber in approximately 45-minutes, except for BWH-a that took around 1.5 hours. The natural decay took almost 9.5 hours to remove 30% of the toluene. Secondly, the Biowall with a high speed was less effective than the Biowall with a low fan speed. Also, the Biowall with a high fan speed showed an oscillation throughout the curve, which might be a toluene desorption back to the air due to the high fan speed. The third observation, for both high and low fan speeds of the Biowall, the second set of tests, which had lower water content, were faster in removing toluene than the first set of tests.
with a higher water content in the growth media of the Biowall. Further analyses for the observations are included later in this section of the results.

4.2.2 1-mL Injection Results

The second series of tests had a 1-mL injection of toluene with an approach similar to the 5-mL injection tests. The Toluene decay was tested for the Biowall with the high fan speed (105 cfm) as well as with the low fan speed (65 cfm). For both fan speeds of the Biowall, in the first set of tests, the plants were watered prior to the tests, while in the second set of tests, which were 24-hours after the first set, the plants had no additional watering. Thus, the first set of tests for each fan speed should have higher water content than the second set of tests.

Figure 4.6 contains the decay rates of toluene for the 1-mL injection tests. The first curve is for the natural decay rate without the presence of the Biowall. The second (BWH-a) and third (BWH-b) curves are for the Biowall with a high fan speed (105 cfm). The fourth (BWL-a) and fifth (BWL-b) curves are for the Biowall with a low fan speed (65 cfm). The curves denoted with ‘a’ refers the first set of tests in which the plants were watered. The curves with a ‘b’ denotation, on the other hand, refers to the second set of tests that were conducted 24-hours after the first set of tests without the addition of water. The vertical axis of the graph has the toluene concentration in parts per millions (ppm), while the horizontal axis has the time of the test in hours. The start (i.e., 0-hours) of all the decay curves indicates the time at which the fan started running.
Figure 4.6 Toluene Decay for a 1-mL Injection for the Biowall with a High Fan Speed (105 cfm) and the Biowall with a Low Fan Speed (65 cfm)

Figure 4.6 also showed very similar observations to the 5-mL injection tests, but with some differences. For all the decays with the Biowall, 50% of the initial concentration were removed within the first 45-minutes. With a lower concentration than the previous series of test, the prominent oscillation for the Biowall with a high speed did not appear in this test. On the other hand, the figure shows a difference between the decay curves of each fan speed in favor to the curves with lower water content. In addition, the Biowall with a low fan speed also had a faster decay rate and final concentration than the Biowall with a high fan speed, which was also the case in the 5-mL injection tests. Additional analyses are discussed later in this section for all the observations combined.
4.2.3 0.2-mL Injection Results

The third series of test were conducted for a low concentration levels (i.e., 1.6 ppm). One test was done for the Biowall with a high speed (105 cfm), and the other test for the Biowall with a low speed. Figure 4.7 shows the two decay curves of toluene for with the Biowall. BWH and BWL are the decay curves for the Biowall with a high fan speed, and the low fan speed, respectively. Additionally, the natural decay without the Biowall are also shown in the figure. Similar to the previous Figure 4.6, the vertical axis shows the concentration in parts per millions (ppm), while the horizontal axis has the time in hours. The start of the curve at 0-hours refers to the time at which the fan was turned on.

Figure 4.7 Toluene Decay for a 0.2-mL Injection for the Biowall with a High Fan Speed (105 cfm) and the Biowall with a Low Fan Speed (65 cfm)
As shown in Figure 4.7, the Biowall also showed a notable removal of toluene with the lowest injection amount of all the series of tests. For both fan speeds of the Biowall, the time, at which 50% of the toluene concentration was removed, was within the first 45-minutes of the testing period. Similar to the previous tests, the Biowall with low fan speed removed the toluene from the chamber faster than the Biowall with a high fan speed. The reason behind the straight lines in the curves was due to the concentration level being read at the minimum possible reading of the PID (i.e., 0.1-ppm).

4.2.4 Multi-injection Results

The last series of tests for the Biowall was a multi-injection of toluene to the chamber. The purpose of this test was to investigate whether the Biowall was able to remove Toluene in multiple of high injections over a short period of time. 5-mL of toluene was injected into the chamber four times in every 12-hours for 48-hours. The chamber door remained closed throughout the test, and the Biowall’s fan was turned off for three minutes during each injection to allow toluene to mix well with the air inside the chamber. The plants were watered once prior to the test, and growth lights were turned off for the first and third injections, while they were turned on for the second and fourth injections.

The multi-injection test was performed for both the Biowall with a high fan speed (BWH) and a low fan speed (BWL) as shown in Figure 4.8. The figure shows the concentration in parts per millions on the vertical axis, while the time in hours is shown in the horizontal axis. The beginning of the time (i.e., 0-hours) is the time at which the fan was turned on after the first injection. Figure 4.8 has two curves. The blue curve (BWH) is a high fan speed and the brown curve (BWL) is the low fan speed.
As shown in Figure 4.8, there are clear differences between the two curves as well as every injection in each of the two curves. The Biowall with a low fan speed showed again to be more effective in removing the toluene from the chamber than the Biowall with a high fan speed. For the Biowall with a high fan speed (BWH) curve, an oscillation appeared to be present in each curve, while a less prominent oscillation appeared in the third and fourth injections for the Biowall with a low fan speed. For both fan speeds, the final concentration for each injection (i.e., after 12-hours) was higher than the precedent injection. The oscillations and the differences in the final concentration are believed to be due microscopic processes such as the diffusion and the biodegradation processes, which
are time-dependent processes. For instance, Wang et al. (2014) used the difference between multi-injection curves of formaldehyde decay in a microbial community to quantify the biodegradation of formaldehyde in the later. Nevertheless, the microscopic processes are outside the scope of this thesis.

4.2.5 Biowall Results Discussion

In all the previous results, the Biowall with a low speed was obviously more effective than the Biowall with a high speed in all the different tests. The main reason behind the difference in the effectiveness of removing Toluene at each speed is believed to be the empty bed residence time (EBRT). EBRT, which is calculated by dividing the airflow rate by the volume of the bed, is simply the time that the air spends inside each tray of the Biowall. In the Biowall case, the EBRT for each try was found to be 0.52-second for the Biowall with a high fan speed, and 0.84-second for the Biowall with a low fan speed. The cumulative EBRTs for all the trays are 2.08 seconds and 3.36 seconds for the Biowall with a high fan speed and low fan speed, respectively. Consequently, when the Biowall was operated at low fan speed, the contaminated air spent more time inside each tray than the operation of the Biowall with a high fan speed.

According to Marie-Caroline Delhoménie and Michèle Heitz from the Université de Sherbrooke, who reviewed various Biofiltration technologies, stated, “to improve biofiltration performance, the EBRT should be greater than the time required for diffusion processes, which is the case for low operating flow rates” (Delhoménie & Heitz, 2005, p. 61). Therefore, since the Biowall with a low fan speed has a higher EBRT, the performance of the low fan speed should be higher than the high fan speed. Additionally, the oscillation in the decay curves of the Biowall with a high fan speed n
the 5-mL injection tests could be for the a similar reason in which the diffusion processes did not have their necessary time to be accomplished, and thus toluene was desorbed back to the bulk air of the chamber from the growth media due to the high fan speed.

Another point to discuss from the Biowall’s results is the relation between the water content and the performance of the Biowall. As the results showed, the Toluene decay rates with higher water content in the root zone had a lower performance than the decay rates with lower water content in the root zone. The reason behind the lower performance with higher water content is believed to be the insolubility of toluene in water. In 2011, Zhiqiang Wang presented results in his dissertation for the single pass efficiency of toluene removal versus different bed water contents when using their Dynamic Botanical Air Filtration (DBAF) System. According to Wang’s results, the higher the water content in the root bed, the lower the performance of toluene removal by the DBAF. Wang also linked the reason of lower performance with higher water content to the insolubility of toluene (Wang, 2011, p. 65).

Overall, the Biowall with both fan speeds were able to remove toluene from the chamber but with different effectiveness. In the 5-mL, 1-mL, and 0.2-mL injection tests, the Biowall with a low fan speed removed up to 90% of the initial concentration within the first two to three hours. On the other hand, and for the same three tests, the Biowall with a high fan speed only removed up to 80% of the initial concentration within the first two to four hours. Therefore, in spite of the initial concentration for all the performed tests, each fan speed had a similar performance in removing toluene from the chamber. Further quantitative analyses for the cleaning performance of the Biowall will be provided in section 4.4 of this chapter.
4.3 Toluene Removal by the Growth Media Without the Plants

Additionally to investigating the removal of Toluene with the Biowall, and for the sake of comparison and better understanding of the Toluene removal, the growth media was also tested alone (i.e., without the presence of the plants). The growth media was tested in both a dry condition, and a wet condition. The growth media in this test, which contained 40% coco-coir, 40% growstone and 20% activated carbon pellets, was new mixture and did not have any previous contact with plants. A 5-mL injection of toluene was the first test for the dry growth media followed by a multi-injection test. Then, the wet growth media was also tested for a 5-mL injection test as well as a multi-injection test. Since the wet growth media was first watered during the experiment, the water content at the beginning of this test only was known and it was approximately 15% (i.e., around 4-liters of water per tray). In all the growth media experiments, only the high fan speed (105 cfm) was operated and tested.

4.3.1 5-mL Injection

The experiments for the growth media followed the same approach and procedure as in the Biowall tests that were discussed earlier. Figure 4.9 shows the Toluene decay curves for both the dry growth media, and the wet growth media in addition to the curve of the natural decay of Toluene. The vertical axis has the Toluene concentration in parts per millions (ppm), and the horizontal axis has the time in hours. The beginning of the time axis (i.e., 0-hours) indicates when the fan started operation.
As shown in Figure 4.9, there is a notable difference between the toluene decay curves of the dry growth media and the wet growth media. Within the first hour, the dry growth media removed 90% of the toluene, while the wet growth media removed approximately 75% of the toluene. After approximately 10-hours of monitoring, the toluene concentration with the dry growth media was below 1-ppm, whereas the concentration was around 5-ppm for the wet growth media. Additionally, the same oscillation, which appeared in the Biowall with the high fan speed, appears with the wet growth media only. This difference between the two curves as well as the oscillations are
believed to be due to the insolubility of toluene in addition to the EBRT, which were previously discussed in the Biowall results with the high fan speed.

4.3.2 Multi-Injection Test

Both the dry growth media and wet growth media were tested with a multi-injection of toluene. Similar to the Biowall’s multi-injection test, a 5-mL of toluene was injected into the chamber four times in every 12-hours for 48-hours. The fan was turned off for 3-minutes during and after the injection to allow the toluene to mix adequately with the air inside the chamber. The chamber door was kept closed throughout the test, and the growth lights were turned on a 12-hours schedule, in which they were turned-off in the first 12-hours of the test. Figure 4.10 shows the decay curves of the multi-injection test in a similar manner to the previous curves.

Figure 4.10 Toluene Decays for Multi-Injection Test for the Dry Growth Media and for the Wet Growth Media with a High Fan Speed (105 cfm)
Figure 4.10 showed similar differences between the dry and wet growth media as in Figure 4.9, in addition to the differences in the final concentration for each injection. For the wet growth media, the final concentration of each injection is slightly higher than its precedent injection. The oscillation, moreover, becomes more prominent after subsequent injection. On the other hand, the dry growth media decay curves did not have a notable difference in the final concentration of each injection nor did they show any oscillations. In other words, the four decay curves for the dry growth media were very similar and did not have any significant differences. The results of the wet growth media versus the dry growth media confirm the effect of the water content to the toluene removal performance by the Biowall.

4.4 Clean Air Delivery Rate Analysis

In order to better understand the decay curves above, two numerical analyses were implemented to quantify the clean air delivery rate (CADR). The first approach was done by constructing a curve fit using the least square method to quantify the decay rate of toluene. The decay rate was then used in equation (3) with the natural decay rate to calculate the CADR. Since the CADR might not be constant throughout the decay curves, the CADR was additionally calculated using the mass conservation of contaminant equation (2) with a specific time step. Both methods and their results are discussed in this section.

4.4.1 CADR – Least Square Curve Fit

The least square method was used to construct a curve fit for all the decay rates that were discussed under section 4.3. ‘Trust region reflective algorithm’ was implemented to optimize the curve fit to the decay curve for the first 10-hours of the test period in order
to find the decay rate. MATLAB software was used as a computational platform, and it provided the algorithm. As mentioned earlier, the CADR was calculated from equation (2) by using the decay rate of each curve and the natural decay rate (i.e., -0.038 h$^{-1}$), which was previously discussed in subsection 4.1.3. For each category, the CADR was an average of two to three tests. For example, in the 5-mL injection test, the CADR of the Biowall with the high speed is an average of the two tests, and so on.

The CADRs for the Biowall with both fan speeds, and the growth media with both conditions (i.e., dry and wet) were quantified. For the 5-mL injection, the Biowall with a high fan speed had a CADR of around 10 m$^3$ per hour (6 cfm), while the low fan speed had a CADR of around 20 m$^3$ per hour (12 cfm). For the 1-mL injection, the Biowall with a high fan speed had a CADR of around 25 m$^3$ per hour (15 cfm), while around 26 m$^3$ per hour (15 cfm) for the Biowall with a low fan speed. In the 0.2-mL injection, CADRs of 20 m$^3$ per hour (12 cfm) and 37 m$^3$ per hour (22 cfm) for the Biowall with a high fan speed and a low fan speed, respectively. The dry growth media and the wet growth media, on the other hand, had CADRs of 43 m$^3$ per hour (25 cfm), and 34 m$^3$ per hour (20 cfm), respectively. These were the results when the least square method were applied for 10-hours on the decay curve to find the decay rate of each decay curve.

The following bar graph (Figure 4.11) shows a visual representation of the calculated CADR results for all the single injection categories. The vertical axis has the CADR in cubic meter per hour. The horizontal axis has the categories of injection at the very bottom of the axis, and type of tests is above the categories. BWH, BWL, GM refer to Biowall with high speed, Biowall with low speed, and growth media (without plants),
respectively. To reaffirm, the following CADRs are based on a curve fit using the least square method over the period of 10-hours of the decay curves.

![Graph showing CADR values](image)

Figure 4.11 Clean Air Delivery Rates for the Biowall with High Fan Speed (BWH) and Biowall with the Low Fan Speed (BWL), in addition to Dry Growth Media (GM Dry), and Wet growth media (GM Wet) with High Fan Speed

As shown in the bar graph from Figure 4.11, the CADR’s results agree with the previously stated observations in section 4.3. For instance, the Biowall with low fan speed decay curves were always below the Biowall with high fan speed decay curves. Similarly, the CADR of the Biowall with the low fan speed had better CADRs, overall, than the Biowall with the high fan speed. Moreover, the dry growth media showed a higher CADR than the wet growth media. The difference between the two growth media
tests confirms again that the addition of water lowers the performance of toluene removal due to the insolubility in water for this specific VOC. Another general observation from the CADR results from the Biowall with low fan speed is that the lower initial concentration, the higher the CADR.

Even though the CADR results agree with the observations on the decay curves, there were several issues that need to be addressed. The curve fit from the least square method was not always a perfect fit throughout the decay curve, especially at the lower concentration levels. The curve fit could be advantageous to some of the decay curves, and disadvantageous for other decay curves. For instance, when the least square method was applied only for the first 2-hours, 1-hour, or 30-minutes of any decay curve, the curve fit appears to be a more perfect fit. Also the shorter the time to which the curve fit was constructed, a higher the decay rate is computed, and thus a higher CADR is found. In short, the CADR appeared to be inconstant throughout the decay curves, but the least curve might just provided an average for what the CADR along the decay curve. To investigate the assumption, the following subsection has further analysis for the CADR.

4.4.2 CADR – Mass Conservation of Contaminants Calculation

In order to thoroughly understand the CADR of both the Biowall and the growth media, the mass conservation of contaminants equation was used to compute the CADR. By using equation (2) and rearranging the variables, the following equation was obtained:

$$CADR = -V \left( \frac{1}{C} * \frac{dc_t}{dt} + k_n \right)$$

Where CADR is the clean air delivery rate in (cubic meter per hour, or cfm), V is the volume of the chamber (ft$^3$ or m$^3$); $k_f$ is the exponential decay rate of toluene with the Biowall (h$^{-1}$); and $k_n$ is the exponential natural decay rate of toluene (h$^{-1}$) (i.e., without the
Biowall); C is the concentration at time t (ppm), and \( C_0 \) is concentration at \( t=0 \) seconds (ppm). Using equation (4), a script was written in MATLAB software to calculate the CADR throughout any decay curve from the beginning of the decay curve to the end of the curve with a specific time step. For the example, if the time step was 1-minute, then the script calculated the CADR for every minute of the decay curve. In addition, a moving average was also included inside the script in order to smoothen the decay curve.

The following page has six different plots (Figure 4.12) that shows the calculated CADRs versus time for the Biowall with both speeds and the growth media with both wet and dry conditions. The two top plots are for the Biowall with high fan speed (left), and the Biowall with the low fan speed (right) for the 5-mL injection test (around 45-ppm peak concentration). The two middle plots are for the Biowall with a high fan speed (left) and low fan speed (right) for the 1-mL injection test (around 10-ppm peak concentration). The two bottom plots are for the dry growth media (left), and the wet growth media (right) for a 5-mL injection test. The horizontal axis shows the time in hours, while the vertical axis shows the CADR in cubic meter per hour. For all the plots, a moving average was applied with a one-minute window, and the CADR was calculated in a 10-seconds time-step. The script did not calculate the CADR when the change in concentration in one time step was equal to zero; therefore, gaps appeared in some of the plots, especially at lower concentration levels, and tests with low concentrations (i.e., 1-mL injection tests).

Additionally, the black dotted line in each plot, indicates the CADR that was calculated by using the least square method after a moving average with one-minute window was applied to the concentration data.
Figure 4.12 Clean Air Delivery Rates versus Time for the Biowall with High Fan Speed (BWH) and Biowall with the Low Fan Speed (BWL) for the 5-mL and 1-mL Injections Tests, in addition to the Dry Growth Media (GM Dry), and Wet Growth Media (GM Wet) for the 5-mL Injection Test with High Fan Speed
The CADRs versus time in Figure 4.12 confirms the assumption that the CADR is not constant throughout the toluene decay curves. By looking at all the plots between 0-hour to 1-hour marks, the CADRs were high in the beginning of the test but then they decreased to the black dotted lines, which are the CADRs calculated by the least square method. For example, the dry growth media test (the lower left corner plot), the CADR was above 100 m$^3$ per hour in the first few minutes of the test, and it was below 30 m$^3$ per hour after 1-hour from the beginning of the test, and similarly on the other plots as seen in Figure 4.12. Even if the moving average was not applied to the data, the similar CADR versus time profile was observed but in a more noisy manner.

For the Biowall with high fan speed and low fan speed, the decline in CADRs in the first hour could be due to the increase in relative humidity. As seen in figure 4.3 for the relative humidity of the Biowall with both fan speeds, the relative humidity was increasing during the first hour of the test before the humidity reached its peak levels of those specific tests. Similarly, the CADR decreases during the first hour for the same tests, and then fluctuates around the mean value as seen in the top two plots of figure 4.12. Thus, the change in relative humidity level could be the main reason for the change in CADR.

Additionally for Figure 4.12, after three to four hours from the beginning of the 5-mL injection tests (i.e., top and bottom plots), and after the first hour in 1-mL injection tests (i.e., middle plots), the CADRs were either scattered and or they increased again. One reason behind this scatteredness is the inability of the photoionization detector (PID) to capture any concentration below 0.1-ppm. For instance, if the actual concentration was, hypothetically, between 3.1-ppm and 3.2-ppm, the sensor will only read either 3.1-ppm
or 3.2-ppm but the PID will not read anything in between. Therefore, the lower the concentrations, especially below 1-ppm, the more scatteredness appeared in the results since the change in concentration in equation (4), which is relative to the change in time and initial concentration, would be either significantly higher or much lower than the actual change in concentration. For the same given reason, the 0.2-mL injection tests were not included in this analysis since the majority of the concentrations were below 1-ppm.

To further understand the results from Figure 4.12, a box-plot was created for the CADRs distribution for each of the six plots. Figure 4.13 shows the box-lots, where the first two boxes from the left are for the 5-mL injection tests for the Biowall with high fan speed and low fan speed, respectively. The third and fourth boxes are for the 1-mL injection tests for the Biowall with a high fan speed and low fan speed, respectively. The fifth box-plot is for the dry growth media and the sixth box-lot is for the wet growth media. Both the dry and wet growth media had 5-mL of toluene for their single injection tests, and they were tested with a high fan speed only. The vertical axis shows the CADR in cubic meter per hour. The red lines in each box-plot indicate the median CADR for each type of test. The outliers were eliminated from the graph to provide a better visualization for the results.
Figure 4.13 The Clean Air Delivery Rates’ Distribution for Biowall with High Fan Speed (BWH) and Biowall with Low Fan Speed (BWL) with Different Injections, in addition to the Dry Growth Media with High Fan Speed (GM dry), and the Wet Growth Media with High Fan Speed (GM wet).

As seen in Figure 4.13, the same observations from the previous sections and their subsections are observed. The Biowall with a low fan speed had a higher CADRs, overall, than the Biowall with a high fan speed in both tests (i.e., 5-mL and 1-mL injections). Similarly, the wet-growth media had lower CADRs in general than the dry growth media. The reasons behind the differences between the two fan speeds were discussed in subsection 4.2.5, and the difference between the wet and dry growth media are discussed in section 4.3. These numerical analyses were applied to confirm the visual observations, and they analyses will be further discussed and summarized later in this section.
4.4.3 Summary and Discussion of CADR results

Using the least square method analysis, the discussion mentioned that the curve fitting was not perfect throughout the decay curves but the CADR from the fitting was assumed to be an average CADRs for the entire curve. In order to investigate the assumption, the mean value of CADRs versus time was computed for each of the results from Figure 4.12, and they were compared to the CADRs from the least square method analysis.

Table 4.1 shows both of the CADRs based on the amount of toluene injection. The lower two rows shows the CADRs, where the top has the CADRs from the least square method, and the bottom one has the mean CADRs from the analysis of this subsection. The CADRs values for the least square method in this table are different than the ones from the bar graph in Figure 4.11 since a moving average with a one-minute was applied to the decay curves before computing them. As mentioned earlier, the same moving average and the same window size was also applied to the results of the CADR versus time.

Table 4.1 Comparison Between the Clean Air Delivery Rates from the Least Square Fitting and the Mass Conservation of Contaminants Equation

<table>
<thead>
<tr>
<th>Toluene Injection</th>
<th>5-mL</th>
<th>1-mL</th>
<th>5-mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biowall Growth Media</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan Speed (m³/hour)</td>
<td>180</td>
<td>110</td>
<td>180</td>
</tr>
<tr>
<td>[cfm]</td>
<td>[105]</td>
<td>[65]</td>
<td>[105]</td>
</tr>
<tr>
<td>CADR (m³/hr) [cfm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Least Square Method</td>
<td>11</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>Mean of CADR versus time</td>
<td>11</td>
<td>23</td>
<td>28</td>
</tr>
</tbody>
</table>

Approximate Peak concentration ppm [mg/m³] 45 [192] 10 [38] 45 [192]
As shown in table 4.1, the CADRs from both methods were quite similar for some tests and different for some other tests. For the 5-mL injection tests of the Biowall with both speeds, the CADRs were almost similar. For the 1-mL test of the Biowall, the high fan speed difference of 2 m$^3$/hr between the two tests, while the difference for the low fan speed was around 9 m$^3$/hr. The least square method was in favor for the dry growth media with 28 m$^3$/hr difference, while the wet growth media had a difference of 3 m$^3$/hr. Overall, the least square method was very close to the mean value of the CADR versus time results except in two cases (i.e., low fan speed in 1-mL injection and dry growth media). In the dry growth media case, as seen in Figure 4.12, the CADRs were very high in the first 30-minutes of the test but then the decreased as the concentration was low. For the Biowall with low fan speed in the 1-mL injection test, the concentration was lower than 1-ppm after the first hour, and therefore CADRs values were high after that time mark due to the PID accuracy issue, which was discussed earlier. In general, the least square method provided an average understanding of the CADR for each of the decay curve, and that was confirmed by the mass conservation of contaminants analysis as seen in table 4.1.

From the previous results, the growth media (without plants) with a high fan speed noticeably showed a better performance in removing toluene from air than the Biowall with the same fan speed. The addition of water to the growth media (without the plants) showed a lower CADR than the dry growth media but a higher one than the Biowall, where all had the same high fan speed of 105 cfm. For example, when looking at the mean CADR from table 4.1, the dry growth media, the wet growth media, and the Biowall with a high fan speed had CADRs of 30, 21, 11 m$^3$/hr (18, 12, and 6 cfm),
respectively. The insolubility of toluene in water could be the main reason for the dry growth media to have a higher CADR than both the wet growth media and the Biowall with a high fan speed. But in the experiment of this thesis, the wet growth media had a higher CADR than the Biowall. If the insolubility of toluene in water was the main reason for the difference between the Biowall with a high fan speed and the wet growth media, then both of them should have, at least, a closer CADR. Hence, there can be other reasons than the water-content that caused the CADR of the Biowall with a high fan speed to be lower than the wet growth media with the same speed.

There can be different assumptions for why the wet-growth media had a higher CADR than the Biowall when both had the same fan speed. Cumulatively, the Biowall’s plants and its growth media mixture were watered more frequently than the stand-alone wet growth media, which was only watered during the wet growth media tests. For this reason, the growth media mixture of the Biowall in general, and the activated carbon pellets in specific, were exposed to more water, and they might had a higher water content than the wet growth media without the plants. In other words, the growth media mixture and its activated carbon pellets in the Biowall’s experiments were moister, or were saturated with water and nutrients, than the stand-alone wet growth media. According to Wolverton’s (1995) patent for his Indoor Humidifier and Air Purifier, the higher the water content in the growth media mixture could potentially lower the air permeability, and thus the reduces air purification (Wolverton, 1995). Looking at Figure 4.4 for the pressure drop across the filter, the wet growth media had a lower pressure drop by 0.02 inches of water columns than the Biowall with high speed. The difference in the pressure drop could be an indicator of higher water content in the Biowall’s growth
media than the stand-alone wet growth media, but the difference can also be for the presence of the plants and their roots. Nevertheless, these assumptions cannot provide a conclusion since the water content was not monitored at all nor was the pressure drop cause by the plants known in the experiments of this thesis.

In spite of the higher CADR of the dry growth media, the Biowall still presents a biological cleaning capability in addition to the adsorptive one. According to Wolverton (1995), the roots of the plants eventually reach the activated carbon pellets, and biodegrade the absorbed VOCs. The biodegradation process by the roots on the activated carbon pellets would keep the pellets air permeable, unless they were constantly saturated with water. On the other hand, once the activated carbon pellets in the dry growth media (without the plants) becomes saturated with VOCs, the absorptive capability of the carbon pellets will ultimately diminish, except if an external process was implemented to purposely clean the carbon pellets from contaminants.

To understand the Biowall performance in the context of biofiltration, the Biowall is compared against other botanical air filtration system and their performance. DBAF was a botanical air filtration system that was examined by Wang et al. (2010) of Syracuse University. Wang et al. (2014) published additional results to their botanical air filter. BI-AMPS was another reviewed system that was developed by Aydogan (2012) of Rensselaer Polytechnic Institute. Both systems were reviewed in details in section 2.3 (Biofiltration in Green Buildings) of the literature review chapter. The characteristics and performances of the DBAF, the BI-AMPS, and the Biowall are summarized and tabulated in table 4.2 in the following page to restate them for an easy reference for comparison.
There are various differences between the three systems in table 4.2. The growth media mixture was different in all the three tests. For example, DBAF has 50% activated carbon in comparison to 20% in the Biowall. DBAF and BI-AMPS both used Golden Pothos only, while the Biowall used Golden Pothos in addition to other two plants. The Biowall had the higher peak concentrations for the injection tests than the other two systems. BI-AMPS had the lowest airflow rates, while DBAF had the highest airflow rates. DBAF and the Biowall had a similar face area and bed thickness, but the size of the chamber was significantly different for all the three systems. Finally, DBAF reported the highest CADRs, then the Biowall and lastly BI-AMPS. The difference in the CADRs is due to the different characteristics of each system in addition to the testing parameters (chamber size and amount of injection).
### Table 4.2 Summary of Performances and Characteristics of The Biowall, and Other Botanical Air Filtration Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Biowall</th>
<th>BI-AMPS&lt;sup&gt;1&lt;/sup&gt;</th>
<th>DBAF&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant(s)</td>
<td>Golden Pothos, Spider Plants and Philodendron</td>
<td>Golden Pothos</td>
<td>Golden Pothos</td>
</tr>
<tr>
<td>Growth Media</td>
<td>40% Growstone, 40% cocoir, &amp; 20% Activated Carbon</td>
<td>41% Growstone, 29% expanded clay, &amp; 30% activated carbon</td>
<td>50% Shale pebbles &amp; 50% granular activated carbon</td>
</tr>
<tr>
<td>Tested VOC</td>
<td>Toluene</td>
<td>Formaldehyde</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td>Typical Indoor Range of the VOC&lt;sup&gt;3&lt;/sup&gt; [ppm]</td>
<td>2 to 8</td>
<td>14 to 88</td>
<td>14 to 88</td>
</tr>
<tr>
<td>Peak Concentration in Experiment [ppm]</td>
<td>11</td>
<td>1.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Chamber Volume [m&lt;sup&gt;3&lt;/sup&gt;]</td>
<td>22.6</td>
<td>1.0</td>
<td>5.1</td>
</tr>
<tr>
<td>Bed Thickness [m]</td>
<td>0.10</td>
<td>0.135</td>
<td>0.15</td>
</tr>
<tr>
<td>Face Area [m&lt;sup&gt;2&lt;/sup&gt;]</td>
<td>1</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Volumetric Flow Rate [m&lt;sup&gt;3&lt;/sup&gt;/hour]</td>
<td>110</td>
<td>180</td>
<td>0.54</td>
</tr>
<tr>
<td>Face Velocity [m/s]</td>
<td>0.03</td>
<td>0.05</td>
<td>0.001</td>
</tr>
<tr>
<td>EBRT [seconds]</td>
<td>3.36</td>
<td>2.08</td>
<td>103.8</td>
</tr>
<tr>
<td>CADR [m&lt;sup&gt;3&lt;/sup&gt;/hour]</td>
<td>29</td>
<td>40</td>
<td>0.54</td>
</tr>
<tr>
<td>CADR/Bed-Area [m&lt;sup&gt;3&lt;/sup&gt;/(hour·m&lt;sup&gt;2&lt;/sup&gt;)]</td>
<td>29</td>
<td>40</td>
<td>4.5</td>
</tr>
</tbody>
</table>

<sup>1</sup> BI-AMPS is the system tested by Aydogan (2012) (as cited in Mietusch, 2015, p. 35).

<sup>2</sup> DBAF is a system tested by Wang et al. (2014) and Wang et al. (2010).

4.5 Chapter Summary

Chapter four discussed and analyzed five different points from the results of the experiment of this thesis. The beginning of the chapter discussed the background contaminants of the environmental chamber as well as the testing conditions: temperature, relative humidity and the pressure drop across the filter. The second and third part of the chapter presented the toluene removal by the Biowall with two different speeds in addition to the toluene removal by the dry and wet growth medias (without plants). The fourth part of the chapter focused on the analysis of the CADR for all the tests in the second and third parts.

There are several outcomes that can be concluded from this chapter. In a sealed envelope such as the environmental chamber of this experiment, the Biowall showed an increase in relative humidity by approximately up to 40%, and an average temperature difference of 1°F. The Biowall with a low fan speed had a better performance than the high fan speed in terms of CADR and pressure drop across the filter due to the lower EBRT of the later. Based on the toluene as a challenge contaminant with 1-mL injection (i.e., approximate peak concentration of 11-ppm), the Biowall with a low fan speed showed an average CADR of 23 cfm (40 m³ per hour). On the other hand, the dry growth media had the highest CADR for the short-term study of this thesis. The addition of water to the growth media reduced the CADR due to the insolubility of toluene in water, which partly explained the lower CADR of the Biowall versus the dry growth media alone in the case of this thesis.
CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Future Work

Subsection 5.1 discusses the future recommendation in terms of design and experiments, in addition to a preliminary energy analysis. The recommendations are based on observations from this thesis that could not be thoroughly analyzed and studied as they were outside the scope of this research, or due to the limitation of the available instrumentation.

5.1.1 Experimental and Design Recommendations

Further studies might be needed to establish a fair comparison between Botanical air filters and activated carbon air filters. For instance, the tested dry growth media without the plants had the same volume of the Biowall’s growth media mixture, which is not a practical size for a commercially available air filter. One aspect of the Biowall, in addition to filtration, is the aesthetic component. Installing four trays of growth media inside a house without the plants and with the size of the Biowall will not have the other aspects of the Biowall. Additionally, the activated carbon filter reaches a breakthrough once the pellets are saturated with contaminants. The Biowall is believed to biodegrade these contaminants from the growth media and its activated carbon pellets. Thus, the Biowall needs to be tested for longer times to investigate the long-term cleaning capabilities. The longer time tests should also provide more realistic levels of a challenge gas than the one of this thesis. In short, botanical air filters should be compared to
the commercially available air filters in terms of cleaning abilities for both short-term and long-term periods, practicality, appearance, and filter lifetime, and also by testing various VOCs (e.g., soluble in water VOCs).

The analysis for the decay curves of the Biowall with both speeds as well as the growth media with both conditions showed that the CADR is inconsistent. Both figures 4-12 and 4-13 show how the CADRs were inconsistent throughout the time of the experiment. Generally, the CADRs were decreasing from high rates during the first 30-minutes to 60-minutes from the beginning of the injection before they fluctuate around the mean value in most of the cases. Due to the low accuracy of the PID, the CADR at low concentration levels were questionable, especially with the 1-mL injection tests. Other than the observation of the inconsistency of the CADR throughout the time of the experiments, conclusive statements cannot be made based on the available results. Therefore, further investigation the applicability of using the CADR for remediating VOCs from air is highly recommended for both biological air filters (e.g., botanical air filters) and adsorptive air filter media (e.g., activated carbon air filters).

In addition to the experimental recommendations, there are several design improvements that should be addressed in the future. Since the activated carbon pellets lose the adsorptive capability when they become moist, placing the pellets in dried area (e.g., top of the growth media) would increase the effectiveness of using these pellets as Aydogan claimed in her dissertation (2012). Controlling the water content inside the growth media is another vital component that needs to be incorporated in the design. As the results showed that the addition of water did not improve the CADR of the Biowall for insoluble in water VOCs. The scarcity of water, on the other hand, would not be a
pleasant environment for the plants. Thus, controlling the water content at a minimally optimized level for the plants’ needs would favor both the plants and the CADR.

5.1.2 Preliminary Energy Analysis

In this subsection, two energy aspects are discussed preliminarily. The first aspect is the energy consumption of the Biowall’s components. The components of the Biowall are the growth lights, fan, and the controller. The other aspect is the potential energy savings in ventilation when the Biowall is incorporated in the HVAC system. The energy analysis was based on the Biowall with a low fan speed since the CADR and the pressure drop across the filter were more promising in the operation of a low fan speed than the high fan speed operation. The analysis will use ASHRAE 62.2 standard as a reference for the ventilation requirement for the median size of typical homes and the median size of new homes. Finally, the cost associated with the saving in ventilation is also presented for various cities in several climate zones.

The analyses on the two energy aspects were preliminary for several reasons. For the Biowall’s operation cost, the capital cost and the maintenance cost are still under research and development since the Biowall is not yet commercialized. On the potential energy savings aspect, any positive or negative impacts of latent heat from the Biowall humidification were not included in the analysis. Any savings in electricity by reducing the operation time of the primary HVAC fan were not a part of this analysis as well. In addition, toluene was the only tested contaminant in the experiments of this thesis; therefore, the CADRs were based on the removal of toluene only. The CADR could be totally different if other contaminants or VOCs were tested. For example, when
formaldehyde, which is soluble in water, was tested against toluene in Wang’s dissertation (2011), the CADRs were significantly higher than the CADRs tests based on toluene. These are some of the reasons that made these analyses preliminary.

5.1.3 Operating Cost

The operating cost of the Biowall is based on three main components and their operation times. The first component is the Biowall’s fan. The Biowall has a power consumption of 6 Watts for a low speed. The fan varies in operation time since it can either run simultaneously with the HVAC system, or it can run based on the homeowner preferences. Since the time of operation of the fan is undetermined, the time is assumed to be 24-hours per day as the maximum possible operating time (i.e., continuous operation). The growth lights, which are another vital component for the plants, have a total power consumption of 87 Watts. As the plants needs around 12-hours of light per day, then the lights operate for 12-hours per day. The controller, that is used to collect data, control the lights and the fan, and irrigates the plants, has a power consumption of 13 Watts and operates for 24-hours.

There are costs that were not taken into account as mentioned earlier. The cost of watering the plants was not included in the analysis for its insignificant value in Indiana, U.S. In other parts of the world, where water is scarce, the cost can be definitely significant. The cost of growth media, and plants themselves were also not taken into account. The growth media and the plants are considered as capital cost. Since the capital cost also includes the plenum of the Biowall and its trays, which were not particularly designed for commercialization, the cost is still undetermined. The fertilizers, which are
considered as a maintenance cost, are still under research as well, and thus they were also neglected in the analysis.

Table 5.1 shows each component, its power consumption, operation time, energy consumption, and the cost of its operation per year. The cost of electricity was based on 12 cents per each kilo-Watt-hour (kWh), which was the approximate national average price for electricity in the United States in 2015 (U.S. Energy Information Administration, 2016). The energy of each component was the result of the multiplying the operating time with the power consumption. The annual cost of operation was based on 365 days for a year.

<table>
<thead>
<tr>
<th>Component</th>
<th>Low Fan Speed (65 cfm)</th>
<th>Growth Lights</th>
<th>Controller</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Watt)</td>
<td>6</td>
<td>87</td>
<td>13</td>
<td>106</td>
</tr>
<tr>
<td>Operation (hours/day)</td>
<td>24**</td>
<td>12</td>
<td>24</td>
<td>N/A</td>
</tr>
<tr>
<td>Energy (kWh/year)</td>
<td>53</td>
<td>381</td>
<td>114</td>
<td>548</td>
</tr>
<tr>
<td>Cost of Operation* ($/year)</td>
<td>6</td>
<td>46</td>
<td>14</td>
<td>66</td>
</tr>
</tbody>
</table>

* Based on 12 cents per kWh, which was the U.S. the approximate average cost of electricity in 2015 (U.S. Energy Information Administration, 2016).
** The fan may not actually be operating for 24 hours per day, but this assumption was made as if the Biowall was on a continuous operation mode.

The total cost of operation for the Biowall and its component is approximately $64 per year as shown in table 5.1. The growth light has the highest cost of $45 per year, and then the controller and the fan that have annual costs of $13 and $6, respectively. The cost operation of the growth lights can be eliminated if the Biowall’s plants had access to natural daylighting. Therefore, the Biowall cost can be potentially reduced from $64 per
year to $19 per year. Another potential saving in the operation cost can be applied to the controller. The controller that is used in the Biowall is designed for larger operations. A smaller micro-controller with lower power consumption can be implemented in the future to reduce the cost of operating the Biowall to below than $19 per year.

From table 5.1, the power required to clean each cubic meter of air can be found. The Biowall with a low fan speed has an average CADR of 23 cfm (40 m$^3$/hour). The total power consumption of the Biowall with a low fan speed is approximately 106 Watts. Thus, the CADR per Watt for the Biowall is approximately 0.22 cfm/Watt (0.38 m$^3$/hour)/Watt). In other words, each 0.22 cfm (0.38 m$^3$/hour) has a power consumption of 1-Watt. In the case the Biowall has a natural daylighting, the CADR/Watt could be 1.21 cfm/Watt (2.11 m$^3$/hour).

5.1.4 Potential Energy Savings

In residential homes, ASHRAE 62.2 standard uses the square footage of a home in addition to the number of bedrooms to determine the required amount of ventilation (ASHRAE, 2013). To have a general understanding of the potential energy savings in using a botanical air filtration system such as the Biowall, the median size of homes and the most common number of bedrooms in the U.S are used in the energy analysis. According to a survey released by the U.S. Department of Housing and Urban Development (2010), 1,800 square feet was found to be the national median size of an occupied home, while 2,300 square feet was the national median size of new homes. From the same survey, three or more were the most common numbers of bedrooms in typical homes as well as new homes. The home sizes and the number of bedrooms from the survey fall within two different square footage categories of ASHRAE 62.2 standards,
which are 1,501 to 2,000 square feet and 2,001 to 2,500 square feet. Additionally, in each category, every different number of bedrooms has different required amounts of ventilation. Therefore, the required amounts of ventilation for three or four bedrooms homes with a square footage between 1,501 and 2,500 square feet are the focus of this analysis since they are representative of a typical home or a new home in the U.S.

To understand how the Biowall would contribute to the ventilation of a home, the CADR is incorporated into the required amount of ventilation that ASHRAE 62.2 provided. In other words, the CADR value will be subtracted from the required amount of outside air ventilation. For this analysis, the average CADR for the Biowall with a low fan speed from the 1-mL injection tests from table 4.1 is used. According to Maroni et al. (1995), 2-ppm to 8-ppm is the range of toluene that is typically found in homes. The 1-mL injection tests with an approximate peak concentration of around 11-ppm was chosen since it provided closer concentration to the typical range of the presence of toluene in homes. Table 5.2 shows the required ventilation for both typical homes and new homes for both three and four bedrooms. The potential reduction in the required ventilation based on the CADR of the Biowall is also provided in the table.

<table>
<thead>
<tr>
<th>Home Square footage</th>
<th>Number of Bedrooms</th>
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<th>With the Biowall (cfm)</th>
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Three and four bedrooms for both typical homes and new homes require ventilation amounts in the range between 90 and 113 cubic feet per minute (cfm) as shown in table 5.2. The addition of the Biowall to the same types of homes and number of bedrooms could potentially reduce the amount of ventilation to a range between 67 and 90 cfm. Thus, in typical and new homes with three and four bedrooms between, the Biowall could potentially reduce the required ventilation rates by 20% and up to 25%.

To represent the potential savings in ventilation as cost savings, data from different climate locations in the U.S. were analyzed to quantify the cost of heating and cooling of ventilated air to a typical home temperature. Temperature data for various cities from different climates were obtained from National Climate Data Center of the National Oceanographic and Atmospheric Administration that was collected from 1973 to 1996 (see Appendix C) Seven cities from five different climates were chosen based on the available data that are listed in both Figure 5.14 and Figure 5.15 at the end of this subsection. For each city, the data had normalized and averaged frequency (hours per year) for different temperatures values between -28 ºF and 122 ºF with a 5 ºF.

Figure 5.1 shows an example for these temperatures and the frequency associated with them, and how they are applied in they are implemented in the energy model of this thesis. The temperatures are presented on the vertical axis as ºF, while the horizontal axis has the cumulative hours of temperatures frequency. The data presented on the figure are based on Peru, IN weather, and it was used as an example since the city experience decent periods of both heating and cooling.
Figure 5.1 Example for the temperature data based on Peru, Indiana Weather that shows when either Heating (light red) or Cooling (light blue) are Required by the Energy Model (the Gap Indicates neither Heating nor Cooling are Required)

As seen in Figure 5.1, the temperature is divided into three regions. The first region on the bottom (light red) is where heating is required and that is below 67 °F. The top region (light blue), which is above 72 °F, is when cooling is required. The region between 67 °F and 72 °F is not included in the cost of heating and cooling. The region was considered as the range of a typical home temperature in which heating and cooling are not needed. The temperature of 70 °F was considered as a baseline temperature to which air needs to be either cooled or heated.
The analysis for heating and cooling outside temperature to a 70 °F was based on a simplified model that only includes sensible energy. The following equation (5) was implemented to find the required rate of heat transfer to heat or cool outside air temperature to 70 F:

\[ q = 1.08 \times Q \times \Delta T \]  

\text{equation (5)}

The heat transfer rate (q) is in British thermal unit per hour (Btu/hour), Q is the volumetric flow rate in cubic feet per minute (cfm), \( \Delta T \) is temperature difference in degree Fahrenheit (°F), and 1.08 is an approximated constant for converting the specific heat to volumetric flow rate based on air density at sea level. The model was used the stated temperature values in the previous paragraph. To find the required energy for heating and cooling, each heat transfer rate was multiplied by the number of hours, which presents the frequency of each temperature within a year. The cost of cooling was based on the electricity rate of 12 cents for each kWh, while the cost of heating was based on $1 per therm for natural gas.

The model was used to analyze the data in three different scenarios for two different types of homes. The two types of homes that were selected are the median size of a three-bedrooms typical home and the median size of a four-bedrooms new home that were described earlier in this section. The choices represent the minimum and maximum required ventilation rates as was presented in table 5.2. The total ASHRAE 62.2 ventilation requirement was used for the first scenario of the model. The second scenario was the combination of ASHRAE 62.2 in addition to one Biowall. The third scenario was based on ASHRAE 62.2 requirement plus two Biowalls.
The model was used to analyze the data in three different scenarios for two different types of homes. The two types of homes that were selected are the median size of a three-bedrooms typical home and the median size of a four-bedrooms new home that were described earlier in this section. The choices represent the minimum and maximum required ventilation rates as was presented in table 5.2. The total ASHRAE 62.2 ventilation requirement was used for the first scenario of the model. The second scenario was the combination of ASHRAE 62.2 in addition to one Biowall. The third scenario was based on ASHRAE 62.2 requirement plus two Biowalls.

Based on the results of the model, the Biowall had higher savings at colder climates than hotter and humid climates if ASHRAE 62.2 standards are implemented in homes. Despite the size of a home, one Biowall could potentially save around $75 per year in a very cold climate, while $55 per year in average for cold climates. Two Biowalls, in addition, could provide up to $146 per year for very cold climates, and around $110 per year for a cold climate. For mixed-humid and hot-humid climates, one Biowall could save up to $38, and $25 per year, respectively. Two Biowalls could save up to, $76, and $50 per year for mixed-humid, and hot-humid climates, respectively. For hot-dry climate, one Biowall could save between $16 and $42 per year, while two Biowalls could save between $31 and $84 per year. These savings in costs cannot be generalized, but the percentages of saving in required ventilation from table 5.2 can be generalized. For instance, for the median size of typical home with three-bedrooms, and the median size of a new home with four-bedrooms, in all of the analyzed cities and climates, the savings were around 25% and 20%, respectively, in spite of the actual costs.
of savings. Similarly for two Biowalls in the same type of houses, except the savings were doubled (i.e., approximately %40 and 50%, respectively).

The results of the model for the two types of homes and three different scenarios for the different cities and their climates are presented in figures 5-14 and 5-15 in the following page. Figure 5.14 is for a median size typical home with three-bedrooms, while Figure 5.15 is for the median size of a new home with four-bedrooms. The horizontal axis shows the city and state grouped based on the type of climate. The vertical axis has the cost of ventilation per year based on the three scenarios: ASHRAE 62.2 only, ASHRAE 62.2 plus one Biowall, and ASHRAE 62.2 plus two Biowalls.

Finally, this was a simplified model that allowed a presentation of a preliminary analysis of the potential for energy savings in ventilation. The principal shortcomings are that the model did not include latent energy for humidification, nor did the model include savings in electricity in reducing the HVAC fan operation. In addition to the model weaknesses, the CADR was only representative of removing one specific VOC (i.e., toluene). Testing other VOCs with different physical characteristics (e.g., solubility in water) would be beneficial for a broader understanding of the potential energy savings based on various contaminants.
Figure 5.2 Annual Costs of the Required Ventilation for the Median Size of a Typical Home with Three-Bedrooms at Different Cities in the U.S. based on ASHRAE 62.2 Requirements

Figure 5.3 Annual Costs of the Required Ventilation for the Median Size of a New Home with Four-Bedrooms at Different Cities in the U.S. based on ASHRAE 62.2 Requirements
5.2 Conclusions

From the results, the performance of the Biowall with both fan speeds can be summarized. With respect to the conditions of the experiment (e.g., sealed chamber with hydronic system), an increase of relative humidity by up to 40% and an average difference in temperature of 1°F were observed in both fan speeds of the Biowall. The pressure drop across the Biowall, on the other hand, was around 0.08 in w.c. in the operation of the low fan speed, and around 0.15 in w.c. in the high fan speed operation. Depends on the water content and possibly the propagation of the plants’ roots, the pressure drop can be different. Nevertheless, the low fan speed operation presented a significantly lower pressure drop that can be in favor to incorporating the Biowall at the return duct of an HVAC system.

The results of the experiments provided an understanding to the Biowall’s removal capacity of toluene in an airtight environment. The Biowall with both high and low fan speed showed significant removal rates of toluene in comparison to the natural decay of toluene in the environmental chamber. At different initial concentration levels, the Biowall with high fan speed removed up to 80% of the initial concentration within the first four hours, while the Biowall with a low fan speed removed up to 90% of the initial concentration within the first three hours. Due to the higher EBRT of the low fan speed (65 cfm), the cleaning ability of the Biowall with this speed was clearly higher than the Biowall with a high fan speed.

The growth media in both wet and dry conditions showed higher cleaning ability of toluene than the Biowall for the short-term study of this thesis. The dry growth media without the plants was able to remove up to 90% of the initial concentration (i.e.,
approximately 45-ppm) within the first two hours, while the wet growth media removed up to 80% of the same initial concentration within the first three-hours. The addition of water to the growth media showed a reduction in the ability of removing toluene from the chamber. The insolubility of toluene in water was the main reason as the adsorptive medium (activated carbon pellets) became highly moist, or maybe saturated, with water. For the same reason, the wet growth media alone showed a higher performance than the Biowall, where both had the same fan speed of 105 cfm, since the Biowall’s growth media was cumulatively watered more than the former. Other reasons for the difference in performance between the wet growth media and the Biowall with a high fan speed could not be determined as they were outside the scope of this thesis.

Two methods were used to quantify the CADR for the decay curves of toluene in all the different tests. The least square optimization method was initially used to find the decay rate constant. Since the optimization method was a nonlinear regression, and determining the perfection of the curve was difficult, the mass conservation of contaminants equation (4) was implemented to find the CADR versus time. The latter analysis revealed that the CADR inconstant throughout the time of each test as shown in Figure 4.12 and Figure 4.13.

However, the mean CADR versus the time of each test was found to be closer to the values found from the optimization method as reported in table 4.1. In the 1-mL injection of toluene tests, which were the closest to realistic levels found in homes, showed CADRs of 18 cfm and 21 cfm for the Biowall with a high fan speed and a low fan speed, respectively, when using the least square optimization method for curve fitting. The mass conservation of contaminants showed mean CADRs of 16 cfm and 26 cfm for
the Biowall with a high fan speed and a low fan speed, respectively, for the 1-mL injection tests.

The CADR of the Biowall was then implemented into a preliminary and simplified energy model to quantify any potential energy savings. The model showed potential energy savings in ventilation that could be up to 25%. According to the model and the available weather data, the Biowall could provide higher savings at colder climates than other types of climates. The latent heat due to humidification of air, which was not a part of the model, could also favor colder climates than the hotter and humid ones.

Finally, the scope and the research question of this thesis were focusing in investigating the capability of the Biowall in remediating air from toluene, and providing potential energy savings. As the results of the experiments showed, the Biowall was able to remove toluene from the sealed chamber significantly in comparison to the natural decay of toluene inside the same chamber without the presence of the filter. Preliminarily, the Biowall presented a promising energy savings in ventilation. Total substitution of other ventilation systems (e.g., natural and mechanical) by the Biowall is still undetermined since further comprehensive and thorough understanding of all aspects of botanical air filtration are still necessary to draw such a conclusion.
LIST OF REFERENCES
LIST OF REFERENCES


APPENDICES
Appendix A  Instruments’ Specifications

MultiRAE Gas Detector (PID)

Wireless Portable Six-Gas Monitor with Advanced VOC Detection Capability

**SPECIFICATIONS**

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<th>Resolution</th>
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1. Additional equipment and software licenses may be required to enable remote wireless monitoring and alarm transmission.
2. RAE Systems recommends calibrating sensors on installation.
3. A two gas combination sensor is required for a 4 gas configuration.
4. Specifications are subject to change.
6. Contact RAE Systems for country specific firmware approaches and certifications.

**ORDERING INFORMATION (MODEL: PGM-6228)**

- Wireless and non-wireless configurations are available
- Refer to the Portable Pricing Guide for part numbers for monitors, accessories, sampling and calibration kits, gas sensors, and replacement parts

**Atomizing Nozzle**

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Asia Pacific: +65-6268-3838

www.raesystems.com
Atomizing Nozzles

Configuration A

Configuration B

Configuration C
Luer Adapter

**125/156 MINSTAC – Female Boss – Female Tube**

**Luer Adapter**

**TMRA0501950Z – PEEK**

![Diagram of Luer Adapter](image1)

**062 MINSTAC – 1/4-28 Flat Bottom Adapter**

**TMDA3204950Z – PEEK – PTFE**

![Diagram of 062 Flat Bottom Adapter](image2)

*Unless otherwise specified, dimensions are in inches (in) or millimeters (mm).*
Appendix B  Schematic

Schematic for sensors, arbitrary airflow direction, and GSD and PID placement
# Appendix C  Weather Data

Weather data used in the energy model

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