THE BIOWALL FIELD TEST ANALYSIS AND OPTIMIZATION

by

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For the many who I carry on for. Your spirits live within and through me

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I acknowledge that failure is an opportunity. Difficulty experienced along the way is the lesson. Humility is the true path to change.

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LIST OF ABBREVIATIONS

Abbreviation	Description
AEL	Applied Energy Laboratory. Purdue University Polytechnic Institute. KNOY Hall Room 425
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BAS	Building Automation System
Biowall	Name of the botanical air filter under review
CEBES	Commercial Buildings Energy Consumption Survey, the U.S Energy Information Administration
DOE	Department of Energy
dP	Differential pressure
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
HEPA	High-Efficiency Particulate Arrestance-filter
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IRB	Instructional Review Board
LED	Light Emitting Diode
MERV	Minimum Efficiency Reporting Value
NASA	National Aeronautics and Space Administration
NCERA-101	North Central Extension & Research Activity-101
PAR	Photosynthetically Available Radiation
ReNEWW	Retrofit Net zero: Energy. Water. Waste.
SBS	Sick Building Syndrome
VOC	Volatile Organic Compound

ABSTRACT

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A residential botanical air filtration system (Biowall) to investigate the potential for using phytoremediation to remove contaminants from indoor air was developed. A full scale and functioning prototype was installed in a residence located in West Lafayette, Indiana. The prototype was integrated into the central Heating, Ventilating, and Air Conditioning (HVAC) system of the home. This research evaluated the Biowall operation to further its potential as an energy efficient and sustainable residential air filtration system.

The main research effort began after the Biowall was installed in the residence. A field evaluation, which involved a series of measurements and data analysis, was conducted to identify treatments to improve Biowall performance. The study was conducted for approximately one year (Spring 2017-Spring 2018). Based on the initial data set, prioritization of systems in need of improvement was identified and changes were imposed. Following a post-treatment testing period, a comparison between the initial and final performances was completed with conclusions based on this comparison.

The engineering and analysis reported in this document focus on the air flow path through the Biowall, plant growth, and the irrigation system. The conclusions provide an extensive evaluation of the design, operation, and function of the Biowall subsystems under review.

CHAPTER 1. INTRODUCTION

The organization of this document follows the approach to conducting the research. The effort centers around articulating the problem statement, posing a research question, identifying the scope of work, and listing overall assumptions, limitations, and delimitations, which also served to keep the research on task. Chapter 1 introduces the research by defining the parameters important to the experimental design. Listed in the following sections are the problem statement, the research question, the scope, the significance, definitions, assumptions, limitations, delimitations, and the hypothesis.

1.2 Problem Statement

Americans spend 90% of their time indoors; where indoor air is 2-5 times more polluted than outdoor air (EPA, 2019). Residential air filtration methods are limited in contaminant removal capability and design life. The limitations in conventional residential air filtration technologies make people vulnerable to indoor air pollution. Consistent indoor air filtration completed to ASHRAE recommendations would reduce Sick Building Syndrome (SBS) related illnesses (ASHRAE, 2016). Botanical Air Filtration and specifically, the Biowall technology, have the potential to help consistently meet indoor air quality standards.

1.3 Research Question

Is the Biowall prototype in a residential home operating within design specifications?

1.4 Scope

The research describes an evaluation of the Biowall prototype located within the ReNEWW home near Purdue University in West Lafayette, Indiana. Observational/experimental studies into the prototype's nominal air flow characteristics, plant growth and behavior, and the functioning of the irrigation system determined what treatments were applied to meet design specifications or improve the systems. The scope of the work was to maximize the system's filtration capability by ensuring that the systems were functioning as designed.

1.5 Significance

In a 2012 commercial building energy consumption survey (CEBES), conducted by the U.S. Energy Information Administration (EIA), 34% of the energy used in commercial buildings within the U.S. went to heating and cooling. A similar survey conducted on residential buildings concluded that 48% of energy consumption in U.S. residences went to heating and cooling (U.S. EIA, 2012). Efforts to minimize the energy consumption of newly developed technologies which effect Heating Ventilation and Air Conditioning (HVAC) energy usage will decrease energy consumption in the U.S. and around the world.

The U.S. Environmental Protection Agency (EPA) reports that on average, Americans spend 90 percent of their time indoors. Advances in HVAC systems lead to increased sealing of buildings. This, combined with the increased use of recycled indoor air puts people at risk of exposure to poor indoor air quality. As far back as 1999 the CBS news show "60 minutes" reported on the negative effects of sick building syndrome (SBS), and how the recycling of contaminated air effects worker productivity.

Botanical air filtration is a concept aimed to improve Indoor Air Quality (IAQ) using a sustainable method while increasing design life compared to current technology. The goal of the Biowall is to remove contaminants (VOCs) from recirculated indoor air. The energy consumption of the Biowall is minimal, periodical filter element replacement is not necessary, and the filtration mechanism is natural (i.e., the plants and their growth media). This forms a system that could have a positive impact on IAQ while taking advantage of a sustainable method as its primary mechanism. Also, it has the potential to reduce outdoor air ventilation rates for maintaining the air quality of a building (Alraddadi, 2016). Therefore, a Biowall could contribute to reduced energy consumption compared to that reported in the energy CEBES survey.

1.6 Definitions

Biowall	The botanical air filter prototype scrutinized during this research.
Building Automation System (BAS)	A BAS combines inputs and outputs of a building control system which allows for the automation of devices and sensors to control the indoor environment and efficiently meet user needs.
Botanical Air Filtration	A biological filter that utilizes aspects of plants to perform a filtration process.
Controlled Environment	A space that utilizes automation and technology to maintain environmental parameters.
Environmental Chamber	An isolated room where all conditions of the environment can be scrutinized, measured, and controlled.
Field Test	A field test is a validation process available to the manufacturing process which scrutinizes the technology under real-world conditions.
Hot Wire Anemometer	A device used to measure air movement.
Indoor Air Quality (IAQ)	A phrase used to describe the condition of air within a building or home.
Sustainable	Meet the present needs without compromising the ability of future generations to meet their needs. (U.N. Report, 1987).
The ReNEWW House	Retrofitted Net-Zero Energy, Water, and Waste (ReNEWW) Home: A cooperative research residential building, sponsored by Whirlpool, located near the Purdue Campus in West Lafayette, Indiana. The Biowall prototype is located within this research home.
Phytoremediation	A biological process which uses plants or microorganisms to remove undesired contaminants from the air, water, or soil.
WebCTRL	The Biowall online BAS control interface.

1.7 Assumptions

The assumption made at the onset of this research is summarized as follows:

- The characteristics of the Biowall at the ReNEWW house, and the properties that affect it were consistent throughout the research data collection period.
- Variations caused by occupants, weather, or other external factors were not considered.

1.8 Limitations

The limitations governing this research are as follows:

- Treatments derived must coincide with the existing infrastructure and algorithm of the Biowall.
- The treatments were limited to the existing Biowall prototype.
- The timeframe of experimentation limited the amount of Biowall systems reviewed.

1.9 Delimitations

The delimitations are as follows:

- The actual bio-filtration mechanism (phytoremediation) and filtration quantification were not evaluated during this study.

1.10 Hypothesis

A subsystem-level assessment of the Biowall prototype will verify system function and identify areas in need of improvement. The treatments imposed because of this work will lead to the prototype running at its design specification level, or better, maximizing the air filtration potential of the prototype.

1.11 Summary

The introductory chapter defines the parameters of this research, including a problem statement and a research question. Definitions of concepts and equipment used to complete this work are provided. The scope, assumptions, limitations, and delimitations are listed to provide a boundary for the topics of this research. Finally, a hypothesis documents the expectations prior to conducting the study.

CHAPTER 2. REVIEW OF LITERATURE

Literature review explores manufacturing product development methodologies, HVAC filtration technologies, botanical air filtration, indoor air quality, controlled environment plant research, and the existing Biowall literature. This review cites publications relevant to the study, particularly as to the design, function, and/or practices of relevant systems of the Biowall prototype at the ReNEWW home.

2.2 Six Sigma and New Product Development

The fundamental thought behind the research described herein was in applying a manufacturing process on the Biowall to drive improvements and record quantifiable changes. The Biowall as it existed at the time of this research was a single prototype installed in a target customer ‘real world’ situation. The prototype was fully implemented into a home with up to three people at a time living in it and thus presented a unique opportunity to validate the system under full operation.

There are many methods for using manufacturing quality control to develop a new product. One well-known method is Six Sigma. It was introduced in 1986 by Motorola to monitor failure data of its products and derived statistics to identify quality concerns (Go Lean Six Sigma, 2012). The appropriate implementation of the Six Sigma method aims to create 99.9996% successful attempts. Maintaining a high success rate serves well for business manufacturing. Designing a consistent level of quality into products is a staple of many successful companies.

The Six Sigma Handbook (Pyzdek and Keller, 2003) interprets the method for achieving a high rate of successful products. As related to production, Pyzdek identifies five overall stages or phases of development leading up to a successful product. They are Define-Measure-Analyze-Improve-Control (Pyzdek and Keller, 2003). In the period between the conception of an actual customer using a component or system, the developers will be most successful if they fulfill each of these five stages.

The Biowall up to the point of this research had been defined. In line with a successful manufacturing theory like Lean Six Sigma (Pyzdek and Keller, 2003), this work initiated a period of Measure-Analyze-Improve onto the system.

2.3 HVAC Development and Regulation

The push to implement HVAC regulation followed a period of growth in the technology. During the late 1990s in the U.S., development of building comfort and control systems for new or retrofitted buildings became a major industry. This development resulted in increased energy consumption. According to the U.S Energy Information Administration (EIA) Commercial Buildings Energy Consumption Survey (CEBES), electrical energy consumption in commercial buildings grew from 38% in 1979 to 61% in 2012 (U.S. EIA, 2012). That growth is largely attributed to the increase in electrically powered HVAC systems implemented during that time. Refrigeration and the rise in computer technology were also contributors to this increase in commercial buildings (U.S. EIA, 2012).

The formation of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) directly relates to the U.S oil crisis in the mid-1970s (ASHRAE, 2004). This was a time that invoked a need to innovate energy usage away from fossil fuels across the board in the United States and abroad and brought the highest energy consuming technologies into focus for improvement. Growth in this area had become significant enough to gain attention from industry standard organizations like ASHRAE, who rose to the forefront of creating standards and codes aimed at maintaining safe building controls and indoor environment technologies while increasing building energy efficiency.

ASHRAE standards take the health and wellbeing of the buildings' occupants into consideration and is a reference to aid in building environmental control companies and manufacturers with system design specifications. ASHRAE Standard 90.1-Energy Standard for Buildings has been widely adopted by countries, states, and municipalities, and is a basic requirement for earning Leadership in Energy and Environmental Design (LEED) certifications. LEED certifications can reward a building owner with tax rebates and a reputation for meeting baseline potential building efficiency guidelines (ASHRAE, 2004).

2.4 Reduce HVAC Energy Consumption

Results of the U.S. EIA CEBES determined that 61% of all commercial building energy consumption is a result, in large part, of expanded use of electrically driven HVAC systems in buildings (U.S. EIA, 2009). Simply said, any innovation that leads to a reduction of energy consumption of HVAC systems will have an impact on the overall energy consumption of buildings.

One method the HVAC industry employs to decrease energy consumption is to recirculate indoor air. Recirculated indoor air is near both room temperature and the desired humidity level. Introducing recirculated indoor air into the HVAC system air supply will require less cooling/heating/dehumidifying from the system and ultimately save energy (Alraddadi, 2016).

The alternative to recirculating air is to draw outside air into the HVAC system. This will supply a more consistent Indoor Air Quality (IAQ) by providing fresh air when introduced into an air supply, the outdoor air may be hot and humid during the summer months, or cold in the winter, as compared to the desired result of indoor comfort. The HVAC system will be required to provide additional energy to heat, cool, and dehumidify the air supply under these conditions (Alraddadi, 2016). The recirculation of indoor air increases the relevance of other processes that make up the HVAC system like air filtration.

2.5 Residential HVAC Air Filtration Technologies

A presentation of widely used HVAC air filtration methods is described in this section. The mechanical air filter shown in Figure 2.1 is the primary method used to clean indoor air in residential buildings. Air filters are designed to improve the quality of air by removing particulate contamination. Filtering is accomplished by forcing return air flow from the HVAC system through the filter. Mechanical air filters like the one shown in Figure 2.1 are generally made of spun fiberglass material, pleated paper, or cloth and are the main line of defense for most homeowners for ensuring appropriate IAQ (Davis, 2015).

Figure 2.1 New air filter.

Air filters vary in their effectiveness in removing contaminants from the air. ASHRAE developed the Minimum Efficiency Reporting Value (MERV) for mechanical air filters. The MERV system establishes a metric for air filter effectiveness that is expressed as a number from 1 to 16, where a higher number indicates a higher level of contaminant removal. The MERV rating chart from ASHRAE Standard 52.2 is included in Appendix A of this thesis. The MERV rating chart identifies that lower MERV rated filters are limited in filtration capability and primarily capture larger particulate matter. Higher MERV rated mechanical air filters remove particulates, as well as contaminants like tobacco smoke and some biologicals.

The limitation of all air filters is revealed through their design life (ASHRAE, 2017). As the filter captures contaminants from passing air, it becomes restricted, loses effectiveness, and risks supplying poor IAQ over time. Figure 2.2 shows a dirty air filter with a relatively low MERV rating that should be replaced. The filter is over 6 months old and physically looks dirty compared to Figure 2.1. Forgotten air filters are common, and a leading source of HVAC malfunction is due to the high restriction of airflow caused by a dirty filter (Davis and Heating, 2015). Dirty or forgotten air filters are a large contributor to poor IAQ to a building. ASHRAE Standard 62.1 (2016) Ventilation for Acceptable Indoor Air Quality recommends that a filter be checked once a month and changed quarterly at a minimum.

Figure 2.2 Dirty air filter to be replaced.

Other residential air filtration methods can target specific contaminants and supplement mechanical air filters. Table 2.1 summarizes techniques that are effective in targeting specific contaminations, but all the technologies have limitations. The EPA (2008) highlights air filtration technologies and their limitations in Table 2.1. For example, UVGI filtration can only target some biologicals; Gas Phase filters target gasses and odors but have shorter design life; PCO cleaners use UV lights and introduce a substance to react with the light to destroy gaseous pollutants but is not completely effective; Ozone generators use UV light with electrical discharge although this is still experimental (EPA, 2008).

Table 2.1. Air cleaning technologies and limitations (EPA, 2008).

Air Cleaning Technologies		**Pollutants Addressed**	**Limitations**
Filtration	Air Filters	Particles	Ineffective in removing larger particles because most settle from the air quickly and never reach filters.
	Gas-Phase Filters	Gases	Used much less frequently in homes than particle filters. The lifetime for removing pollutants may be short.
Other Air Cleaners	UVGI	Biologicals	Bacterial and mold spores tend to be resistant to UV radiation and require more light or longer time of exposure, or both, to be killed
	PCO	Gases	Application for homes is limited because currently available catalysts are ineffective in destroying gaseous pollutants from indoor air.
	Ozone generators	Particulates, gases, biologicals	Solid as air cleaners, they are not always safe and effective in removing pollutants. By design, they produce ozone, a lung irritant.

The importance of the information presented in Table 2.1 (EPA, 2008) and the information within this section shows that HVAC air filtration has limitations. Delayed upkeep of mechanical air filters and the components of supplemental air filtering technologies put at risk the supply of contaminated air to a building or possibly HVAC system failure. The removal of all contamination from an air supply is a difficult task.

2.6 Indoor Air Quality (IAQ)

In a paper called "On the history of indoor air quality and health," the author J. Sundell calculates that more than half of the body's air intake during a lifetime is inhaled in the home (Sundell, 2004). Sundell concludes that as a result, most illnesses caused by environmental exposure stem from indoor air. An enclosed space like a building or a home prevents free air movement. The result of that creates a concentration in the air of both the pollutants that accompany human processes and contaminants embedded in building materials and creates a poor IAQ (Sundell, 2004).

Several factors and practices contribute to the IAQ of a modern building. The HVAC industry is in pursuit of energy efficiency, sparked by the 1970s-oil crisis in the U.S. resources were focused on the issue of venting HVAC treated air out to the environment. Using energy to heat, cool, or dehumidify and then venting it out the window was a waste of energy. This developed the practice of sealing buildings against leaks to the outside (ASHRAE, 2004).

Recirculated indoor air makes up a portion of the air supply introduced into a residential building. HVAC systems use recirculated indoor air as a way of saving energy. Mechanical air filters are effective in filtering out particulates but have limitations; gaseous and/or biological contaminations are not targeted by this technology (ASHRAE, 2017). Mechanical air filters are the primary air filtration method for residential buildings.

The importance of IAQ on a building occupant contributed to the creation of ASHRAE standard 90.1, which indicates that an indoor air supply must be filtered (ASHRAE, 2004). HVAC system designers are required to provide a system which supplies IAQ free of contaminants, hazardous particulates, gaseous byproducts, and VOCs per this standard (ASHRAE, 2004). Conforming to

ASHRAE 90.1 and implementing a regular maintenance schedule is the industry standard for supplying a healthy IAQ to a building.

2.7 Sick Building Syndrome (SBS)

A breakdown in HVAC air filtration processes creates vulnerabilities and raises the possibility of providing to provide poor quality of indoor air. Poor IAQ is known to be a source of acute respiratory illness, allergies, asthma, prolonged coughs, headaches, and tiredness just to name a few. The cause of these symptoms had largely been overlooked in the past, dismissed as common illnesses. The correlation with time spent indoors linked poor IAQ to these symptoms and led to the official recognition of SBS (Fisk, 2000).

Frisk (2000) discusses SBS and explains that a loss in worker productivity leads to lost revenues for businesses. Building occupants may experience SBS when exposed to poor IAQ. Poor indoor air supply can significantly affect worker productivity in commercial/business settings; as workers breathe in contaminated air, they experience SBS symptoms. Addressing SBS brings estimated potential savings of $40-$200 billion a year nationally by reducing worker illnesses caused by poor IAQ (Fisk, 2000).

One outlying point observed by researchers of IAQ filtration (Alraddadi, 2016; Leuner, 2016; Newkirk, 2012; and Rajkhowa, 2016) is the need to address air filtration to ensure a safe supply of recirculated indoor air to a building's occupants. Successful innovation in recirculated indoor air filtration will provide a safe level of IAQ, reduce the overall energy consumption of a building's HVAC system, and decrease SBS related illnesses.

2.8 Botanical Air Filtration

In the late 1960's environmental scientist, Bill Wolverton and his team, working for the U.S. military, discovered that plant roots could be used to filter agent orange from Florida waterways (NASA, 2007). Following this work, the National Aeronautics and Space Administration (NASA) funded the Wolverton team to explore phytoremediation, the process of using the rhizosphere of plants to filter contaminants from an air supply for deep space exploration (Wolverton, 1997). This work quantified the air filtration capability of various plant species.

Based on 27 years of research, "The NASA Guide to Air-Filtering Houseplants" was derived. The plants identified in this study are known for the following: their ability to remove carbon based and VOC contaminants from the air, non-toxicity to human plant owners, ease of growth, and expected lifespan (Rokas, 2017).

Research into botanical air filtration led to the development of a residential application called the Biowall (Leuner, 2015). The Biowall targets VOCs through phytoremediation (Alraddadi, 2016), and some particulates through the selected growth medium (Wang and Zhang, 2011).

2.8.1 The Biowall

The current study builds on research related to Biowalls that has been underway at Purdue University since 2010. Purdue's first Biowall was incorporated into a research home that was built for the 2011 U.S. Department of Energy Solar Decathlon. Subsequent Biowall research was conducted in the Applied Energy Laboratory at Purdue University to increase understanding of plant health and indoor air quality characteristics. Guided by the new information, a second Biowall prototype was developed and evaluated in a laboratory setting before deployment into a research home in spring 2016.

A detailed description of the Biowall systems as they existed at the onset of this research was best described by Hannes Leuner (2016): Design and Evaluation of a Full-Scale Botanical Air Filter to Improve Indoor Air Quality in Energy Efficient Buildings. Topics, systems, and procedures from the literature which are important to this research are discussed in the following subsections.

2.8.2 The ReNEWW Home

The botanical air filter prototype (the Biowall) is installed in the Retrofitted Net-Zero Energy, Water and Waste (ReNEWW) Home in West Lafayette, IN. Figure 2.3 shows that it is a typical bungalow style home. The home was built 80 years ago and was fully renovated as part of the ongoing research within it. The ReNEWW home utilizes local resources to supplement demand and meet an annual net-zero energy goal.

Figure 2.3 The ReNEWW home in West Lafayette, Indiana.

The ReNEWW house in Figure 2.3 has a goal higher than net zero energy. It aims to match annual living consumption in energy and water with local resources and renewable systems output. The ReNEWW Home employs photovoltaic (PV) electricity, geothermal heating/cooling, rainwater catchment, and filtration, solar thermal water heating, high-efficiency appliances, smart building automation, and botanical air filtration to meet the net-zero energy goal (Whirlpool, 2017).

2.8.3 The Biowall Prototype

The Biowall is the prototype botanical air filter reviewed during this research. It uses plants and phytoremediation to filter VOCs from the indoor air supply of the ReNEWW home. The Biowall prototype was designed and built prior to this research and orients four plant trays in a vertical configuration to have air pulled through them (Rajkhowa, 2016).

The Biowall prototype is an integral part of the ReNEWW home HVAC system and is positioned at the living room intake air duct. While the HVAC system is meeting heating or cooling demands of the home, the air is pulled through the root environment of the four plant trays, initiating the bio-air filtration process to occur. This system utilizes a Building Automated System (BAS) manufactured by Automated Logic to operate the different functions, sensors, and systems that make up the Biowall. The BAS allows for automation of the growth systems, records data, and makes that data available online through a website that can be monitored and facilitates remote operation (Leuner, 2016).

Figure 2.4 is a block diagram that breaks down the design and operation of the Biowall as defined by Rajkhowa (2016). The diagram in Fig. 2.4 illustrates that the system combines plant growth, technology, engineering design, automation, and research into a concept that seeks to improve the IAQ of residential buildings (Rajkhowa, 2016). The Biowall provides a controlled environment to facilitate plant growth which in turn completes air filtration.

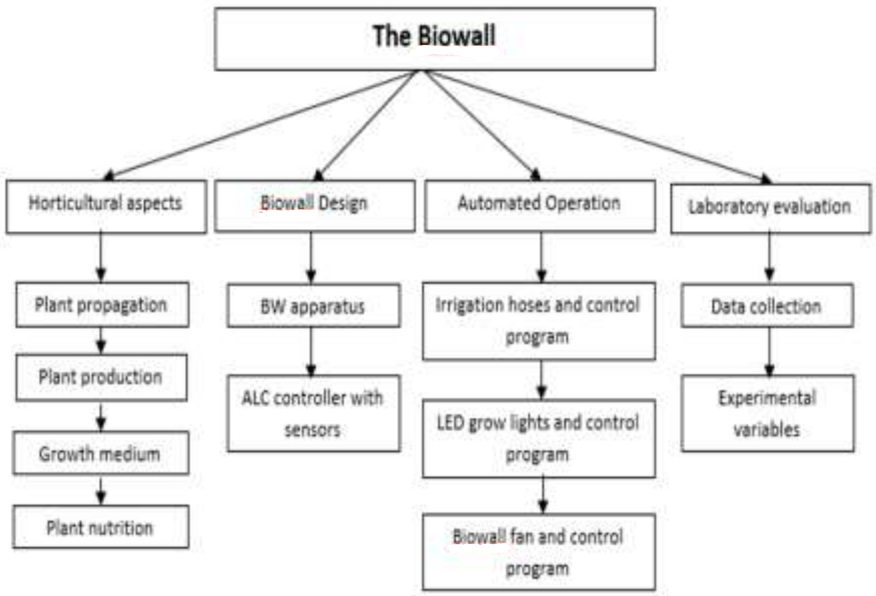


Figure 2.4 Block diagram breaking down the Biowall design and operation (Rajkhowa, 2016).

2.8.4 Air Flow Through the Biowall

The design of the biowall requires air to flow through the plant trays when the ReNEWW home HVAC system is turned on. Facilitating the phytoremediation process allows microbiology within plants roots to filter out VOCs from the passing air as per Wolverton (1997). Air is pulled through one of the four plant trays and converges into a single duct which feeds the HVAC supply. A side view schematic with arrows representing the intended air flow path from Leuner (2016) is referenced in the Appendix.

2.8.5 Plant Irrigation

Figure 2.5 shows the Biowall irrigation plumbing schematic. The figure illustrates that the irrigation system of the Biowall uses the home water supply. Water is supplied to the plants through a 3/8-inch soaker hose located at the bottom of each plant tray. The BAS runs a computer script which executes the daily watering interval. When the solenoid valve is activated, water is delivered to the bottom of each plant tray (Leuner, 2016).

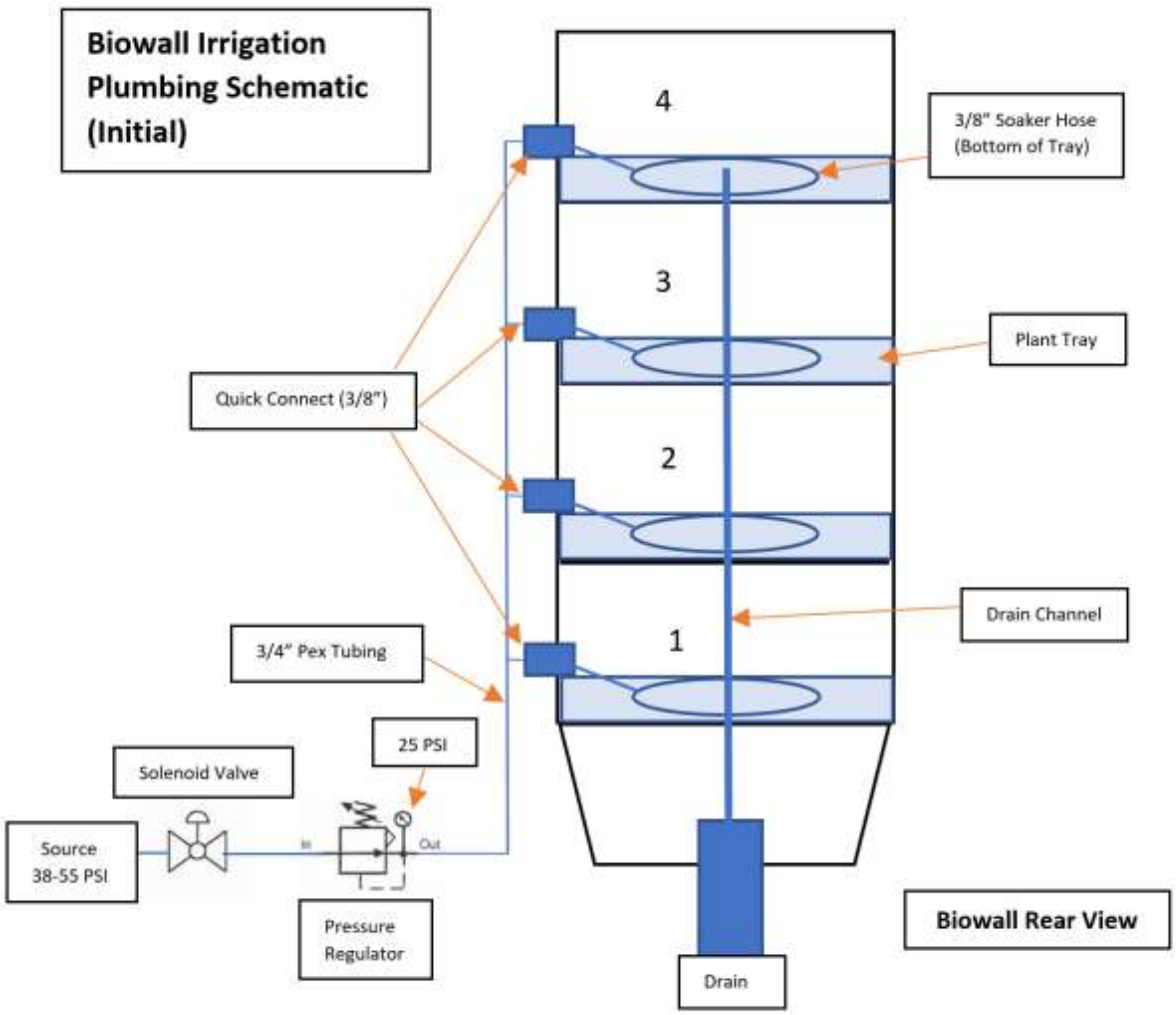


Figure 2.5 Biowall irrigation plumbing schematic (rear view).

The ReNEWW home utilizes a rainwater catchment and filtering system as the primary water supply (~38 PSI). When the rainwater supply is depleted, the water source switches to West Lafayette City water supply (~55 PSI).

The Biowall irrigation system supplies moisture to the plant trays through a 3' length of 3/8" soaker hose arranged in a spiral and positioned at the bottom of each plant tray under the growth media.

Figure 2.6 is a picture of the soaker hose configuration from Leuner (2016). The figure shows that the 3/8" soaker hose is positioned above a thin layer of growth medium and tied in a spiral to the bottom of the plant tray. The hose is then covered with growth medium and plants. A quick connect fitting is positioned at the inlet of the hose to connect to the Biowall plumbing and is capped at the end.

Figure 2.6 Biowall plant tray and soaker hose orientation.

Specifications of the Biowall irrigation system are summarized as follows (Leuner, 2016):

- Solenoid valve operated.
- Activated by the BAS based off a daily irrigation schedule.
- Irrigation cycle: 15 sec/day.
- A soaker hose is located at the bottom of the plant trays, in a spiral orientation.
- The average flow rate of 2.39 L/min per tray.
- Functioning pressure regulated at 25 PSI.
- Quick disconnect of soaker hose positioned at each tray for easy removal.

2.8.6 Biowall Lighting

The lighting system of the Biowall is operated by the BAS to turn the lights on and off based on a daily schedule. Figure 2.7 shows one plant shelf of the Biowall and the light emitting diodes (LEDs) positioned above. The system utilizes three 12" strips of broad-spectrum plant growth LEDs in series per tray (Fig. 2.7). The LEDs are held in position with heat resistant double-sided adhesive (Leuner, 2016).

Figure 2.7 A single Biowall plant tray shelf with broad-spectrum plant growth LEDs.

Leuner (2016) explains the constraints in the Biowall lighting design. In most cases, an indoor Biowall will not have enough natural lighting to support plant growth. Plant growth LEDs were used to supply the plant trays with adequate photoperiod and light intensity. Specific lighting frequencies are beneficial to plant growth and flowering primarily within the red and blue portions of the visible spectrum. However, the combination of these two colors alone provides a light that is not comfortable for human use.

To accommodate human comfort while meeting the lighting demands of the air filtering house plants, the LED brand Tsujiko Co. Ltd.'s model EL-NO1-LT104F-DQM-D2420 are used in the Biowall for plant growth light and an eye-pleasing look. The light appears as soft white.

The specifications of the lighting system are summarized below (Leuner, 2016):

- LED Brand: Tsujiko Co. Ltd.'s EL-NO1-LT104F-DQM-D2420
- Quantity: Three 12" strips per tray (in series)
- Voltage: 24VDC
- Photosynthetic Available Radiation (PAR): 77.5 µmol/m^2s
- Frequency Wavelength: Approx. 430 nm

- Lighting Interval: 9.5 h/day
- LED distance from tray: 12"

2.8.7 Biowall Plant Trays and Fertilization

The Biowall utilizes a porous growth medium to pull air through the plant's roots. The growth medium consists of 40% coconut fiber, 40% Growstone, 20% activated carbon pellets. The growth medium mixture does not have nutrients to offer plants (Rajkhowa, 2016).

The tray and Biowall are made of food grade stainless steel. The dimensions of one tray are 18" x 22" x 4." To promote uniform air flow throughout the Biowall, various sized perforated holes (large up front, small in back) are cut out from the bottom of the tray. The plant tray is filled with the growth medium mixture and the plants are established in the growth medium to allow the roots to grow.

To enable survival during the exposure of air passing by the roots, the plants required a period of acclimation to the plant trays. The acclimation period was 3-6 months within a plant nursery environment. Leuner (2016) proposed that to promote efficient botanical air filtration, the plant and its roots need to be healthy.

Rajkhowa (2016) explains that fertilization is the key to maintaining a healthy plant. While the plants are acclimating to the Biowall plant trays, nutrients are delivered bi-weekly to the plants through an aqueous solution. The fertilizer (FloaDuo) is a water-soluble plant fertilizer formulated in A and B solutions. The recommendation is to use the 'strong grow' blend (3-parts A: 1-part B) (Rajkhowa, 2016). The strong grow blend encourages root growth during early shoot development.

While the Biowall plant trays of the prototype are filtering air, Osmocote smart release plant fertilizer pellets (outdoor/indoor) are to be added every six months at half the recommended amount (Rajkhowa, 2016). The use of fertilizers must take into account exposure to the residents of the home and must not affect human health.

2.9 Air Filtering Plants

The NASA Clean Air Study (1989) was conducted by NASA and the Associated Contractors of America (ACOA). It identified indoor house plants as capable of removing toxins from the air. The goal was maintaining clean air within space capsules. The study identified that volatile organic compounds (VOC) such as benzene, formaldehyde, and trichloroethylene are removed from the air by having plants growing within an indoor space (Wolverton et al, 1989).

In Plants and Soil Microorganisms: Removal of Formaldehyde, Xylene, and Ammonia from the Indoor Environment (Wolverton, 1993), research into a series of air filtration experiments using house plants was presented. Plant species VOC removal rates were presented dependent upon temperature and pot size. House plants were used for their long life as well as ease of growth and access.

Several sources summarized the results of The NASA Clean Air Study (Wolverton et al, 1989) to provide a list of the top air filtering plants. For example, the article; NASA Reveals a List of the Best Air-Cleaning Plants for Your Home (Rokas, 2017) discusses the NASA Clean Air Study and recommends plants to be used for air filtration purposes. The plant growth experiment completed within this research followed the NASA Clean Air Study for species section and practices.

2.10 Plant Experimentation in Controlled Environments

The North Central Extension & Research Activity-101 (NCERA-101) is a committee of industry professionals organized by the United States Department of Agriculture (USDA) to provide information to plant scientists regarding controlled environment experiments. NCERA-101 has published a set of guidelines that can be used to measure and report on plant growth experiments conducted in a controlled environment (controlledenviroments.org). The establishment of an international standard for recording data from and reporting on plant experimentation within a controlled environment simplifies experiment replication and verification. The Minimal Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms or Chambers is published on the NCERA-101 website (controlledenvroments.org) and is referenced in the appendix of this paper. The Biowall provides a controlled environment for plant growth and thus Biowall studies environment parameters reported in this thesis follow the NCERA-101 guidelines.

2.11 ASHRAE Handbook Fundamentals: Measuring Air Flow Through a Duct

The ASHRAE fundamentals handbook (2017) defines recommendations for measurement and analysis of parameters related to HVAC systems.

The handbook illustrates the pattern of air velocity measurement points in rectangular or circular ducts (Figure 2.8). To determine the air flow through a duct, the ASHRAE fundamentals handbook (2017) recommends using a hot wire anemometer to record multiple air velocity measurements. Understanding that the air flow through a duct will not be uniform throughout, the recommendation calls for taking multiple air velocity measurements at strategic points as shown in Figure 2.8 and calculating the average of the total measurements to estimate the air flow rate.

Measurement points of a rectangular duct are determined through a given fraction multiplied by the width or height (Fig. 2.8). A circle multiplies the diameter by the given fraction and repeats the measurements every 60 degrees from the x-axis. An average of the measurements will represent a velocity in feet per minute (ft/min). To determine the air flow in cubic feet per minute (CFM), multiply the velocity (ft/min) by the area (ft^2). In general, air velocity is minimal at the walls of the duct and greatest at the center.

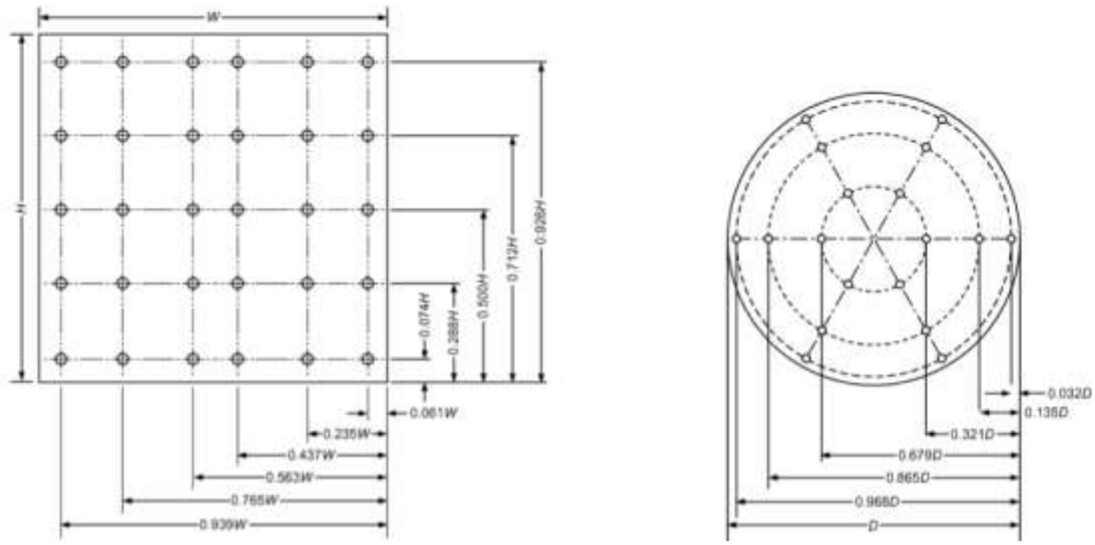


Figure 2.8 ASHRAE Handbook-Fundamentals air flow through duct measurement point locations in rectangular and circular ducts.

ASHRAE reports the result to be deflated by 3% to 4% and is a good approximation to determining the volumetric flow rate at that location (ASHRAE, 2017).

2.11.1 Hot Wire Anemometer and Air Velocity Measurement

The hot wire anemometer used for this research is the TSI VELOCICALC Plus 8386 (Figure 2.9). It was set to record air velocity in feet per min (ft/min). The device has a telescoping wand that makes point measurements of air velocity. A grid of measurements can be recorded and used to estimate air flow rates.

Figure 2.9 Hot wire anemometer TSI VELOCICALC Plus 8386.

2.12 Summary

The literature review presented in this chapter explored past works which have importance to the design and operation of the Biowall at the ReNEWW home. This information provided insight into understanding the Biowall and informed the researcher of system specifications. Based on this review and presented in the following chapters, the establishment of practices and identification of resources needed to complete the evaluation were made.

CHAPTER 3. RESEARCH METHODOLOGY

The Biowall prototype at the onset of this research presented a unique opportunity to test the systems within its target environment. Following a method of product development like the one discussed in The Six Sigma Handbook (Pyzdek and Keller, 2003), this work took advantage of the real-world situation of the Biowall to "Measure-Analyze-Improve" the systems already in place before proceeding with full-scale production and commercialization.

The physical testing of the Biowall prototype identified anomalies to various systems. This research took an experimental approach to apply treatments to those anomalies. This chapter explains the experimental design and documents the initial state of the systems under review. Completed summer 2017 through spring 2018, three anomalies were targeted: the air flow behavior through the Biowall plant trays, plant growth experimentation, and plant irrigation optimization.

3.1 Experimental Design

The experiment applied the Six Sigma Handbook method of product development to produce identifiable instances of system changes on the Biowall prototype. The overall structure of the experiment recorded initial data, applied a treatment, recorded final data, and analyzed for changes. This method was applied to three specific aspects of the Biowall. Airflow analysis and irrigation optimization items followed the Field Experiment, One Group Pre-Test/Post-Test design. This method isolates the subsystem observed in a field environment, performs intent-based measurements and documentation, and applies an experimental treatment.

The plant growth experiments were best fulfilled by using the Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms or Chambers (NCERA-101). The study evaluated environmental conditions, plant species growth, and treatments applied to the plant trays. The outcome documented plant tray set up and plant growth within the Biowall. This work improved the function of the Biowall and aesthetics as well as expanded the number of demonstrated plant species grown within the Biowall environment.

Data and observations recorded as part of these experiments resulted from weekly Biowall visits, and BAS trend data. The regular schedule fulfilled the pre-test/post-test data requirement and the implementation of treatments.

3.2 Initial Assessment and Methodology

Beginning in January 2017, an assessment of the Biowall prototype under full operational conditions was conducted. Trends in physical measurements and other observations were used to assess the Biowalls nominal characteristics. Through this assessment, areas for subsystem improvement, better management, and upgrades were identified.

The method imposed a validation to the subsystems that make up the prototype. The result included a list of anomalies for Measure-Analyze-Improve. To accommodate the timeframe of this research, measuring and modifying the subsystems were prioritized. This process was instigated by the researcher and validated by the Principal Investigator (PI) to weigh the impact that added improvements could have on the overall effectiveness of the Biowall.

From the initial assessment of the Biowall function, three aspects were the focus during the scope of this research and were topics evaluated under the experimental design. The topics are summarized below:

1. **Air Flow Analysis**-Determining the air flow path through the Biowall plant trays provided a representation of the bio-air filtration process and quantified the amount of passing air fulfilling the design path.
2. **Biowall Plant Growth**- Demonstrated plant growth and increased understanding of plant behavior within the Biowall environment is essential to the viability of the concept. Just as important is aesthetic value; a product of superior functionality is not as commercially viable without aesthetic appeal. This study is a vehicle to address issues related to plant growth and plant tray set up within the Biowall.
3. **Irrigation Optimization**-The plant irrigation system of the Biowall is vital to maintaining healthy plant trays and thus bio-filtration capability. The work to optimize this system

assessed the initial configuration and worked within the established framework to derive a treatment which will improve moisture delivery to all four plant trays.

The following sections document the methodology used to complete the described work.

3.3 Air Flow Analysis

The Biowall design pulls air through the plant trays to complete the filtration process before sending it to the HVAC system for heating or cooling. Air flow through the plant's roots is essential for the phytoremediation process to be completed. During the initial validation assessment, evidence indicated that air was bypassing the plant trays.

The audible sound of bypassing air was noticed during a regular visit and initiated the process to investigate air flow through the Biowall. The finding was an indication that not all the air was following the intended path. With an understanding that air not exposed to the plant’s roots will not complete the filtration process, an air flow analysis was prioritized.

3.3.1 Initial Air Flow Assessment

Following the indication that air was flowing outside of the plant growth trays, an investigation into the air flowing through the Biowall, and the conditions within the subsystem which may affect it, was initiated. The investigation observed the physical condition of the air seals, the consistency of plant growth medium, the change in pressure from inlet to the outlet (delta pressure, dP), the BAS trend data, and documented air velocity at strategic points within the Biowall.

3.3.2 Plant Tray Air Seals (Initial)

Figure 3.1 shows tray 3 during the initial phase of this experiment. An initial inspection of the spaces between the Biowall and Biowall housing revealed the presence of growth medium rocks and debris jammed between them. This finding is indicated with arrows in Figure 3.1. Wedged debris between the Biowall housing and plant trays compromised the air seal.

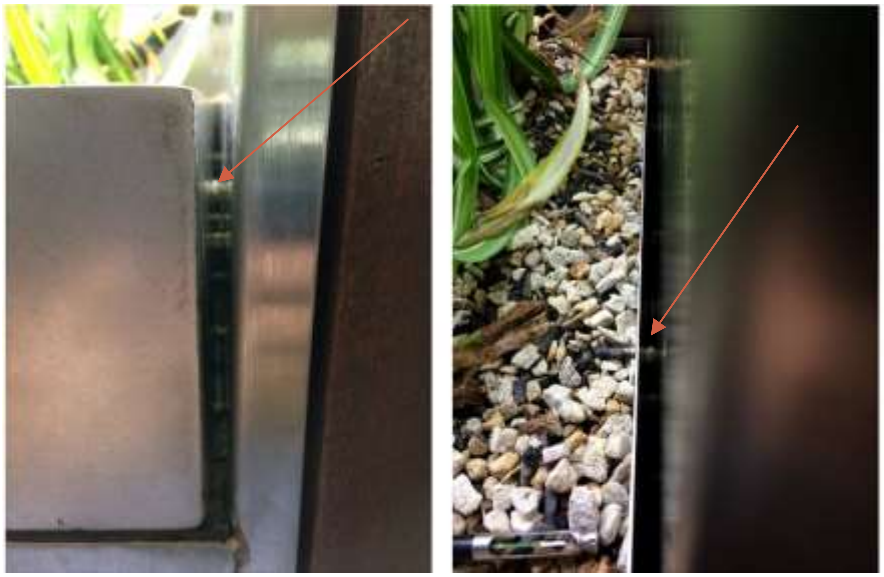


Figure 3.1 Initial air seal assessment revealed Growstone rocks between the plant trays and Biowall housing.

To inspect the air seals, the Biowall plant trays were removed from the housing to get a clear view of the conditions under the trays and between the housing. Figure 3.2 shows the Biowall frame following this step. Note: The plant tray shelves are numbered from the bottom (tray 1) to the top (tray 4).

Figure 3.2 The Biowall housing with plant trays removed. Tray 1 (Bottom). Tray 4 (Top).

The rocks and growth medium found outside of the plant trays as seen in Figures 3.1 and 3.2 are an indication that the trays were overfilled. A visual inspection of the Biowall indicated that the plant tray appeared to have inconsistent depths of growing medium with overflow. A measurement of the growth medium within the plant tray confirmed the observation.

Figure 3.3 shows plant tray 4 in its initial condition. The minimum and maximum depth measurement points are indicated with numbers and arrows. The physical measurements (top to bottom) of the growth medium depth in this tray are 1). 87.4 mm (the growth medium is below the tray rim); and 2). 117.6 mm (the growth medium is higher towards the center). The difference in depth between these two measurements is 30.2 mm. The three other trays show a similar result.

Figure 3.3 Tray 4 at an initial condition shows varying growth medium depths. (1) minimum, (2) maximum growth medium depth.

The condition of the plant trays observed during the initial air seal assessment indicates that varying growth medium depths and overflow negatively affect the Biowall airflow design. The actions taken to address these initial findings related to the plant growth medium are presented in the following sections.

3.3.3 Initial Air Flow Analysis Experimental Markers

A close look into the Biowall housing, plant tray seals, growth medium depth, and trend data defined the initial conditions of the airflow analysis. Four observations are identified below as a result of the initial assessment. These issues directed the air flow path to the outside of the plant trays instead of through them.

1. Growstone from the plant growth medium is an obstruction between the plant trays and Biowall air seals. Debris between the air seal and tray can compromise the seal (Figure 3.4, # 1).
2. White marks on the side of the Biowall housing indicates that growstone rocks have been wedged between the plant trays and the housing wall. This issue is also apparent in Figure

3.1. Wedged rocks will deform the metal over time and can cause permanent structural damage to the plant tray air seal design (Figure 3.4, # 2).

3. The tray seals on the rear corners of all four plant tray shelves are torn. A torn air seal opens a pathway for air to bypass the plant trays (Figure 3.4, # 3).
4. Inconsistent growth medium depth shown in Figure 3.3 creates a higher restriction in the areas with more growth medium. This forces inconsistent air flow through the trays. The inconsistency in growth medium depth and overflow is the source of growstones and debris found during the initial assessment. This issue will be addressed as part of the plant growth experiment.

Note: Figure 3.4 is a picture of the top tray shelf (tray 4) with the plant tray removed from the Biowall at the time of initial inspection.

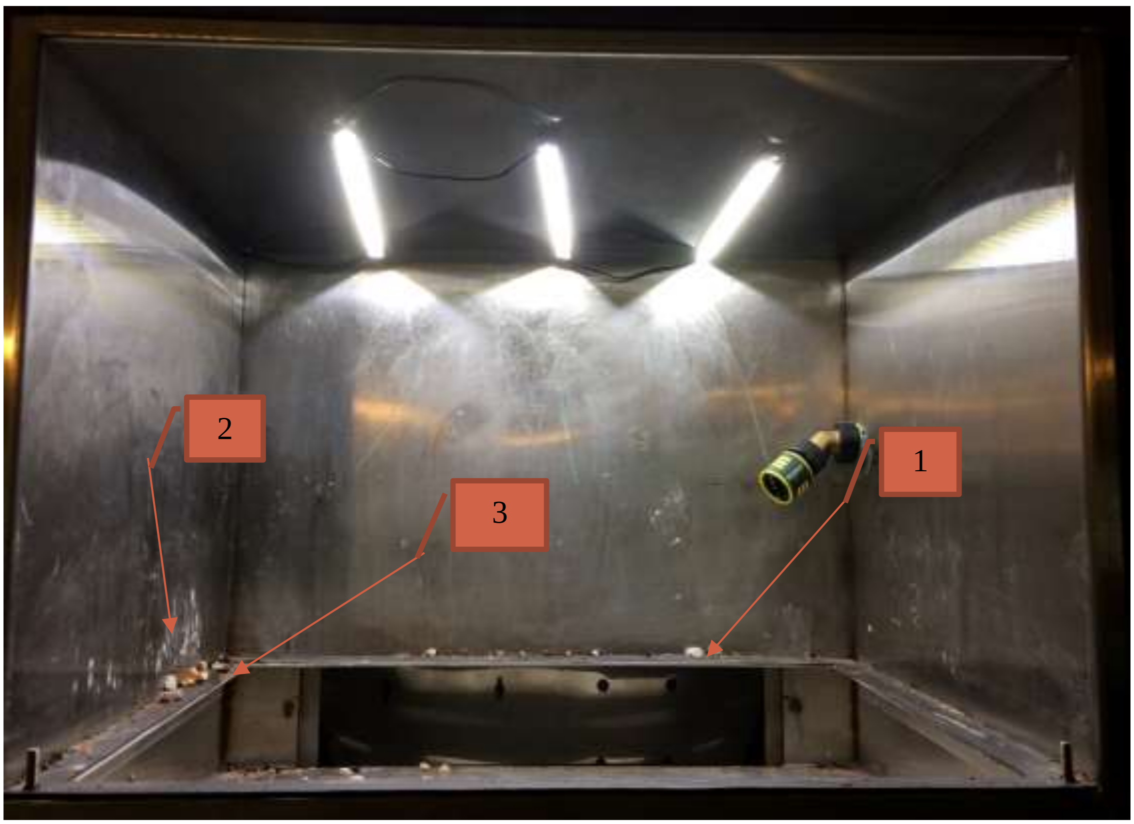


Figure 3.4 Biowall shelf 4 with tray removed: 1). Growstone obstructing air seal. 2). Signs of Growstone wedged against the housing. 3). Damaged/torn air seals.

The observations of the initial assessment as exhibited in Figures 3.1 to 3.4 supported the initial conclusion that air was bypassing the plant trays. At this point, a pause in action was taken to quantify the air path through the Biowall prior to applying treatments to address the issues which are a fulfillment of the initial data requirement of the experimental design.

3.3.4 Air Flow Profile

The air flow profile of the Biowall was completed with direction from The ASHRAE Handbook-Fundamentals; Measuring Air Flow Through a Duct (2017) as referenced in section 2.11. An initial air velocity profile that recorded measurement through and around the plant trays was completed. The plant trays were treated as a rectangular shaped duct. Hot wire anemometer model VELOCICALC PLUS MULTI-PARAMETER VENTILATION METER 8386 was used to record air velocity (ft/min) within the Biowall (Fig. 3.5).

Figure 3.5 Hot Wire Anemometer (TSI VELOCICALC Plus 8386) used to record air velocity readings through the Biowall.

The anemometer (Fig. 3.5) probe was extended to the desired measurement location. The conditions during data collection were completed with the HVAC system off, and the Biowall supplemental fan on high. This setting was selected for its controllability; the supplemental fan is activated easily with the BAS.

Using the hot wire anemometer, a series of measurements was completed to create an air velocity model of the Biowall at the time of measurement. The data can be seen in Appendix K. Data were collected at 44 key positions within and around the Biowall plant trays (11 data points per tray). These measurements, entered into a CAD model, provide an initial and post-treatment air velocity profile. The sum of air velocity measurements within the trays compared to outside the trays quantifies a percentage of the air measured.

Figure 3.6 shows the measurement points for one plant tray shelf. The X's in Figure 3.6 indicates the measurement locations used to record air velocity within the shelf. The red X's represent measurement points recorded within the plant tray. The blue X's represent measurements taken outside of the plant trays (between the cracks). This process was repeated within each of the four plant tray shelves to create an air velocity profile.

Figure 3.6 Initial air measurement positions per tray indicated with an X. Red). Measurement within the tray. Blue). Measurement outside the tray.

3.3.5 Air Flow Treatment Methodology

Following documentation of the initial air flow condition through the Biowall plant trays, three treatments were imposed to restore the system to its designed air flow state:

Treatment 1: The first action removed all debris found during the initial inspection from the air seals of the Biowall (Figure 3.7). Figure 3.7 is a picture of one tray shelf with the plant tray removed following the cleaning. The tools used to clean the shelves were a shop vacuum, spray bottle with water, and a clean cloth. The aim was to remove all obstacles from the air seal insulation areas.

Figure 3.7 Biowall plant shelf with tray removed following Treatment 1. The arrows point to tearing in tray air seals.

As indicated with arrows in Figure 3.7, the cleaning of the debris revealed tears in the air seal insulation. A pattern of torn seals in the rear corners of each plant tray was revealed. This is represented through the picture of tray 2 in Figure 3.7. Damage to the air seal can create pathways for air to bypass the plant trays.

Treatment 2: Repair the torn areas of air seal throughout each Biowall shelf. The repair of tray 2 can be seen in Figure 3.8. All torn insulation was removed and replaced with similar insulation material.

Figure 3.8 Tray 2 following Treatment 2 showing replacement of torn air seal insulation.

Treatment 3: Establish plant trays to meet design specifications. The makeup of the plant trays determines air flow through them. Critical issues identified during the initial air flow assessment of the trays: mixing a growth medium that is consistent throughout all the plant trays; establishing an even growth medium depth within each plant tray; and the relocation/optimization of the irrigation hoses.

Treatment 3 was a result of the two experiments developed in detail in the following sections. The post-treatment results are presented within an air velocity profile shown in Chapter 4.

3.4 Plant Growth Experiment

Issues found during the initial assessment of the Biowall systems related to the plant trays are reported in the air flow methodology of the previous section. Fulfillment of Treatment 3 of the air flow experimental methodology will require the establishment and deployment of new plant trays to the Biowall in place of the initial set. The need to implement improved growth medium conditions initiated a review of Biowall plant growth in general. The plant growth experiment was the method used to meet those needs.

The Biowall plant growth experiment was conducted to:

1. Identify initial design critical conditions within the Biowall plant trays.
2. Follow literature (Rajkhowa, 2016) and refer to initial findings to implement plant trays which meet the Biowall design requirements.
3. Practice a vital component of the Biowall concept (plant growth).
4. Provide replicable data for future Biowall plant tray growth and aesthetic considerations.

3.4.1 Initial Plant Tray Analysis

Building on an evaluation of the conditions recorded during the initial air flow assessment, the plant tray assessment documents the initial conditions of the Biowall plant trays. The Minimum Guidelines for Measuring and Reporting Environmental Parameters for experiments on Plants in Growth Rooms or Chambers document (NCERA-101) aided this assessment by indicating functions that are vital to plant growth. The parameters reviewed as part of the initial assessment are plant tray contents, growth medium depth, growth medium consistency, Photosynthetically

Available Radiation (PAR) intensity, and distribution, photoperiod, air flow, temperature; humidity, pH and nutrients, water delivery, and plant measurements. The parameters found to be out of design specification during the initial assessment are presented below:

- Revealed during the initial air flow assessment, the growth medium within the plant trays was at varying depths. This inconsistency was the source of debris which compromised the air seal design. Figure 3.9 shows tray 4 during the initial plant tray assessment. As reported in section 3.3.2, the physical measurements of the growth medium depth in this tray are 1). 87.4 mm (the growth medium is below the tray rim); and 2). 117.6 mm (the growth medium is higher towards the center). The difference in depth between these two measurements is 30.2 mm. The three other trays show a similar result.

Figure 3.9 Tray 4 during the initial assessment shows that the growth medium within the plant tray has inconsistent depths.

- Observed during the initial assessment, tray 3 of the Biowall showed light shading in some areas. Figure 3.10 is a picture of tray 3 during the initial assessment. In this image it can be seen that: 1). The spider plant (*Chlorophytm comosum)* was the dominant plant in this tray; 2). Plant leaves were blocking the LED lighting from the lower canopy; 3). The shading at the bottom right corner and crowding of the spider plant eliminated ground crawling plants.

Figure 3.10 The Biowall Tray 3 during the initial assessment shows the spider plant (Chlorophytm comosum) as the dominant plant.

- As part of the initial assessment, a test plant tray was deployed in the Biowall for observation. Figure 3.11 shows a picture of the test tray installed in the Biowall. In it were a pair of 5-year-old Golden Gate Ficus bonsai trees. The trees became desiccated and died over a short period of filtration.

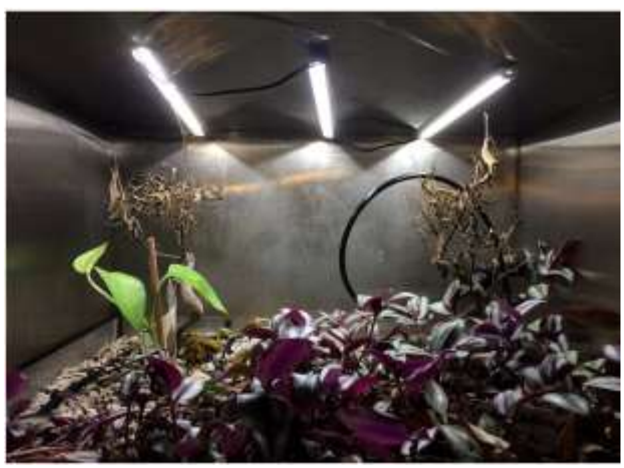


Figure 3.11 A test plant tray with two dead 5-year-old ficus trees.

3.4.2 Plant Growth Experiment Guidelines

A list of goals and considerations for the plant experiment developed following the observations made during the initial plant tray assessment. Addressing the items as part of the plant growth experiment will help meet design specifications. These are listed below:

1. The growth medium within the trays should have an equal constancy and depth to promote equal air flow and avoid overflow to the plant tray air seals.
2. Plant orientation within the tray should consider the species growth characteristics to avoid LED shading observed during the initial plant tray assessment (Fig. 3.10), i.e. tall plants in the back; smaller or ground crawling plants up front.
3. A period of acclimation of the plants to the plant trays and growth medium prior to implementation in the Biowall will allow for roots to establish and increase plant survivability.
4. Documentation of the Biowall environmental parameters during the experiment was intended to meet the Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms or Chambers. These data will enable replication of the experiment and the conditions encountered during this study.
5. A demonstration of growing various air filtering plant species within the Biowall plant tray environment will increase the aesthetic potential of the plant trays.

3.4.3 Plant Experiment Methodology

The procedure for implementing the Biowall plant growth experiment referenced the literature (Rajkhowa, 2016) for growth medium consistency, fertilization, and designed parameter settings. Completion of the experimental design required a second and third set of new Biowall trays to be prepared. The third set of trays replaced the second set following removal from the Biowall for review and post-experiment measurements. Based on the initial validation assessment, the issues related to the plant trays were addressed within the new sets of trays. The resources used and method employed during the experiment are explained in the following sections.

3.4.4 Biowall Environmental Measurements

The environmental conditions during the plant growth experiment were recorded to best fulfill the Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms or Chambers document (NCERA-101) from the literature review. These data can be found in the appendix.

3.4.5 Plant Selection

The NASA Clean Air Study (Wolverton et al, 1989) led to the identification of air filtering plants. These plants have been experimentally shown to filter contaminants (VOCs) from the air through microbes that survive within the plant roots. The plants were chosen for their documented ability to grow in low light, have low fertilization requirements, be easy to care for and have aesthetic value. A selection of plants was made from the NASA Clean Air Study to perform the plant growth study within the Biowall environment. The common and scientific names of the plants used in this study are listed in Table 3.1.

Table 3.1 List of plants selected for the Biowall plant growth experiment.

Common Name	*Scientific Name*
English Ivy	*Hedera Helix*
Ficus	*Ficus Benjamina*
Golden Pathos	*Epipremnum Aureum*
Heartleaf Philondendron	*Philodendron Cordatum*
Marginata	*Dracaena Marginata*
Oyster Plant	*Tradescantia Spathacea*
Spider Plant	*Chlorophytm Comosum*
Wandering Jew	*Trascenda Zebrina*

3.4.6 Growth Medium Mixing

To ensure a consistent growth medium mixture throughout all four plant trays, a single large batch was mixed in a cement mixer. The recipe followed Rajkhowa (2016). The growth medium for this study was made up of 40% Botanicare Cocogro Coir fiber, 40% Growstone; 20% activated carbon pellets (by volume).

3.4.7 Plant Tray Orientation

Establishing new plant trays addressed the findings observed during the initial assessment. The plants used were propagated from existing plants or bought from a nursery in 3-inch pots. Over the summer of 2017, a plant nursery was created to foster new plant trays. Four new plant trays were established and given time to acclimate to the growth medium.

To collect final data from the second set of plant trays at the end of the experiment, the third set of trays was established in the nursery. The third set of plant trays allowed the removal of the second set from the Biowall to collect final measurement data.

Figure 3.12 shows one of the trays during its acclimation period in the nursery. The nursery conditions seen in Figure 3.12 followed Rajkhowa (2016) growth recommendations and allowed for root spread to occur throughout the trays. The method to address the issue of shading seen during the initial assessment is shown in the figure; the big plant (*dracaena marginata)* was planted in the center and towards the back of the plant tray. The smaller plants (*epipremnum aureum and philodendron cordatum)* were planted around the large plant and towards the front. This format was followed throughout all the plant trays and encouraged similar PAR to all plants within the tray.

Figure 3.12 A new plant tray acclimating in the plant nursery.

To address growth medium overflow into the air seals and inconsistent growth medium depth, the growth medium was maintained at 90 mm in depth throughout the entire tray (13 mm below the tray rim). This is best seen in Figure 3.12 by referencing the top of the growth medium to the rim of the plant tray.

3.4.8 Plant Experiment Implementation

In October 2017, the new plant trays were deployed to the Biowall and the initial set of plant trays were returned to the plant nursery. The initial set of trays were dissembled to gain dimensional measurements of the plants and roots. During the six-month final validation period, the new plant trays in the Biowall were observed and environment parameter data recorded. During this time, the third set of plant trays was established to begin the acclimation process in the nursery.

After six months of active filtration within the Biowall, the second (after) set of plant trays were returned to the nursery for final plant measurement and documentation. These measurements are reported in Appendix K.

3.5 Biowall Irrigation Optimization

The initial validation assessment of the irrigation system indicated that the optimization of the water delivery location and total volume delivered to the tray could be improved. Added work into the irrigation system had significant effectiveness throughout the Biowall plant growth systems and was prioritized into this research. The optimization worked within the existing Biowall plumbing to develop a plant soaker hose configuration which restricts water flow to a low level, delivers a more consistent plant tray saturation and provides conditions for more consistent air flow. The following sections discuss the conditions found during the initial assessment and defines the methodology used in the design.

3.5.1 Initial Irrigation Assessment

The initial assessment of the irrigation system revealed inconsistencies from design specifications. The findings are highlighted as follows:

- As part of the initial assessment, the growth medium was removed from the initial set of plant trays to observe the irrigation hose condition. Figure 3.13 shows a picture of tray 3 with the growth medium removed. The inspection showed that the soaker hose position did not have a layer of growth medium beneath it. Also, the soaker hose was not oriented in a consistent spiral (Figure 3.13). Referenced from the literature review in Figure 2.6, the soaker hose should be positioned on top of a layer of growth medium and tied in equal spacing to the bottom of the plant tray. This is a variation from the Biowall design.

Figure 3.13 Tray 3 with growth medium removed after initial assessment reveals the irrigation soaker hose condition.

- Observing the soaker hose position in Figure 3.13, the hose is obstructing some of the holes at the bottom of the plant tray. The initial air flow analysis discussed in section 3.3 identified that air flow through the plant trays was limited. The soaker hose is serving as an obstruction in Figure 3.13 and is a further restriction to the air flowing through the Biowall as designed.

- Figure 3.14 is a picture of plant tray 2 from the initial set of plant trays. A look into the growth medium in the picture revealed that Osmocote fertilizer pellets intended to feed the plants were not dissolved (highlighted with red circles). An added search into the remaining growth medium from the initial set of plant trays identified many undissolved fertilizer pellets. This an indication that moisture saturation was not consistent throughout the tray and the plants were being deprived of nutrients.

Figure 3.14 Initial plant tray 3; fertilizer pellets not dissolved.

- A pipe knock issue was reported by the ReNEWW home residents when the Biowall irrigation was triggered on. The knocking noise was reported to be intermittent; it did not always knock. An investigation confirmed the pipe knock and identified that the noise only occurred when the ReNEWW home filtered rainwater supply was in use. This symptom is noted as part of the initial assessment of the irrigation system.

3.5.2 Irrigation Optimization Goals

Initial observation of the irrigation system within the Biowall indicated that the positioning of the initial soaker hoses limits its ability to saturate the entire plant tray. This indication derived from the condition of the fertilizer pellets found in the growth medium. Equal moisture spread through the trays would have dissolved the pellets. Also, the position of the hose obstructs airflow holes (essential for air filtration) at the bottom of the plant trays (Fig. 3.13). This further contributes to the lack of air flow through the plant trays found during the initial air flow assessment. The pipe knock experienced only when the rainwater catchment system was in use indicates a large water demand by the irrigation system when triggered. The low pressure of the ReNEWW home rainwater catchment system (38 PSI) was insufficient to meet the water volume demand of the Biowall irrigation, causing the pipes to knock. This did not happen when the city water was in use at ~55 PSI.

These findings led to the development of a plant tray irrigation hose configuration that addresses these issues. A list of goals for this optimization was formulated and are explained in the following bullet points:

An optimized irrigation hose configuration must:

- utilize the existing Biowall irrigation plumbing, valve, and control system.
- reduce water delivery volume per tray.
- relocate the irrigation apparatus to the top of the tray.
- provide equal moisture spread throughout the plant trays.
- provide water volume per tray within 10 percent of each other (close to equal).
- operate at low pressure and provide extended irrigation periods designed not to oversaturate the trays (cause increased restriction).

3.5.3 Irrigation Optimization Methodology

The new plant tray hose configuration had to work within the constraints of the existing plumbing and controls of the Biowall. Common ¼” drip irrigation components provided the format used in the design. A drawing showing the optimized plant tray hose design from the top and side views of a single plant tray is presented in Figure 3.15.

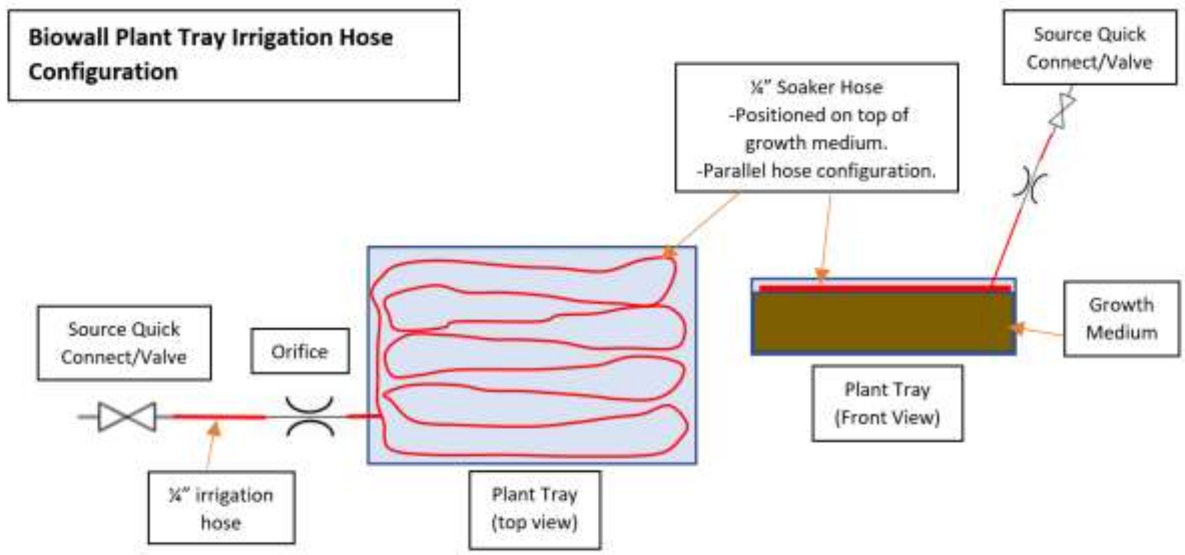


Figure 3.15 Drawing of optimized Biowall plant tray irrigation hose configuration (top and side view).

The drawing in Figure 3.15 illustrates a ¼" soaker hose configured in a parallel loop strung across the top of the plant tray growth medium area. Relocation of the hose to the top of the plant tray aims to provide moisture throughout the growth medium. The hoses were held in position using stakes. A 5/8" to ¼" threaded reducer at the inlet of the hose configuration allows for easy installation to the Biowall plumbing. This configuration was designed to fully saturate the plant tray (from top to bottom), remove the airflow obstruction created by the larger diameter bottom positioned hose configuration, and minimize water draw from the source to addresses the pressure issue (pipe knock) identified during the initial assessment.

The varying height of the Biowall plant tray shelves and low operating pressure of the irrigation system posed a challenge to delivering equal moisture delivery to each tray. Water will follow the path of least resistance. Without components designed to confront fluid behavior, the bottom tray did receive more water than the top. To meet the goal of delivering water volume to each tray within 10% of each other, orifices of different size were implemented at the inlet of each hose (Fig. 3.15).

In determining the actual size of each orifice per tray, the orifice equation which takes known/desired parameters from each tray to solve for a diameter relative to the plant tray shelf position and the overall head was employed. The orifice equation is presented below:

The Orifice Equation

$$Q = CdA\sqrt{2gh}$$

Where:

- Q=Flow (cubic cm per second).
- Cd=coefficient of discharge.
- A=area of the orifice (cm square).
- g=acceleration from gravity (9.81 m/s^2).
- h=head acting on the centerline (cm).

The diameter of the orifice was solved for given the desired flow rate, coefficient of discharge of water, acceleration from gravity, and distance of head above the lowest point in the plumbing. The resulting area allowed to solve for the diameter drilled into a purchased drip irrigation emitter and was implemented onto the irrigation hoses of each tray (Fig. 3.15). The bottom tray has the smallest orifice diameter at 0.254 m high to limit water flow. The top tray has the largest orifice size at 1.778 mm high to encourage increased flow to that tray.

3.5.4 Irrigation Optimization Implementation

Paired with treatments imposed during the Biowall plant growth experiment, the old irrigation hoses were removed and replaced with the new irrigation hose configuration illustrated in Figure 3.15. The improved plant tray set up, in conjunction with implantation of the new irrigation hoses combined to meet Treatment 3 of the airflow methodology. The result of this treatment is presented as the “after” column in section 4.1.1 showing the profile of air velocity measurements after the changes. A period of applied testing worked to establish an irrigation interval and duration.

CHAPTER 4. RESULTS

4.1 Air Flow Analysis Results

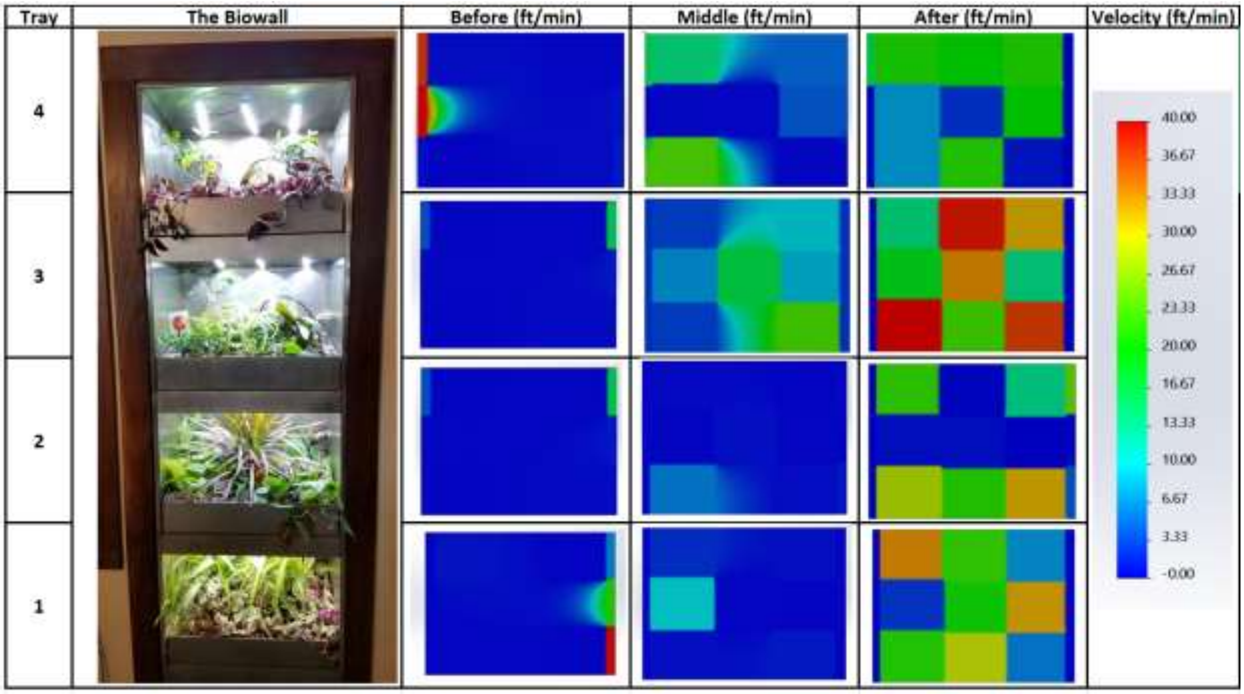
The results of the treatments described in Chapter 3 are presented in this chapter. The following sections present the initial and final results of significance for each treatment imposed.

4.1.1 Air Velocity Profile

The series of air velocity measurements taken throughout the Biowall as described in Chapter 3 are reconciled into a Solidworks model to illustrate the air profile through the Biowall during its initial and post-treatment states.

Table 4.1 provides representations of the air flow analysis results measured prior to and after the treatments described in Chapter 3. In the table, a picture of the Biowall is represented with the number of the trays (Left): the bottom tray is 1; the top is tray is 4. Each row in Table 4.1 corresponds to the Biowall picture and shelf position. The “Before” column in the figure represents the corresponding Solidworks air profile from the initial air velocity measurements. The “Middle” column represents the air profile following Treatment 1. The “After” column represents the air profile following Treatment 2. All measurements were recorded with a hot wire anemometer in ft/min. A color gradient is used to represent air velocity shown in the right column of Table 4.1; blue indicates no flow and red indicates the most flow (~40 (ft/min)). The raw data that made up Table 4.1 is shown in Appendix K.

Table 4. 1Biowall air velocity profile Before, Post-Treatment 1 (Middle), and Post Treatment 2 (After).



The ‘Before’ column (Table 4.1) uses a color gradient to illustrate the initial air measurements in a Solidworks model. This data point shows air flowing through the left and right cracks, outside of the plant trays only. This finding was consistent throughout all four trays. The ‘Before’ column of Table 4.1 illustrates the data from the initial assessment and shows that most of the air flow through the Biowall inlet is bypassing the plant trays.

The ‘Middle’ Column (Table 4.1) follows the application of Treatment 1 described in Chapter 3 and shows air flow through the outside of the plant trays is decreased. Air flowing through the plant trays is increased. The color gradient seen in the Middle column represents this change of air movement compared to the ‘Before’ data set through the Biowall.

The ‘After’ Column (Table 4.1) shows a final air velocity profile recorded after Treatment 2 described in Chapter 3. The color gradient indicates that most of the air flow is directed through the plant trays; a result of the treatments applied. A small amount of air is still bypassing plant trays 2 and 4.

Note: The post-treatment air velocity profile measurements presented in Chapter 4 were increased to 60 measurements per profile for higher resolution (15 measurement points per tray).

4.1.2 Air Velocity Quantification

To quantify the air velocity measurements into a percentage, a summation of the air velocity readings recorded going through the tray is compared to the sum of readings recorded at the right and left outside cracks. The two are calculated into a percentage of air flow through and outside the plant trays. Based on the initial air velocity measurements, a percentage of air going through the plant trays compared to outside the plant trays is shown in Figure 4.1. The data used to calculate this is presented in Appendix K.

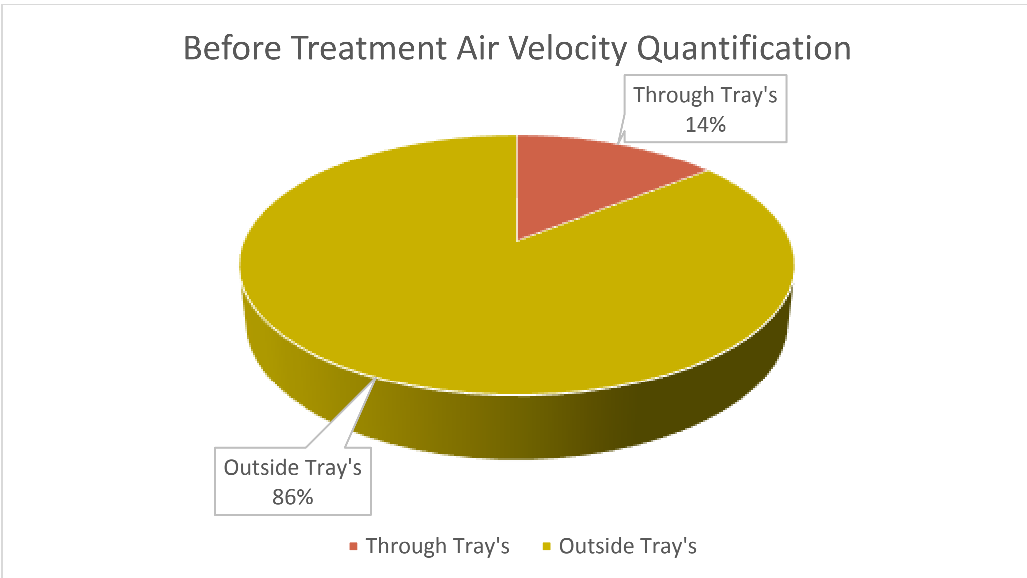


Figure 4.1 Pie chart signifying the percent of all air velocity measurements through vs. outside the trays (initial).

As indicated in Figure 4.1, based off the initial profile of air going into the Biowall, 86 percent of the air velocity measured is moving through the left and right outside cracks; 4 percent of the air is going through the plant trays.

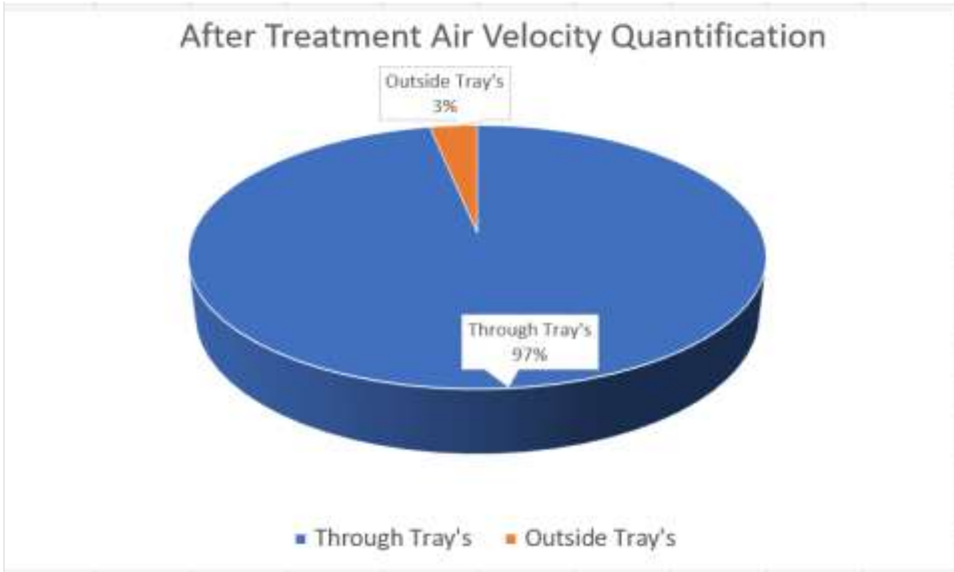


Figure 4.2 Pie chart signifying the percent of air velocity measurements through vs. outside the plant trays (After).

Figure 4.2 represents the percentage of air going through the Biowall plant trays vs. outside of the trays following the application of the treatments. The result shows that 96.7 percent of the air measured is going through the plant trays; 3.3% is going through the right and left cracks.

4.1.3 Differential Pressure (dP) Trend Data

This section discusses the differential pressure (dP) trend data recorded during the airflow analysis. This data is an indication of the level of restriction between the inlet and outlet of the Biowall. Figure 4.3 is a direct screenshot of the differential pressure trend data from before and after Treatment 2 of the airflow analysis. This is viewed through the BAS online networking interface for the Biowall.

Figure 4.3 shows trend data measured in inches-of-H2O (Y-axis) over time (X-axis). Region 1 (red) in the figure represents the differential pressure before Treatment 2. A continuation of the data identified during the initial assessment shows the maximum dP is ~0.063 in-H2O; minimum ~0.058 in-H2O and does not show a significant change in dP over time mirroring HVAC cycles. Region 2 (green) represents dP following Treatment 2: replacement of plant trays and relocation of irrigation hoses. A spike in dP followed by a slow decline mirrors the irrigation interval. In

Region 2 the dP increases to ~0.123 in-H2O (an indication that the plant tray is saturated and air flow is restricted) and decreases to ~0.085 in-H2O over time (a representation of the tray saturation declining over time). Region 3 (Blue) shows what the dP looks like when the bypass door is opened and is a flat line hovering a little over 0.02 inches-H2O.

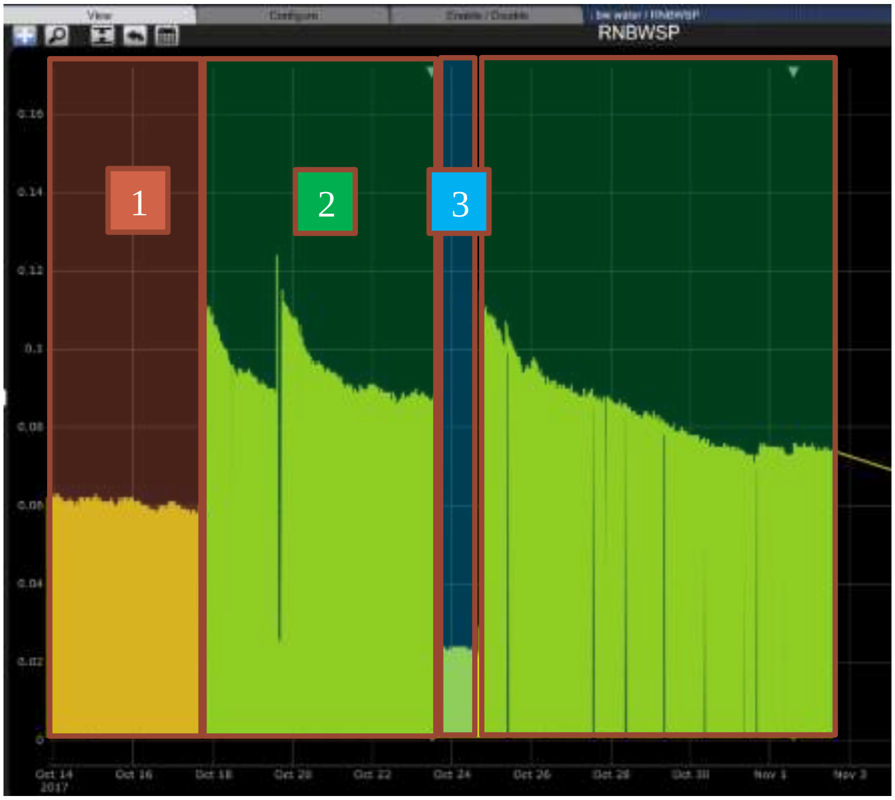


Figure 4.3 Differential Pressure trend data representing before (1) and after (2) airflow treatments, as well as an open bypass door (3).

Figure 4.3 shows what the dP trend data looks like before the treatments (Region 1), after Treatment 2 (Region 2), and with the bypass door open (Region 3). Through this data, three states of the Biowall air flow can be seen. The open bypass door served as a reference to what non-restricted air movement appeared to be.

4.2 <u>Biowall Plant Growth Experiment</u>

The results from the plant growth experiment conducted in the Biowall are shown in this section. The results shown are from data collected during the experiment. The raw data can be found in

Appendix K. To allow replication of the plant growth experiments within the Biowall, the parameter reporting format typically follows the International Committee for Controlled Environment Guidelines (controlledenvironments.org).

4.2.1 The Biowall Before and After

Figure 4.4 shows a side by side view of the Biowall as it looked at the onset of this research (left) and following the implementation of the second set of plant trays described in the methodology (right). The following were implemented as part of the treatments: the growth medium was mixed in a single large batch to pursue consistency; the growth medium was maintained at an even level at 19 mm from the top of the rim; the plants were oriented to provide the greatest PAR possible to each plant; the plants were arranged to increase the Biowall aesthetic value; and the plants were acclimated in a plant nursery environment prior to implementing for air filtration to allow for root spread and increase survivability of the filtration process.

Figure 4.4 The Biowall before (left) and after (right) implementing new plant trays.

4.2.2 Biowall Environmental Parameter Results

The Biowall parameter measurements recorded during the experiment are presented in Appendix E. The experiment was conducted in 55.8 cm x 45.72 cm plant trays for a total growth area of 1.02 m^2. The Biowall was equipped with Tsujiko Co. Ltd LEDs mounted 30.5 cm above the plant trays. A downward air flow distribution pulls indoor air through the plant trays and supplies the plants with a renewed air flow. The CO_2 conditions inside the room are assumed to be nominal atmospheric. The average room air temperature was 22.4 degrees C (s.d. +- 4.8 degrees C) during the light period. The photosynthetically available radiation (PAR) at the top of the plant tray was 77 umol/m^2-s during the 8.5-hour photoperiod. The average relative humidity in the room was 45.7% (s.d. $\pm$13.7 %). The plants were grown in 0.026 m^3 of growth medium per plant tray. The medium content was 40% coconut fiber, 40% growstone, 20% activated carbon pellets. The plants were irrigated by the Biowall irrigation system 2 times daily for 30 seconds. The plant trays were not fertilized during this experiment, having only received the home water supply. A nutrient test of the growth medium showed a deficiency for nitrogen, sufficient phosphorous, and adequate potassium. The pH of the growth medium was 7.5.

4.2.3 Plant Dimension Measurement Reconciliation

The plant dimension measurements recorded during the experiment are presented in Appendix K. Plant measurements included root diameter, plant height, and plant spread diameter following the return of the initial and second set of plant trays to the nursery. Root spread is the most important measurement to botanical air filtration. A list of the plants with the highest to lowest root spread from this experiment are listed below.

1. Ficus
2. Marginata
3. Spider Plant
4. Wandering Jew
5. Golden Pathos
6. Oyster Plant
7. English Ivy
8. Heartleaf Philondendron

4.3 Irrigation Optimization Results

The Biowall irrigation hoses were reconfigured to meet the optimization goals determined in section 3.6.2. The treatment implemented the design shown in Figure 4.5. The bottom residing 3/8" soaker hose was removed and was replaced with a ¼" soaker hose positioned at the top of the tray. The final specifications of the new irrigation hose configuration are defined in Table 4.2.

Table 4.2 Biowall irrigation specifications before and after.

Specifications	Before	After
Irrigation Interval (Daily)	15 secs	30-90 sec
Flow Rate* (L/min)	2.39	0.78
Working Pressure (PSI)	20	35
Soaker hose location in the tray	Bottom	Top

* The amount of water delivered per tray.

Table 4.2 documents irrigation system specifications before and after the treatments were applied. As a result of the treatments, the irrigation interval increased from 15 seconds to 60 seconds. The flow rate decreased from 2.39 L/min (per tray) to 0.78 L/min (per tray). The working pressure of the system increased from 20 PSI to 35 PSI and the soaker hose location was moved from the bottom of the plant tray to the top of the tray. Figure 4.5 shows a single tray installed in the Biowall with the new irrigation hose configuration installed in it.

Figure 4.5 Biowall plant tray with optimized irrigation hose configuration.

Final Biowall irrigation specifications:

- Solenoid valve operated.
- Activated by the BAS according to a daily irrigation schedule.
- Irrigation cycle 30-90 sec/ day.
- ¼” soaker hose configuration positioned on top of the plant tray.
- Orifice sized to provide equal flow to each tray (larger on top).
- The average flow rate of 0.79 L/min.
- Operating pressure regulated at 35 PSI.
- Quick disconnect of soaker hose positioned at each tray for easy removal.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The research presented in this paper applied a manufacturing validation method in an experimental format to the Biowall subsystems. To answer the research question, an analysis of the initial conditions identified subsystems to focus on. The three phases of the method “Measure-Analyze-Improve” were applied. Documentation of initial and final conditions resulted in a comparison to derive the conclusions made in this chapter.

5.1 Air Flow Analysis Conclusions

The air flow analysis results in present two forms of observing air flow through the Biowall: the air velocity profile (Table 4.1) and differential pressure (dP) trend data (Figure 4.3). These outputs provided quantifiable results of the air flow path through the Biowall before and after the treatments were applied. The initial column in the air velocity profile in Table 4.1 indicates that most of the air measurements recorded were not going through the plant trays (87%). Following the treatments applied to address this finding, a majority of the air velocity readings (97%) were measured through the trays. The treatments reversed the trend of air flow bypassing the trays.

Differential pressure (dP) trend data corresponds to the previous finding following Treatment 2 (Fig. 4.3). After the experimental treatments were applied, the HVAC cycle and an increase in dP following the irrigation interval with a gradual decrease over time can be seen in the trends. The indication is that saturated plant trays create more resistance to air flow and is seen as high dP in the trend data. The dP declines as the plant tray water evaporates over time, seen as the downward slope in Fig. 4.3. This type of pattern can only be seen if the air flow is going through the plant trays and corresponds with the ‘after-treatment’ air velocity profile (Table 4.1). The conclusion is that as a result of this research, most of the air is flowing through the plant trays as designed. The filtration potential of the Biowall prototype is increased.

Moving forward: after the application of treatments during the period of work, a percentage of the air measured continues to bypass the plant trays. Future iterations of the Biowall should consider these results into the development of improved air seals and consider a different configuration, materials, and/or the use of fasteners.

5.2 Biowall Plant Growth Experiment Conclusions

This technology is wholly designed to facilitate the phytoremediation of indoor air. By definition, a healthy plant root zone is essential for the filtration process to occur. Plant growth is the single most important aspect of the Biowall function. This research implemented plant growth within the Biowall to provide increased documentation on this aspect.

The plants and the makeup of plant trays are a big factor in Biowall performance. Initial findings exemplified the importance of maintaining a consistent equal depth of growth media and orienting the plants within the tray. The documentation of environmental parameters is presented in Appendix E. This documentation provides future researchers and Biowall owners with the information to replicate this work as the use of Biowall's continues.

The Biowall holds the potential to be an aesthetically pleasing contribution to a home. A result of this work expanded known air filtering plant species grown within this environment. The demonstrated knowledge gained during the variety of plant growth studies within the Biowall provides plant tray designers with an array of possibilities to create trays which bring an eye-pleasing functioning component to a home. For example, the most successful plant root growth seen in this study was the ficus tree. This opens the potential for a Bonzi tree themed Biowall. It is important to note that not all plants are safe for use. Certain plants produce chemicals that are harmful to humans or animals, and pollen from flowers can irritate due to allergies. Any plant species used within the Biowall should have a considerable amount of research behind it before use. For a list of well-researched air filtering plants, consult the literature review of this paper.

5.3 Irrigation Optimization Conclusions

Irrigation is the primary plant life support system of the Biowall prototype. The delivery of moisture to the plant trays not only keeps the plants alive, but the method and location of delivery can encourage root growth throughout the media. Water consumption is especially relevant in the

ReNEWW home as the treated rainwater supply of the home is limited. As seen during the initial validation phase, the hose location and configuration can affect air flow. These factors, along with reports of pipe knocking when irrigation was initiated, motivated the consideration of irrigation within the scope of this research.

The final irrigation hose configuration worked within the existing Biowall plumbing to optimize moisture delivery by relocating the irrigation hose to the top of the tray, decreasing the diameter of the hose to more accurately control the amount of water delivered, and configuring the hose in a way that disperses moisture throughout the entire tray. The size and position of the hose minimize the obstruction of airflow, and the smaller hose reduced water flow from the supply, thus eliminating the pipe knocking.

Determining an irrigation interval accompanied the new hose configuration. The dP trend data seen through the BAS served well to observe when the trays were saturated (high dP) and when the trays were dry (low dP). It was apparent through the trend data that an optimized irrigation interval can vary with environmental conditions like a change of season and weather. Further work can utilize technology and automation to activate an irrigation cycle when the dP, or the signal from a moisture sensor reaches a certain minimum.

5.4 Conclusion

The activity of "Measure-Analyze-Improve" on a prototype product is an effective method to improving systems and components prior to full-scale production. At the same time, making improvements can be an endless task which can be draining of resources and lead to the end of a concept before it has had the opportunity to reach the market. Engine manufacturers create deadlines by releasing annual models. The work that is left undone or in need of "Measure-Analyze-Improve" is prioritized for the following year. The Biowall is nearing a point where it can stop being research and become a product itself with its first model year being an iteration of this prototype, and future versions can follow.

In conclusion, and with the work completed in this research in mind, future development of the Biowall concept should consider implementing the plant growth method developed during this and previous research as part of the routine. Regular maintenance of the Biowall subsystems such as the seating of the air seals and performing irrigation hose checks will ensure consistent function. The substituting of the control system from a BAS to something more affordable will make the Biowall accessible to a wider range of customers. And a thorough filtration quantification which evaluates known contaminants within indoor air and the Biowalls' ability to remove them will place this concept in a good position to be commercialized.

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APPENDIX A. THE MERV CHART

Chapter Section 2.5 references the MERV rating system of mechanical air filters. The MERV rating chart for mechanical air filters is shown in the chart below.

Table A.1 MERV rating chart

MERV RATING CHART

Standard 52.5 Minimum Efficiency Reporting Value	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
					≥99.999% eff. On .10-.20 pm
20	n/a	n/a	< 0.30 pm particle size	Cleanrooms	Particles
19	n/a	n/a	Virus (unattached)	Radioactive Materials	Particles
18	n/a	n/a	Carbon Dust	Pharmaceutical Man.	Particulates
17	n/a	n/a	All Combustion smoke	Carcinogenetic Materials	≥99.97% eff. On .30 pm Particles
16	n/a	n/a	.30-1.0 pm Particle Size	General Surgery	**Bag Filter**- Nonsupported
15	>95%	n/a	All Bacteria	Hospital Inpatient Care	microfine fiberglass or
					synthetic media, 12-36 in. deep, 6-
14	90-95%	>98%	Most Tobacco Smoke	Smoking Lunges	12 pockets
					Box Filter- Rigid Style Cartridge
					Filters 6 to 12" deep m ay use
13	89-90%	>98%	Proplet Nuceli (Sneeze)	Superior Commercial Buildings	lofted or paper media.
12	70-75%	>95%	1.0-3.0 pm Particle Size	Superior Residential	**Bag Filter**- Nonsupported
			Legionella		microfine fiberglass or
					synthetic media, 12-36 in. deep, 6-
11	60-65%	>95%	Humidifier Dust	Better Commercial Buildings	12 pockets
			Lead Dust		
					Box Filter- Rigid Style Cartridge
					Filters 6 to 12" deep m ay use
10	50-55%	>95%	Milled Flour		lofted or paper media.
			Auto Emissions	Hospital Laboratories	
9	40-45%	>90%	Welding Fumes		
					Pleated Filters- Disposable,
8	30-35%	>90%	3.0-10.0 pm Particle Size	Commercial Buildings	extended surface area, thick with
					cotton-polyester blend media,
			Mold Spores		cardboard frame
7	25-30%	>90%	Hair Spray	Better Residential	
					Cartridge Filters- Graded density
					viscous coated cube or pocket
			Fabric Protector		filters, synthetic media
6	<20%	85-90%	Dusting Aids	Industrial Workplace	
					Throwaway- Disposable
			Cement Dust		synthetic panel filter.
5	<20%	80-85%	Pudding Mix	Paint Booth Inlet	
					Throwaway- Disposable
4	<20%	75-80%	>10.0 pm Particle Size	Minimal Filtration	fiberglass or synthetic panel filter.
			Pollen		
3	<20%	70-75%	Dust Mites	Residential	**Washable**- Aluminum Mesh
			Sanding Dust		
2	<20%	65-70%	Spray Paint Dust		
					Electrostatic- Self charging
			Textile Fibers	Window A/C Units	woven panel filter.
1	<20%	<65%	Carpet Fibers		

APPENDIX B. AIR FLOW PATH THROUGH THE BIOWALL

Figure B.1 below shows a side view schematic of the Biowall and illustrates the design air path through the plant trays. As illustrated in the figure, the air is pulled through the trays when the HVAC system is turned on and/or the supplemental fan is engaged. The air flow path (illustrated by blue arrows) starts at the left side of the schematic (the home living room) and the air is pulled through one of four plant trays. After filtration, the air is directed to the HVAC supply. The figure also represents the temperature, humidity, pressure, and relative humidity sensor locations (#'s 1, 2, 3, 4, 5, 10), the irrigation schematic (#'s 8, 9), and the supplemental fan and controls (#'s 6, 7, 11).

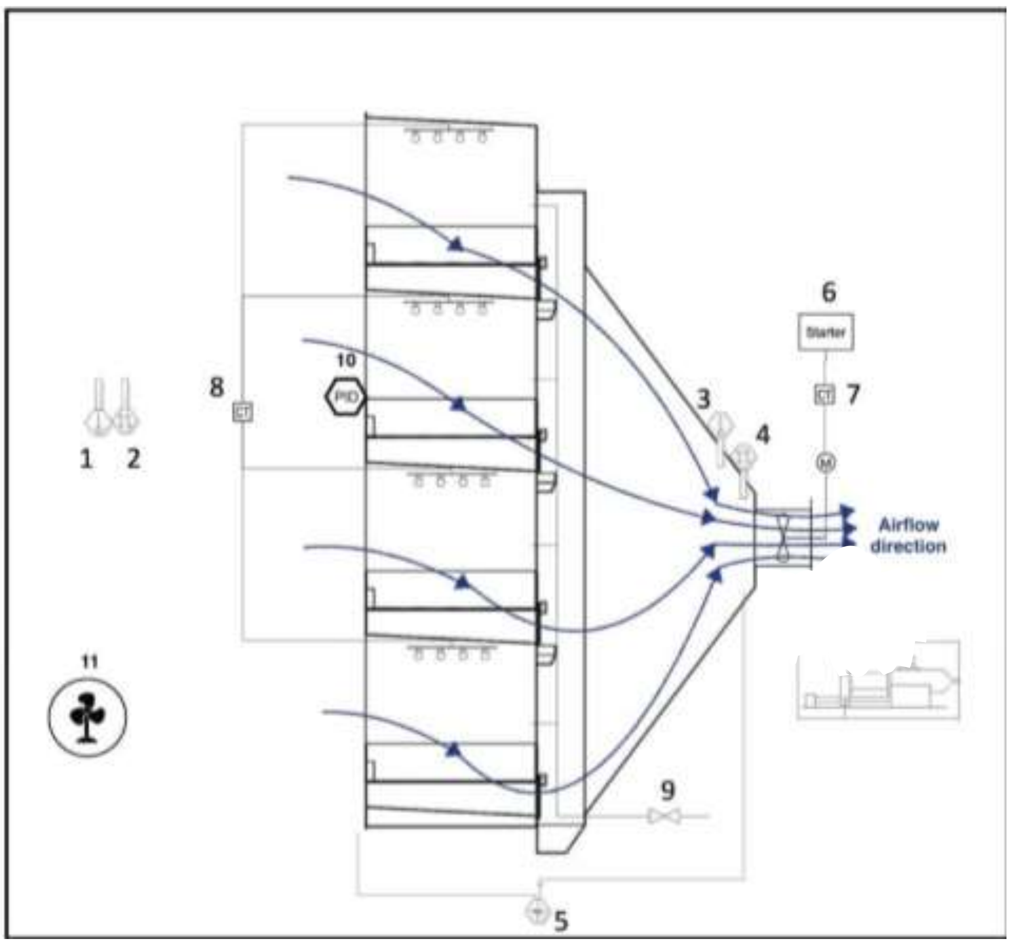


Figure B.1 Biowall schematic (side view).

The air path analysis presented in this study in the form of an Air Velocity model shown in Table 4.1 is made using the raw data recorded during regular visits to the prototype. The data used to make the air velocity profile is shown in the following pages. The tables represent each data measurement taken using a hot wire anemometer in the Biowall at different stages of treatment application.

APPENDIX C. DELTA PRESSURE (DP) TREND DATA AND AIR FLOW

Another view of air flow through the Biowall can be observed through the BAS differential pressure (dP) trend data. This sensor records the pressure at the inlet and outlet of the Biowall to record a change in air pressure in inches of H2O. The Biowall functions when the home HVAC system is cycled on. The cycling of the HVAC system will move air through the Biowall and create a change in pressure between the inlet and outlet.

Figure C.1 below shows dP trend data as observed through the BAS networking website called WebCTRL during the initial assessment. The differential pressure is recorded in inches of H2O (y-axis), over time recorded August 30 through September 27, 2017 (x-axis). The dP trend data during the initial conditions showed a maximum of ~0.065 in-H2O and minimum of ~0.059 in-H2O (a change of .006 in-H2O).

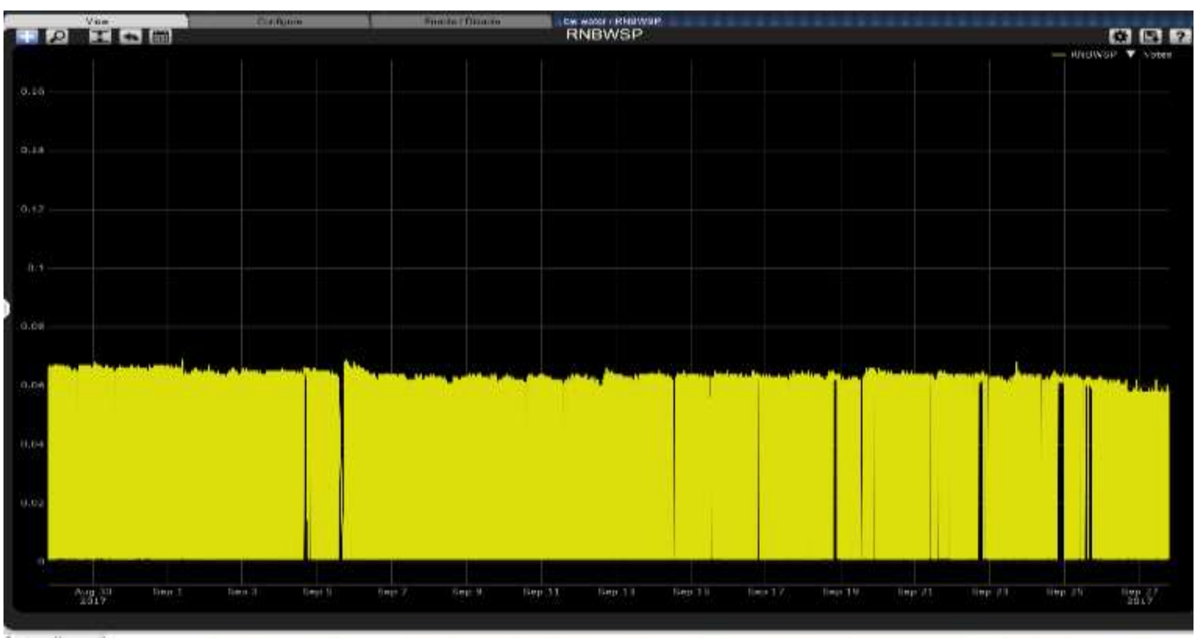


Figure C.1 Biowall differential pressure trend data seen through the BAS interface WebCTRL.

The significance of the dP data shown in Figure C.1 is to document dP during the initial assessment. As the HVAC pulls air through the growth media, a restriction is imposed on air flow. Also, the moisture content of the plant trays adds to the restriction. The restriction is seen through a change in pressure between the inlet and outlet. When dP was observed during the initial assessment of the Biowall, some spikes in dP can be seen. The maximum change in dP is ~0.006 in-H2O and does not show the HVAC system cycling on and off. This is quantifiable evidence that the air flow through the Biowall is bypassing the plant trays.

APPENDIX D. NCERA-101 MINIMUM GUIDLINES FOR MEASURING AND REPORTING ENVIRONMENTAL PARAMETERS FOR EXPERIMENTS ON PLANTS IN GROWTH ROOMS AND CHAMBERS

NCERA-101 Environmental parameter measurement recommendations for experiments on plants in growth rooms and chambers was chosen as it best fits the condition of the Biowall placement situation within the ReNEWW research home. The table from www.controlledenvrionments.org is shown below.

Table D.1 NCERA-101 Minimum Guidlines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

International Committee for Controlled Environment Guidelines

Parameter to measure		Units [1]	Where to measure	When to measure	What to report
Radiation	**Photosynthetically active radiation (PAR)** [2]	$\mu mol\ m^{-2}\ s^{-1}$	Top of plant canopy in centre of growing area	At start and end, and every 2 weeks of the experiment	Average and standard deviation. Radiation source (type, model, and manufacturer)
and	**Photoperiod**	h			Duration of light and dark periods
Temperature	**Air**	°C	Top of plant canopy in centre of growing area	Daily during each light and dark period, at least 1 hour after light/dark change	Average and standard deviation
	Liquid culture	°C	Within solution under plants	As above for air temperature	Average and standard deviation
Atmospheric moisture	**Water vapour pressure deficit (VPD)**	kPa	Top of plant canopy in centre of growing area	Daily during each light and dark period, at least 1 hour after light/dark change	Average and standard deviation
or	**Relative humidity (RH)**	%	As above for VPD	As above for VPD	Average and standard deviation
Carbon dioxide [3]		$\mu mol\ mol^{-1}$	Top of plant canopy	At least hourly	Average and standard deviation
Air velocity [3]		$m\ s^{-1}$	At one or more representative canopy locations	At least once during the experiment	Average and standard deviation
Watering		litre (L)		Daily	Frequency, amount and type of water added
pH	**Liquid culture**	pH	In the bulk solution	Before and after pH correction	Average and standard deviation
Electrical conductivity (EC) [3]	**Liquid culture**	$S\ m^{-1}$	In the bulk solution	Before and after EC correction	Average and standard deviation
Substrate				At start of the experiment	Type and volume per container, components of soil-less substrate, container dimensions
Nutrition	**Solid media**	$mol\ kg^{-1}$ (dry)		When added or replenished	Nutrients and their form added to soil media
	Liquid culture	$mmol\ L^{-1}$		Daily, or when replenished	Ionic concentration in initial and added solution. Aeration if any. Volume of initial solution
Room or chamber properties	**Specifications**				Floor area. Manufacturer and model if available
	Barrier beneath lamps				Indicate if present and its composition
	Air flow				Indicate whether up, down or horizontal

1 Report in other multiples or sub-multiples of indicated units if more convenient.

2 Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies, and manufacturers of quantum sensors. When diurnal PAR is ramped, integrals should be reported, e.g. in $mol\ m^{-2}\ d^{-1}$.

3 This parameter should be reported if records are available and always when it is a variable under investigation. For more information, consult the detailed guidelines published as ANSI/ASAE Engineering Practice EP411.4 (2002) 'Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers'. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.

APPENDIX E. PLANT EXPERIMENT ENVIRONMENTAL CONDITIONS

Shown below are the Biowall nominal environmental conditions recorded during the plant growth experiment. This data aspired to fulfill NCERA-101 recommendations.

Table E.1 Biowall environmental conditions

Parameter to measure		**Average Value**	**Standard Deviation/Description**
Radiation	Photosynthetically Active Radiation (RAR)	77.5 umol/m^2-s^2	Automated
	Photoperiod	8.5 h/day	Automated
Temperature	Input Air	22.4 C	4.8 C
Atmospheric moisture	Relative Humidity (zone)	45.7%	13.7 %
Carbon Dioxide		umol-mol-1	
Air Velocity	Average total input	1.62 m/s	0.232 m/s
Watering	Per tray (0.75 L/min)	0.375 L	2 times daily
pH	Growth Medium	7.5	n/a
*Tray Nutrient Content	Nitrogen	N1- Deficient	n/a
	Phosphorous	P3- Sufficient	n/a
	Potassium	K2- Adequate	n/a
Substrate	Per Tray	0.026 m^3	Cococoir 40%; Growstone 40%; Activated Carbon 20%
**Nutrition	Liquid Culture	Flora Duo A & B (Strong Grow Blend)	Once a week during tray acclimation.
Room or chamber properties (Biowall)	Plant Tray Area	1.022 m^2	0.26 m^2 Per Tray
	Barrier beneath lamps	30.5 cm	
	Air Flow	down	Pulled through tray

Biowall plant growth study parameter measurements.

* Tray nutrient content recorded with Luster Leaf Products Inc. Soil Test Kit. Nitrogen, Phosphorous, and Potassium were recorded with individual chemical tests from this kit. The individual sample results provide a color which is comparted to a given 0-4 scale (0 depleted; 4 surpluses) to indicate the elements level within the sample.

** Nutrition is delivered in an aqueous solution during plant to tray acclimation period in the lab only. During the period of this research, the plant trays were not fertilized while on the Biowall. Tap water only is delivered through the irrigation system. Fertilization delivered to plant trays while filtration is in the process will have to meet Instructional Review Board safety standards for human experimental exposure (a fertilizer that won't hurt the home residents will need to be researched).

APPENDIX F. PLANT DIMENSIONS

The table below reports the plant measurements recorded during the plant growth experiment. Presented are the average and standard deviation dimensions of each species in (cm).

Table F.1 Plant dimensions

Plant		**Root Diameter (cm)**	**Plant Height (cm)**	**Spread Diameter (cm)**
English Ivy	*Average*	*10.16*	*12.07*	*33.02*
	Std. Dev	*1.27*	*0.64*	*12.70*
Ficus	*Average*	*39.69*	*28.70*	*n/a*
	Std. Dev	*0.95*	*0.76*	*n/a*
Golden Pathos	*Average*	*17.96*	*18.22*	*35.56*
	Std. Dev	*4.26*	*8.21*	*10.78*
Heartleaf Philondendron	*Average*	*8.89*	*10.16*	*21.59*
	Std. Dev	*3.81*	*2.54*	*3.81*
Marginata	*Average*	*32.13*	*35.88*	*44.45*
	Std. Dev	*9.27*	*2.22*	*11.43*
Oyster Plant	*Average*	*12.70*	*22.86*	*n/a*
	Std. Dev	*0.00*	*0.00*	*n/a*
Spider Plant	*Average*	*30.36*	*31.99*	*50.80*
	Std. Dev	*14.03*	*11.80*	*17.55*
Wandering Jew	*Average*	*26.03*	*25.82*	*40.59*
	Std. Dev	*8.26*	*13.97*	*0.00*

APPENDIX G. INDIVIDUAL EXPERIMENT VARIABLES

This thesis consists of three experiments. There are a separate set of variables that affect each. The dependent, independent, and confounding variables for each experiment are listed in the following sections and subsections.

G.1 Dependent Variables

The variables that are dependent on conditions for each experiment are listed in the following subsections:

Dependent Variables (Air Flow Analysis)

- Bio-air filtration effectiveness is dependent on the air flowing through the plant trays.
- Total air flow through the Biowall is dependent on HVAC and/or supplemental fan status.

Dependent Variables (Plant Growth Study)

- Plant health and root spread are dependent on the function of the biowall plant life support systems.
- The aesthetic value of the plant trays is dependent on variety and organization of plants.

Dependent Variables (Irrigation Optimization)

- Total water consumption of Biowall per watering cycle is dependent on irrigation duration and irrigation apparatus size and configuration.

G.2 Independent Variables

The variables that are independent of the research reported in this thesis, for each experiment, are listed below:

- The installation of the Biowall was done within the constraints of the ReNEWW house and completed prior to the beginning of this research. The Biowall prototype design, fabrication, and positioning are independent of this research.

- The ReNEWW House, its residents, the activities taking place, and weather changes experienced during this research is independent of this research.

G.3 Confounding Variables

There are several variables that can be affected by multiple variables within the Biowall. The confounding variables for each of the three experiments are discussed below.

Confounding Variables (Air Flow Analysis)

- Air flow through the Biowall plant trays can be affected by: tray air seals, growth medium depth, growth medium consistency, plant tray moisture content, and plant root density.
- The discharge humidity and temperature can be affected by the zone temperature and humidity, tray saturation, and the time of year.

Confounding Variables (Plant Growth Study)

- Plant Health within the Biowall environment are affected by; the irrigation system; airflow through plant trays; lighting; growth medium consistency; and growth medium nutrient content.
- Plant lighting resources per plant are dependent on plant orientation within the tray and/or plant growth within the tray.
- The growth medium can vary in constancy from nonuniform batch mixture or from extended filtration periods in the Biowall.

Confounding Variables (Irrigation Optimization)

- Water delivery volume per tray can be affected by the physical height of the tray and operational condition of irrigation hoses.
- Irrigation spread per plant tray can be affected by irrigation hose orientation and/or growth medium consistency.

APPENDIX H. BIOWALL LED WIRING UPGRADE

Discussed in the initial field-testing period of the lighting system are areas where improvements can be made. Identified were; heat being added to air passing through the trays by the LEDs, hand soldered points creating hazards to the system, shading of the lighting by certain plants, and the acknowledgment that LED technology could have advanced since the implementation of the initial system.

Considering these results, a lighting upgrade added to the safety of the system and increased available lighting for the plants.

The work completed removed the existing LED strips and sent them out to Inspired LED Phoenix Arizona to be professionally soldered. This action removed the potential hazard of soldered wires becoming loose, causing a short, or creating a hazard.

APPENDIX I. PLANTS AND EXCESSIVE AIR FLOW

Figure I.1 is a picture of the initial plant tray 3 after the Biowall fan was locked on for 14 days. The plants in the figure show yellowing and stress; the effect of extended air flow through the roots.

Figure I.1 A plant tray following 14 days of continuous air through the roots shows plants deprived of moisture.

APPENDIX J. STATEMENT OF WORK

Prior to completing the research presented in this paper, the researcher created a high-level flow chart which served to guide the work through the various aspects of work.

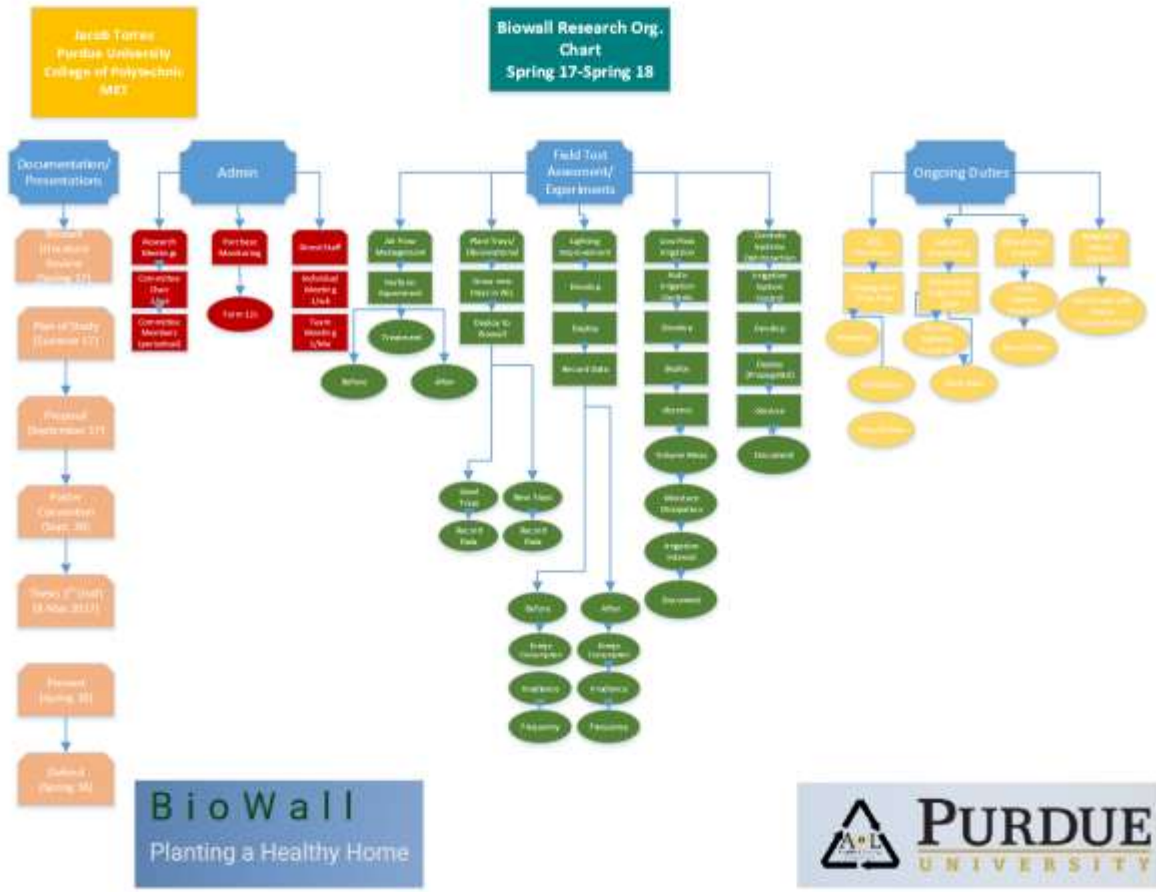
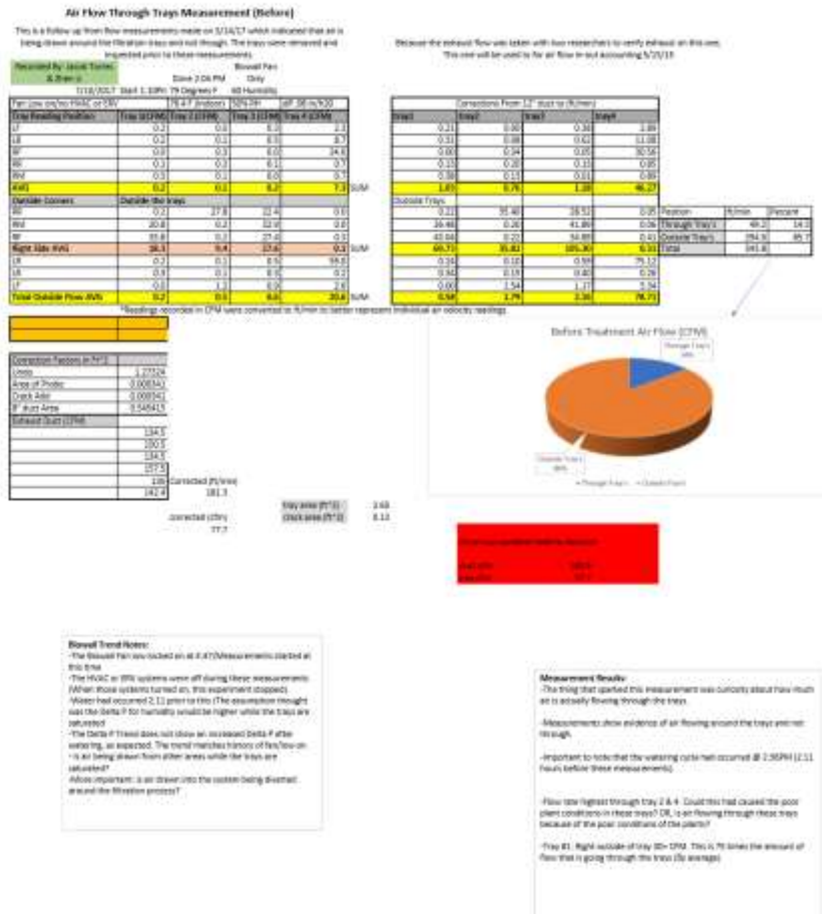


Figure J. 1 Statement of work flowchart

APPENDIX K. RAW DATA



K 1Initial Air Velocity and Environment Measurements

Air Flow Through Trays Measurement (Middle)

The trays were removed, cleared of debris, and inspected prior to these measurements.

Recorded By: Jacob Torres & Joe Overdorf

Biowall Fan only

This middle data set was used because there were two researchers working on this measurement. The HVAC system did not turn on. Also the sample sizes were increased to seek ASHRAE handbook recommendations.

Date 11/16/2017 End: 2:52

Fan Low on/no HVAC or ERV					Corrections From 12" duct to (ft/min)			
Tray Reading Position	Tray 1(CFM)	Tray 2 (CFM)	Tray 3 (CFM)	Tray 4 (CFM)	Tray 1	Tray 2	Tray 3	Tray 4
LF	0.3	7.7	1.0	31.0	0.4	9.8	1.3	39.5
LB	1.3	0.4	1.0	19.0	1.6	0.4	1.3	24.2
ML	5.9	0.1	6.9	0.3	7.4	0.1	8.8	0.3
MM	0.0	0.8	20.1	0.2	0.1	1.0	25.6	0.2
MR	0.0	0.1	9.4	5.3	0.0	0.1	12.0	6.7
FM	11.3	0.4	22.2	0.5	14.4	0.5	28.3	0.6
RF	0.6	0.6	27.8	0.1	0.8	0.7	35.4	0.1
RB	0.3	0.0	11.2	6.2	0.4	0.0	14.3	7.9
m								
AVG	**2.5**	**1.2**	**12.5**	**7.8**	3.323	11.937	77.820	71.925
Outside Corners	**Outside the trays**							
RR	0.0	0.5	0.0	0.0	0.000	0.395	0.000	0.000
RM	0.0	0.0	0.0	0.0	0.000	0.028	0.005	0.000
RF	0.0	1.4	0.0	0.0	0.000	1.757	0.006	0.000
Right Side AVG	**0.0**	**0.6**	**0.0**	**0.0**	0.000	2.180	0.011	0.000
LR	0.0	0.0	0.0	**21.3**	0.009	0.011	0.001	27.120
LM	0.1	0.2	0.1	0.0	0.076	0.267	0.153	0.008
LF	0.0	0.0	0.0	0.0	0.049	0.005	0.038	0.000
Total Outside Flow AVG	**0.0**	**0.1**	**0.1**	**7.1**	0.150	0.284	0.192	27.128

*Readings recorded in CFM were converted to ft/min to better represent individual air velocity readings.

Notes

Make notes of anything going on in the house, or biowall

Entire team showed up today

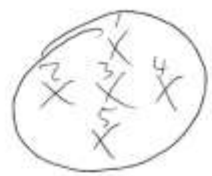
Jacob has determined that tray 4 is dead and needs replaced

Increased irrigation intervals to 3

	ft/min	Percent
Tray sum	244.3	89.1
Crack Sum	29.9	10.9
Total	274.2	

tray area (ft^2)	2.60
crack area (ft^2)	0.13

Correction Factors in Ft^2	
Undo	1.27524
Area of Probe	0.000341
Crack Add	0.000341
8" duct Area	0.545415
Exhaust Duct 1	149.5
2	158.5
3	148
4	
5	
Average (FPM)	152
total flow (cfm)	105.6



K 2 Middle Air Velocity and Environment Measurements

Air Flow Through Trays Measurement (Final)

After Treatments: the trays with even growth medium/new irrigation configuration/Tray seal repair were installed in the Biowall. The final step in the Treatments.

This was the last measurement. Christmas Day 2017

Recorded By: Jacob Torres

Biowall Fan only

Date	12/26/2017		14
Time	5:24 PM	68.8	Humidity 27.5

Every reading was corrected to remove 12" diameter area from reading

Notes
Christmas day after
lots of snow outside

8 degrees
some kind of air leak in tray 2
turned irrigation off at 2nd interval for day to not effect this reading

Fan Low on/no HVAC or ERV					Corrections From 12" duct to (ft/min)			
Tray Reading Position	**Tray 1(CFM)**	**Tray 2 (CFM)**	**Tray 3 (CFM)**	**Tray 4 (CFM)**	**tray1**	**tray2**	**tray3**	**tray4**
LF	19.9	25.9	36.8	6.7	25.3	33.0	46.9	8.5
LB	31.2	20.5	13.2	19.5	39.7	26.1	16.8	24.8
ML	2.4	0.6	17.3	6.6	3.1	0.8	22.0	8.4
MM	18.8	0.7	31.0	2.3	23.9	0.9	39.5	2.9
MR	30.0	0.1	12.9	18.4	38.2	0.1	16.4	23.4
FM	26.5	20.1	21.2	20.0	33.7	25.6	27.0	25.5
RF	5.2	29.5	34.4	0.9	6.6	37.6	43.8	1.1
RB	6.2	12.5	29.6	19.7	7.9	15.9	37.7	25.1
mr	20.4	0.3	36.0	20.3	26.0	0.4	45.8	25.8
AVG	**17.8**	**12.2**	**25.8**	**12.7**	20.7	22.7	30.9	12.5
Outside Corners	**Outside the trays**							
RR	0.0	22.8	0.0	0.0	0.0	29.0	0.0	0.0
RM	0.0	0.3	0.0	0.0	0.0	0.4	0.0	0.0
RF	0.0	**4.0**	0.0	0.0	0.0	5.1	0.0	0.0
Right Side AVG	**0.0**	**9.0**	**0.0**	**0.0**	0.0	11.5	0.0	0.0
LR	0.0	0.0	0.0	[illegible]	0.0	0.0	0.0	19.1
LM	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.0
LF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Outside Flow AVG	**0.0**	**0.1**	**0.0**	**5.0**	0.0	0.1	0.0	6.4

*Readings recorded in CFM were converted to ft/min to better represent individual air velocity readings.

Position	ft/min	Percent
Through Tray's	464.1	96.3
Outside Tray's	18.0	3.7
Total	482.1	

tray area (ft^2)	2.60
crack area (ft^2)	0.13

*In the final percentage the sum of measurement points mirrored the initial set.

Correction Factors in Ft^2	
Undo	1.27324
Area of Probe	0.000341
Crack Add	0.000341
8" duct Area	0.545415

Exhaust Duct 1	142		
2	409		
3	103		
4	51		corrected
5	164	Corrected FPM	flow (CFM)
Average (FPM)	174	221.5	120.8

K 3 Final Air Velocity Environment Measurements

5.5.2 K.4 Plant Measurements

Table K.1 Plant measurements (before).

Before	Plant Type	Plant Height (in)	Plant Spread (in)	Root Spread (in)	Growth Medium	General Notes Grow Tips
# 1	Spider Plant	13		8	High Point: Low Point: *Difference: 0.500* Root Depth: Spider: 1.5	- High stress - Drying out - Noticeable water spots - Golden very shaded - Bottoms are dying
	Golden Pathos	15		10.5	Golden: 2	
# 2	Spider Plant	25		13	High Point: Low Point: *Difference: 2* Root Depth: Spider: 2	- High Stress - Poor Health - More than half dead - Lower shading issues - Spider plant: new growth from
	Wandering Jew	17		12	Wandering: 1.5	off-spring
# 3	Spider Plant	13 Tallest leaf: 17	28	12	High Point: 4.6250 Low Point: 3.4375 *Difference: 1.1875* Root Depth: 0.25	- Golden Pathos plant was not found so data could be recorded - Noticeable Hole in medium - Hill in medium = unequal air flow
# 4	Spider Plant *Large*	13	26	Major Axis: 12 Minor Axis: 9 *(Ellipse shaped)*	High Point: 4.125 Low Point: 3.500 *Difference: 0.625* Root Depth- Large: 0.125 Small: Exposed	- Good health overall - Transcenda Zebrina was dead so no data could be recorded - Screen Rusted out - Irrigation not working - Growth medium falling out - No Phytoremediation - Unequal watering - 3 inch water line, Top layer no water
	Spider Plant *Small* *Planted 5/1*	6	10	3		

Table K.2 Plant measurements (after).

Second Plant	Plant Type	Plant Height (in)	Plant Spread (in)	Root Spread (in)	Growth Medium	General Notes Grow Tips
	Spider	**9**		**8.5**		
	philandrinum	**5**	**7**	**5**		
# 1	Ficus	11		16	High Point: Low Point: *Difference: 0.500* Root Depth: Spider: 1.5	- High stress - Drying out - Noticeable water spots - Golden very shaded - Bottoms are dying
	From home	9		5	Golden: 2	
# 2	Helix Ivy Spider Tradcendinita	4.5 9.5 7.25	8 9	4.5 8.5 6	High Point: Low Point: *Difference: 2* Root Depth: Spider: 2	- High Stress - Poor Health - More than half dead - Lower shading issues - Spider plant: new growth from
	Ficus	12.5		11.5	Wandering: 1.5	off-spring
# 3	Spider Phil TradICENDINITA	12 3 6	16 10 16	7.5 2 7	High Point: 4.6250 Low Point: 3.4375 *Difference: 1.1875* Root Depth: 0.25	- Golden Pathos plant was not found so data could be recorded - Noticeable Hole in medium - Hill in medium = unequal air flow
# 4	*Pathos* Spider	6.5 16	14 25	8 *23*	High Point: 4.125 Low Point: 3.500 *Difference: 0.625* Root Depth- Large: 0.125 Small: Exposed	- Good health overall - Transcenda Zebrina was dead so no data could be recorded - Screen Rusted out - Irrigation not working - Growth medium falling out - No Phytoremediation - Unequal watering - 3 inch water line, Top layer no water

Table K.3 Plant measurements (test trays).

Test Trays	Plant Type	Plant Height (in)	Plant Spread (in)	Root Spread (in)	Growth Medium	General Notes Grow Tips
# 1	Spider	10.8	22	18		
# 2	Ficus	11.6		15.25		
	Zebrina	6	20	5.5		
	pathos					Did not survive
# 3	Marignat	15	22	16.3		
		13.25	13	9		
	pathos	6.5	18	7		
		5.7	17	6.5		
		5.25	5	7		
# 4		6	12	5		
		5.25	18	5.5		
	Spider	11.25	24	18		
	Helix	4	18	3.5		

Table K.4 Plant measurements reconciled.

Summation of plant data collected

Planty Species	Root Diameter	Plant Height	Spread
Chlorophytm comosum (Spider Plant)	8	13	
	13	25	
	12	13	28
	12	13	26
	3	6	10
	8.5	9	
	7.5	12	16
	23	16	25
	18	10.8	22
	8.5	9.5	9
	18	11.25	24
Average	11.95455	12.59545	20
St. Dev	5.524551	4.645157	6.910137
Trascenda Zebrina	12	17	
	5.5	6	20
Average	10.24652	10.1651	15.98203
St. Dev	3.25	5.5	0
Philodendron cordatum (Heartleaf philodendron)	5	5	7
	2	3	10
Average	3.5	4	8.5
St. Dev	1.5	1	1.5
Epipremnum aureum	5	9	9.5
Average	5	9	9.5
St. Dev	0	0	0
(Golden Pathos)	10.5	15	14
	8	6.5	14
	7	6.5	18
	6.5	5.7	17
	7	5.25	5
	5	6	12
	5.5	5.25	18
Average	7.071429	7.171429	14
St. Dev	1.678191	3.231746	4.242641
Ficus benjamina	16	11	
	15.25	11.6	
Average	15.625	11.3	#DIV/0!
St. Dev	0.375	0.3	#DIV/0!
Hiedra helix (English Ivy)	4.5	4.5	8
	3.5	5	18
Average	4	4.75	13
St. Dev	0.5	0.25	5
Tradisenda	6	7.25	
	7	6	16
Average	6.5	6.625	16
St. Dev	0.5	0.625	0
Tradescantia spathacea	5	9	
Average	5	9	#DIV/0!
St. Dev	0	0	#DIV/0!
Dracanea marginata	16.3	15	22
	9	13.25	13
Average	12.65	14.125	17.5
St. Dev	3.65	0.875	4.5

K.5 The Average and Standard Deviation of all Plant Measurements

Table K.5 The average and standard deviation of all plant measurements.

Plant		Root Diameter	Plant Height	Spread Diameter
English Ivy	Average	10.16	12.07	33.02
	Std. Dev	1.27	0.64	12.70
Ficus	Average	39.69	28.70	n/a
	Std. Dev	0.95	0.76	n/a
Golden Pathos	Average	17.96	18.22	35.56
	Std. Dev	4.26	8.21	10.78
Heartleaf Philondendron	Average	8.89	10.16	21.59
	Std. Dev	3.81	2.54	3.81
Marginata	Average	32.13	35.88	44.45
	Std. Dev	9.27	2.22	11.43
Oyster Plant	Average	12.70	22.86	n/a
	Std. Dev	0.00	0.00	n/a
Spider Plant	Average	30.36	31.99	50.80
	Std. Dev	14.03	11.80	17.55
Wandering Jew	Average	26.03	25.82	40.59
	Std. Dev	8.26	13.97	0.00
CM Conversion	2.54			

K.6 Plant Tray Nutrient Measurements

Table K.6 Biowall plant tray nutrients.

Biowall Nutrients

Biowall Tray Conditions	Carbon Pellets	Coconut Fiber	Growstone	Total
pH	N/A	7.5	>=7.5	7.5
Nitrogen	N/A	N1-Deficient	N/A	N1-Deficient
Phosphorous	N/A	P3-Sufficient	N/A	P3-Sufficient
Potassium	N/A	K2-Adequate	N/A	K2-Adequate

Tray nutrient content recorded with Luster Leaf Products Inc. Soil Test Kit. Nitrogen, Phosphorous, and Potassium were recorded with individual chemical tests from this kit. The individual sample results provide a color which is comparted to a given 0-4 scale (0 depleted; 4 surplus) to indicate the elements level within the sample.

PUBLICATIONS

Growing Aesthetics into the Biowall

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ABSTRACT

Indoor Air Quality (IAQ) is an increasing concern in residential construction, particularly homes that are consciously designed for high efficiency. The IAQ problem occurs because efficient homes tend to be air tight, but without adequate exchange of outside air pollutants such as Volatile Organic Compounds (VOC's) can achieve concentrations that are higher than desired. Biowalls are an innovative technology for addressing IAQ concerns by using the natural ability of plants to remove airborne contaminants. This paper summarizes Biowall research that is currently being conducted in a research home located in the Midwest with a particular emphasis on aesthetic considerations. It is difficult to find plants that thrive in a Biowall environment. A study identifying varying species of plants which will survive in this environment enhances the Biowall designer's ability to add a variety of colors, textures, and sizes to plant trays and achieve a presentation that is appealing for a Biowall owner.

1. INTRODUCTION

Current work on botanical air filtration has benefitted from previous research on improving residential Indoor Air Quality (IAQ). Understanding this research requires knowledge of current building design, Heating Cooling Ventilating and Air Conditioning (HVAC) trends, insight to residential air filtering methods, and a background in phytoremediation research.

1.1 Indoor Air Quality (IAQ)

The air that fills the space within a building is called indoor air. The amount of contaminates within the indoor air determines IAQ. After being exposed to the people and processes occurring within a building, indoor air will pick up contamination that is harmful to people. The Environmental Protection Agency (EPA) identifies indoor air pollution as one of the top five environmental health risks (EPA, 2008).

Table 1 identifies three categories of indoor air pollutants identified by the EPA. Particulate matter includes dust, smoke and pollen. Common Volatile Organic Compounds (VOC's) include formaldehyde and toluene. Biologicals like bacteria and mold spores are byproducts of activities people do indoors. There is not one air cleaning technology that removes all three categories of contaminants shown in Table 1. The value in this research is realized in providing a variety of technologies that can be deployed for improving residential IAQ.

Table 1: Summary of Indoor Air Contaminates (EPA, 2008)

Indoor Air Pollutants	**Pollutant Source**
Particulate Matter	Dust, smoke, pollen, animal dander, tobacco smoke
Volatile Organic Compounds (VOC's)	Formaldehyde, toluene, adhesives, paints, cleaning products, pesticides, some air fresheners
Biologicals	Bacteria, mold spores, viruses, dust mites

1.1.1 ASHRAE & IAQ

Recognizing the impact poor IAQ is having on people, a report at the 2016 American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) IAQ Conference stated; "there is strong evidence that investments in home IAQ can reduce healthcare costs" (Bahnfleth, 2018). Exposure to poor IAQ is magnified by both efficient building design and energy saving practices for HVAC systems. Energy efficient buildings are sealed off from the outside to avoid venting treated air to the environment. Indoor air is recirculated into the air supply for its temperature and humidity properties, requiring an HVAC system to perform less heating or cooling (AHRAE, 2016).

1.2 Sick Building Syndrome (SBS)

Studies have shown that the amount of time spent indoors increases Sick Building Syndrome (SBS) occurrences (EPA, 1991). Symptoms like prolonged coughs, headaches, tiredness and respiratory issues, regularly written off as common illnesses, correlate with time spent indoors and an inadequate supply of fresh air (EPA, 1991). SBS health concerns are not surprising given that Americans spend more than 90% of their time indoors; where the indoor air is 2-5 times more polluted "than the worst outside air" (EPA, 2004). This concern is not new. SBS has been recognized as a major issue facing Americans health for some time. As early as 1999, the conditions that lead to high SBS occurrences were profiled on "60 minutes" (1999).

The reports and studies mentioned in ("60mins," 1999); (EPA, 1991); (EPA, 2004); (ASHRAE, 2016); share a common theme about IAQ. Filtration of air contaminants prior to circulation to the building and its inhabitants is important to providing a good IAQ. A proper air filtration strategy developed with knowledge of the processes occurring within the building can reduce SBS occurrences and improve Americans health (Bahnfleth, 2018).

1.3 Residential Air Filtration Technologies

Understanding widely used air filtration methods is essential to developing a new technology to improve IAQ. The mechanical filter shown in Figure 1 is the primary method used to clean indoor air in residential buildings. Air filters are designed to improve the quality of air by removing the particulate contamination summarized in Table 1. Filtering is accomplished by forcing return air flow into the HVAC system through the filter. Filters are generally made of spun fiberglass material, pleated paper, or cloth and are most homeowners main line of defense for insuring appropriate IAQ (Davis, 2015).

Figure 1: New Air Filter

What is not widely known is that filters vary in their effectiveness in removing contaminants from air. ASHRAE and other organizations took on this uncertainty and developed the Minimum Efficiency Reporting Value (MERV) for mechanical air filters. The MERV system establishes a metric for air filter effectiveness that is expressed as a number from 1 to 16, where a higher number indicates a higher level of contaminant removal. Table 2 is a MERV rating chart from ASHRAE Standard 52.2 that identifies lower MERV rated filters as limited to filtering larger particulate matter. Higher MERV ratings still remove particulates like tobacco smoke, but also removed biologicals like some types of bacteria.

Table 1: ASHRAE Standard 52.2 MERV Rating Chart

MERV RATING CHART

Standard 52.2 Minimum Efficiency Reporting Value	Dust Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	[illegible]	[illegible]	[illegible]
19	n/a	n/a	[illegible]	[illegible]	[illegible]
18	n/a	n/a	[illegible]	[illegible]	[illegible]
17	n/a	n/a	[illegible]	[illegible]	[illegible]
16	n/a	n/a	[illegible]	General Surgery	Bag Filter: [illegible]
15	[illegible]	n/a	All Bacteria	Hospital Inpatient Care	[illegible]
14	[illegible]	[illegible]	Most Tobacco Smoke	Smoking Lounges	Box Filter: [illegible]
13	[illegible]	[illegible]	[illegible]	Superior Commercial Buildings	[illegible]
12	[illegible]	[illegible]	[illegible] Legionella	Superior Residential	Bag Filter: [illegible]
11	[illegible]	[illegible]	Humidifier Dust Lead Dust	Better Commercial Buildings	[illegible]
10	[illegible]	[illegible]	Milled Flour		Box Filter: [illegible]
9	[illegible]	[illegible]	Auto Emissions Welding Fumes	Hospital Laboratories	
8	[illegible]	[illegible]	[illegible]	Commercial Buildings	Pleated Filters: [illegible]
7	[illegible]	[illegible]	Mold Spores Hair Spray	Better Residential	Cartridge Filters: [illegible]
6	[illegible]	[illegible]	Fabric Protector Dusting Aids	Industrial Workplaces	Throwaway: [illegible]
5	[illegible]	[illegible]	Cement Dust [illegible]	[illegible]	
4	[illegible]	[illegible]	[illegible]	[illegible]	Throwaway: [illegible]
3	[illegible]	[illegible]	Pollen Dust Mites	Residential	Washable: [illegible]
2	[illegible]	[illegible]	Sanding Dust Spray Paint Dust		
1	[illegible]	[illegible]	Textile Fibers Carpet Fibers	Window A/C Units	Electrostatic: [illegible]

The limitation to all air filters is revealed through their design life (ASHRAE, 2017). As the filter captures contaminants from passing air, it becomes restricted, loses effectiveness, and looks dirty. Figure 2 shows a dirty air filter with a relatively low MERV rating that should be replaced. Forgotten air filters are common, and a leading source of HVAC malfunction is due to the high restriction of airflow caused by a dirty filter (Davis, 2015). Dirty or forgotten air filters are a large contributor to poor IAQ to a building. It is recommended that a filter be checked once a month and changed before it appears like the one shown in Figure 2.

Figure 2: Dirty air filter to be replaced

Other air filtration methods can target specific contaminants and supplement mechanical air filters. The EPA (2008) summarizes these technologies in Table 3. Ultraviolet (UV) and gaseous air filtration technologies are available to target gaseous phase contaminants, and biologicals from the contaminants described in Table 1. With their effectiveness in specific targeting, brings tradeoff in limitations. The EPA (2008) highlights the limitations in each technology in Table 3; UV lights can target some of the biologicals listed in Table 1; Gas Phase filters target gasses and odors; PCO cleaners use UV lights and introduce a substance to react with the light to destroy gaseous pollutants; Ozone generators use UV light with electrical discharge (experimental) (EPA, 2008).

Table 2: Air Cleaning Technologies and Limitations (EPA, 2008)

Air Cleaning Technologies		**Pollutants Addressed**	**Limitations**
Filtration	Air Filters	Particles	Ineffective in removing larger particles because most settle from the air quickly and never reach filters.
	Gas-Phase Filters	Gases	Used much less frequently in homes than particle filters. The lifetime for removing pollutants may be short.
Other Air Cleaners	UVGI	Biologicals	Bacterial and mold spores tend to be resistant to UV radiation and require more light or longer time of exposure, or both, to be killed
	PCO	Gases	Application for homes is limited because currently available catalysts are ineffective in destroying gaseous pollutants from indoor air.
	Ozone generators	Particulates, gases, biologicals	Solid as air cleaners, they are not always safe and effective in removing pollutants. By design, they produce ozone, a lung irritant.

1.4 Phytoremediation & Botanical Air Filtration

In the late 1960's environmental scientist Bill Wolverton, working for the U.S military led a team which discovered that plants roots filtered Agent Orange from Florida waterways (NASA, 2007). Following this work the National Aeronautics and Space Administration (NASA) funded Wolverton to explore phytoremediation-or using the rhizosphere of plants roots to filter contaminants from an air supply, for deep space exploration (Wolverton, 1997).

Based off 27 years of research, "The NASA Guide to Air-Filtering Houseplants" list was derived. These plants are identified for; their ability to remove carbon based and VOC contaminants from the air; non-toxicity to human plant owners; ease of growth; and expected lifespan (Rokas, 2017)..

Research into botanical air filtration led to the development of a residential application (Lerner, 2015). Relating to the gaseous methods discussed in Section 1.3, botanical air filtration targets VOC's through phytoremediation (Alraddadi, 2016), and particulates, along with some gases through the selected growth medium (Wang, 2011). A Biowall has several benefits that can assist a traditional MERV-rated air filter to improve IAQ.

1.5 The ReNEWW Home

The botanical air filter prototype for this research is installed in the Retrofitted Net-Zero Energy, Water and Waste (ReNEWW) Home in West Lafayette, IN. Figure 3 shows that it is a typical bungalow style home. The home was originally built 80 years ago, but was heavily renovated as part of ongoing residential research. The ReNEWW home utilizes local resources to supplement consumption within the home to meet an annual net-zero energy goal.

Figure 3: The ReNEWW Home

The ReNEWW Home (Fig. 3) has a goal higher than net zero energy. It aims to match annual living consumption in energy and water with local resources and renewable systems output. The ReNEWW Home employs photovoltaic (PV) electricity, geothermal, rainwater catchment and filtration, solar thermal heat catchment, high efficiency appliances, smart building automation, and botanical air filtration to meet the net-zero energy mission.

2. THE CONDITONAL PLANT GROWTH STUDY

The experiment for this paper is a conditional plant growth study completed in the botanical air filter prototype (Biowall) located in the ReNEWW home. The purpose of this ongoing experimentation is to expand the types of plants used for botanical air filtration to target indoor contaminants. This study incorporated and evaluated more known air filtering plants into the list of known acclimate-able plants identified during previous research (Rajkhowa, 2016).

Bringing diversity into the Biowall growth trays adds an important aesthetic component to Biowall design. It widens a designer's ability to meet user tastes. During fall 2017 through spring 2018, plant growth experiments utilizing various known air filtering plants expanded the toolkit of which plants that can be grown in this Biowall environment.

2.1 The Biowall

The Biowall project conducted introductory research to evaluate VOC (Toluene) filtration ability in an environmental chamber setting (Alraddadi, 2016). The growth medium used for this research was selected to target some organic compounds and particulate matter (Wang, 2011). The Biowall prototype, shown in Figure 4, was derived from previous research and orients four plant trays in a vertical duct that is an integral part of the ReNEWW home HVAC system.

Figure 4: Biowall in the Research Home

Figure 4 shows the Biowall applied to the living room indoor air intake vent of the ReNEWW Home. It is a supplement to the home's HVAC mechanical air filter. The Biowall is designed to target particulates, CO2's, and VOC contaminations from the air.

A contribution to an energy efficient, sustainable, method of supplying quality indoor air, the Biowall prototype uses a Building Automated System (BAS) to control lights, irrigation, and data monitoring sensors. Its function and trend data are available to researchers through an online WebCTRL website. When the HVAC system in the house is on, air is drawn through the plant trays before circulating it to the home.

2.1.1 Biowall Experimental Timeline

The Biowall prototype was installed in the ReNEWW Home in spring 2016. Commissioning work consumed the first year of operation. In spring 2017 through spring 2018, preliminary research to field test the Biowall systems was conducted; the home was occupied during this period and this work provided an in depth system validation. The quantification of air filtration capability of this prototype within the ReNEWW Home will be focus of future research as this concept seeks validation.

2.2 Experimental Methodology

Phytoremediation utilizes the rhizosphere of plants roots to complete the filtration process. Figure 5 shows plants in Biowall plant trays acclimating to the growth medium in a in lab nursery on Purdue campus. This allows for root spread through the growth medium and increases filtration efficiency in the Biowall (the more roots, the higher capacity for phytoremediation). A three month acclimation period is needed for the plants roots to grow and develop in the trays.

The growth medium in the plant trays in Figure 5 are developed to be a porous semi-aqueous growth medium which air can be pulled through. The selection of this growth medium was aided by research conducted by Wang (2011). Care and fertilization followed a prescription derived by Rajkhowa (2016) and is an aqueous nutrition delivery method. Upon maturation, the plant tray is taken to the ReNEWW House and placed in one of four plant wall trays of the Biowall to filter indoor air. Plants are prepared at a young age for use in Biowall plant trays. Figure 5 also shows propagation of new plants. Propagation is completed six to twelve months in advance of Biowall use.

Figure 5: in lab Biowall Plant Tray Acclimation Nursery

As a limitation of this research, fertilizer was not used in the growth trays while installed in the Biowall. Possible unknown effects on resident health demanded further investigation into fertilization prior to use. For that reason, the plant trays have an expectancy of 3-6 months of EFFECTIVE filtration capability due to the lack of nutrients. A plain indicator of the Biowall filtration efficiency status is plant health; an unhealthy plant is not performing filtration efficiently.

2.3 Experiment Plant Selection

The golden pathos, chlorophytm comosum, philodendron cordatum, and hiedra helix are plants from the NASA Guide to Air-Filtering Plants that showed success in growth from previous Biowall research conducted by Rajkhowa (2016) and were included in this study as well. The ficus benjamina, dracanea marginata, aglaonema modestum, sansevieria trifasciata laurentii, trascenda zebrina and tradescantia spathacea were also added to this study for their air filtering properties as well as variation in colors and growth. These plants and more are shown in Figure 6 from the NASA Guide to Air-Filtering Houseplants (Rokas, 2017).

Figure 6: plants from the NASA Guide to Air-Filtering Houseplants (Rokas, 2017)

3. RESUTS

The study started with an initial set of filtration trays deployed prior to this research; trays dating to the Biowall prototype installation (spring, 2016). Those trays embodied the initial data set (Fig. 7, left). The initial data (left) is limited in plant species to those listed in section 2.3. Once acclimated and deployed to the Biowall, the plant trays prepared as part of the conditional plant growth study replaced the initial data set and are the after data (Fig. 7, right). There is a marked increase in plant species variation in Fig. 7 (right) as compared to the initial data set Fig. 7 (left).

Figure 7: Biowall Initial (left); Biowall after (right)

The conditional plant growth study required a period of in-lab plant growth verification and preparation followed up with regular ongoing plant growth maintenance. During this time, plant/root dimensions were recorded, nutrition measurements were made, and plant growth observations were made to see what plants thrived. This data served as the documentation that identified successful plants; the results being a documentation of known air filtering plants with a demonstration of their ability to survive in the Biowall environment.

Through the methodical use of varying plant species, the ability to bring variation in color to manipulate plant tray appearance with known air filtering plants is demonstrated. Figure 7 shows limited plant variations initially (left), and increased plant variation after (right).

3.1 Biowall Plants

Table 4 identifies the eight plant species that survived the initial plant tray growth period, and the conditional plant growth study performed in the Biowall. The result of this research provides a variation of known filtering plants for the Biowall designer, or owner to make aesthetically pleasing plant trays. Also, as each plant can target different contaminates (Wolverton, 1997), this work is a caveat to future research into contamination targeting.

Table 3: Eight successful air filtering plants that grow in the Biowall

Plant Name	Picture	Plant Name	Picture
Chlorophytm comosum (Spider Plant)		Tradescantia spathacea	
Ficus benjamina		Philodendron cordatum (Heartleaf philodendron)	
Dracanea marginata		Hiedra helix (English Ivy)	
Epipremnum aureum (Golden Pathos)		Trascenda Zebrina (Wandering Jew)	

6. CONCLUSIONS

The conditional plant growth study within the Biowall is an expansion from the four-original known air filtering plant species verified through Rajkhowa (2016). The eight successful plants from NASAs know air filtering plant list which thrived in the Biowall environment, are shown in Table 4. The plants are; chlorophytm comosum; darcaena marginata; ficus benjamina; golden pathos; hedera helix; philodendron cordatum; tradescantia spathacea; tracenda zebrina.

This research addresses the need to understand plant behavior in the Biowall and increases variation in plant species known to grow in this environment. The result brings color, size, and plant arrangement capabilities to the Biowall designer or owner; inviting a day where a functional Biowall will not only contribute to a healthy indoor environment, but add beauty to the home by providing plant tray arrangements for holidays, change of season, or meet the owner's personal preference.

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