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ABSTRACT

According to the U.S. EPA Americans spend 90 percent of their time indoors where indoor air is two to five times more polluted than outdoor air. Toxins in the built environment have been found to cause adverse physical and mental health effects on occupants and are estimated to cost the U.S. 125 billion dollar annually in lost productivity. To address this challenge a novel botanical air filter was developed for improving indoor air quality in buildings. The "Biowall" is envisioned as an integral part of the heating and cooling system for a home or small commercial building; where it will remove airborne contaminants by leveraging the natural ability of plants to metabolize harmful volatile organic compounds. This research evaluated a prototype Biowall in an environmental chamber where temperature, relative humidity and toxin levels were precisely monitored. A known amount of contaminant was introduced into the chamber and then its decay was monitored both with and without the botanical air filter. The results showed that the Biowall reduced VOC levels by 60% without having an adverse effect on the relative humidity of the occupied space. This data was used to develop and calibrate a thermodynamic model of the Biowall. Long term, this research could lead to the development of performance based standards for indoor air quality that save energy by reducing the amount of outdoor ventilation air used for maintaining high levels of indoor air quality.

1. INTRODUCTION

1.1 Problems in IAQ

IAQ is a key topic in the built environment because people spend 90% of their time indoors (U.S. Environmental Protection Agency, 1989). Indoor air is typically two to five times more polluted than outdoor air (Wallace, 1987) due to the presence of harmful toxins off-gassed by manmade products such as sealants, adhesives and cleaners. Many of these contaminants are Volatile Organic Compounds (VOCs); substances that contain carbon and are gases at atmospheric conditions. VOCs are the main cause of respiratory illness, allergies, asthma, skin irritation, headaches, and fatigue (Fisk, 2000; Goldstein & Galbally, 2007).

Some of society's weakest members, such as the elderly, are the most at risk to poor indoor air quality due to lifestyle habits and weakened immune systems (Coelho, Steers, Lutzler, & Schriver-Mazzuoli, 2005). Depending on the type and quantity of VOCs present, adverse health effects can become more extreme. For example, toluene is a compound commonly found in personal care products and has been identified as a neurotoxin that can cause brain damage and behavioral disorders in children (Grandjean & Landrigan, 2014).

1.2 Relationship to the Built Environment

It was estimated in 2000 the U.S. loses 125 billion dollars annually in decreased productivity due to poor IAQ (Fisk, 2000). Since that time, the potential for lost revenue due to poor IAQ has increased because of energy-efficient residences that are being built today. One key to building an energy-efficient house is limiting the amount of air exchange with the outdoors because it is costly to heat and cool. The Law of Unintended Consequences applies in this situation because a positive step in one area (reducing energy) frequently has negative side effects in another area (poor IAQ). A solution that optimizes IAQ and energy efficiency is needed.

A number of methods improve indoor air quality, but they offer an incomplete solution. One obvious option is removing the source of VOCs by using organic materials, but that is limited in application because only certain products are VOC free. The next best strategy is to bring in outside air through mechanical ventilation to dilute the concentration of toxins. However, when temperatures outside are not the same as indoors, heating or cooling energy is required to make up the difference. An Energy Recovery Ventilator (ERV) is a heat exchanger that reduces the energy penalty of outside air, but there is still room for improvement because VOCs can accumulate whenever the ERV is not running.

1.3 Solution: Botanical Air Filtration

One solution to the competing problems of indoor air quality and energy efficiency is botanical air filtration. In 2011, researchers at Syracuse University evaluated a botanical air filter in a building. Their device used a fan to pull air across a carbon filter that had plants growing in it. The researchers reported significant improvements to air quality and also the potential to reduce HVAC energy consumption by up to 15% (Wang & Zhang, 2011) due to reduced heating/cooling of ventilation air in the HVAC system.

This research has its “roots” in earlier research conducted by NASA in support of deep-space travel. In the 1980s researcher Bill Wolverton quantified the VOC-removal potential of various plant species (Wolverton & McDonald, 1982). More studies were conducted to expand this research, but the psychological and particulate aspects were not investigated until Alan Darlington found biofilters could improve employee morale without introducing an abundance of allergens (Darlington et al., 2000).

The same year the Syracuse University article was published, Purdue University earned a second-place finish in the Solar Decathlon, an international competition where teams of university students design and build net zero energy homes. Purdue’s entry featured an innovative biofilter known as the Biowall; a living wall of plants that was directly incorporated into the home’s HVAC system (Rodgers, Handy, & Hutzel, 2013). The current biowall research is focused on improving the first version of the Biowall by refining the prototype and evaluating it in a laboratory setting.

2. METHODOLOGY

The purpose of this research was to evaluate the potential for using botanical air filtration to improve indoor air quality in residences, the indoor space where we spend the majority of our time. More specifically, the focus of the research was to evaluate the Biowall’s energy impact on an HVAC system by observing its outside air reduction and sensible/latent load creation. The Biowall is designed to be integrated with the central air conditioning system of a home. Contaminated air from the building passes through the Biowall before being routed by the return air ductwork to the fan/coil unit of the air conditioning system.

2.1 Experimental Apparatus

Figure 1 identifies the main components of the Biowall. The plenum is a stainless steel box, roughly 6’ x 2’ x 2’ (2m x 0.6m x 0.6m), that houses the filter media, plants, and lighting. The filter media is mounted on a trellis along with two LED strip lights that are mounted on either side of the plenum. The cross sectional view shows a spray irrigation system that uses a waterline, small mist nozzles and a concentrated tank of fertilizer, which is siphon diluted to water the plants. Although not shown in Figure 1, the Biowall uses a simple controller to automate lighting (on/off), watering (on/off), and air flow (on/off).

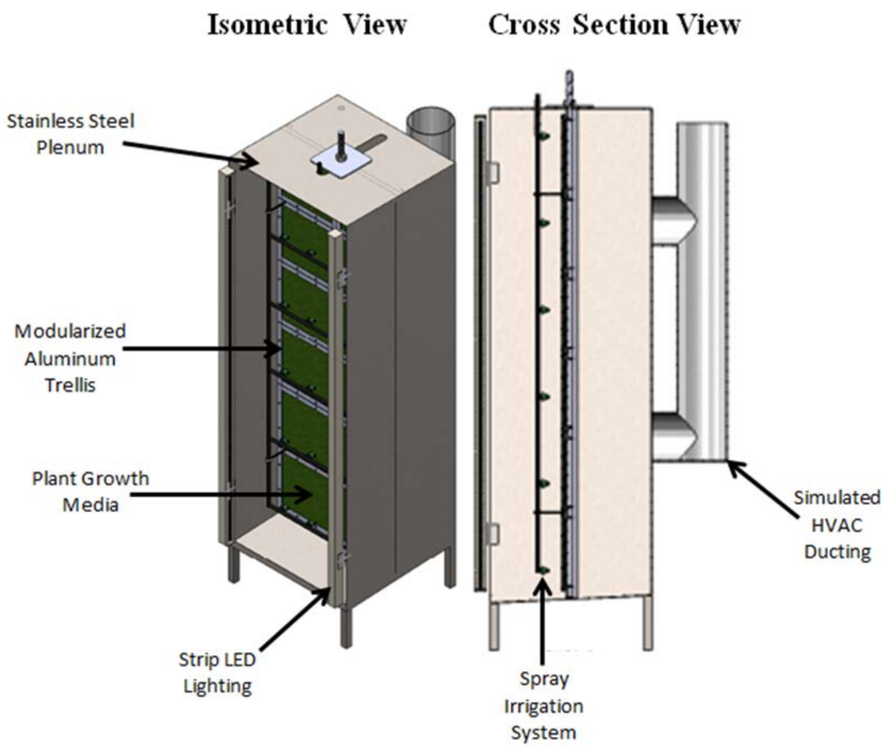

Figure 1: Multiple views of the Biowall Apparatus

2.2 Experimental Setup

Figure 2 shows the sealed, VOC free test chamber and equipment used for evaluating the Biowall. The image to the left is the exterior of the test chamber along with computer-based data acquisition equipment and sensors mounted on a tripod for measuring air properties; such as temperature, humidity, and VOC levels. The image to the right is the interior of the test chamber showing the Biowall and more instrumentation for measuring air properties.

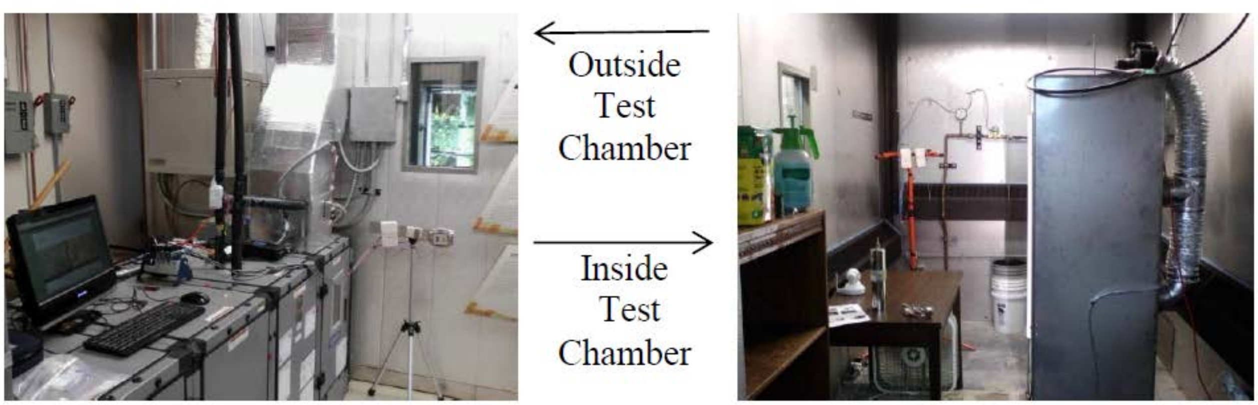

Figure 2: Biowall test chamber and instrumentation

2.3 Experimental Protocol

Figure 3 summarizes the five primary mechanisms for reducing toxins in the air of a building. Surface deposition and air leakage are a function of the building envelope (or a test chamber during an experiment). Adsorption and absorption are a function of the filter media. The "bull's-eye" of Figure 3 is air cleaning by microbes that are present on or in the root structures of plants. Microbes were the basic mechanism targeted for study during this research project.

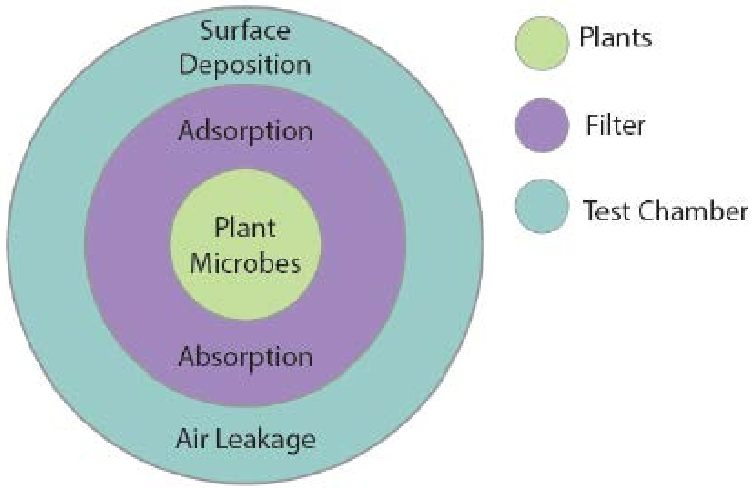

Figure 3: Mechanisms for contaminant removal from air

An experiment was designed to test the Biowall's plants ability to remove gaseous contaminants from air in real time. The methodology was adapted from earlier botanical air filtration research where a known contaminant was introduced into a test chamber and the exponential decay was monitored (Wang & Zhang, 2011). For the experiment, the permissible 8-hour exposure limit from OSHA for toluene (200 ppm) was introduced into the test chamber. The concentration of toluene was measured via air quality units over a 300-minute test period. After data collection, toluene values were normalized based on peak concentration, and an exponential decay curve was fit to the data to yield a time constant.

The Experiment measured the exponential decay of toluene with the Biowall in the test chamber. The Baseline repeated the same test, except that the growth medium was removed from the Biowall. Deposition and leakage affected both tests in the same way. Furthermore, absorption and adsorption are believed to be small in the Biowall growth medium because toluene is insoluble with water and no activated carbon is present. The equation below shows that the difference between the Experiment and the Baseline isolates the impact of the plant microbes by themselves.

$$\underbrace{(\text{Deposition} + \text{Leakage} + \underset{\text{small}}{\cancel{\text{Absorption}}} + \underset{\text{small}}{\cancel{\text{Adsorption}}} + \textbf{Microbes})}_{\text{Experiment (with BW)}} - \underbrace{(\text{Deposition} + \text{Leakage})}_{\text{Baseline (no BW)}} = \underbrace{\underline{\textbf{Microbes}}}_{\text{Result}}$$

The experiment was repeated multiple times to verify the results. The data were then evaluated for statistical significance. A matched pairs t-test was conducted to observe the difference between samples at each point in time. A high level of confidence was achieved because a large amount of data were available for each test.

3. RESULTS

3.1 Indoor Air Quality Results

Figure 4 shows the indoor air quality data for the generation and decay of toluene. The normalized toluene concentration within the chamber is shown on the y-axis; starting from 70%. The duration of the test on the x-axis is expressed in minutes. Two data sets are presented for the two scenarios previously discussed. In both cases the curves peak around 100 minutes and follow one another until 180 minutes. Both decay scenarios were characterized by an exponential decay.

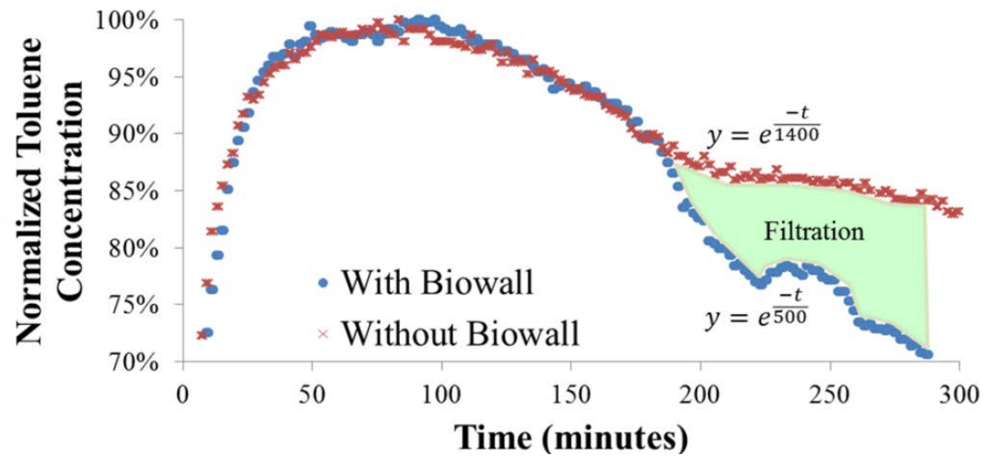

Figure 4: The Biowall's Improvement of IAQ

The difference between these two curves provides insight on the effect the Biowall has at improving indoor air quality. Based on the exponential decay constants, it was shown that a Biowall can improve indoor air quality three times faster than not having a Biowall. Comparing the two data sets with a matched pairs t-test after 180 minutes provides a P-value of less than 0.01. This means that the difference between the two curves is not random, but statistically significant with greater than 99% certainty.

Particulate matter (PM) sensors were used to monitor whether the Biowall was producing mold spores, pollen or bacteria. These sensors typically gather a particle count of anything less than a specified size. For example, a PM 10 sensor counts the number of particulates present that are less than ten micrometers in size. PM 2.5 and PM 10 steady state values were within comfortable limits for IAQ with and without the Biowall (<20 & <40 μg/m^3, respectively).

3.2 Biowall Modeling

Figure 5 is a schematic that illustrates the operation of the Biowall. One important factor is that some of the air was forced through the growth medium while some was intentionally bypassed to avoid excessive pressure drop and drying of the plant roots. Another important factor is that the Biowall growth medium was kept moist so that it acted as an evaporative cooler for the ventilation air. The growth medium decreased the air temperature while increasing the air relative humidity.

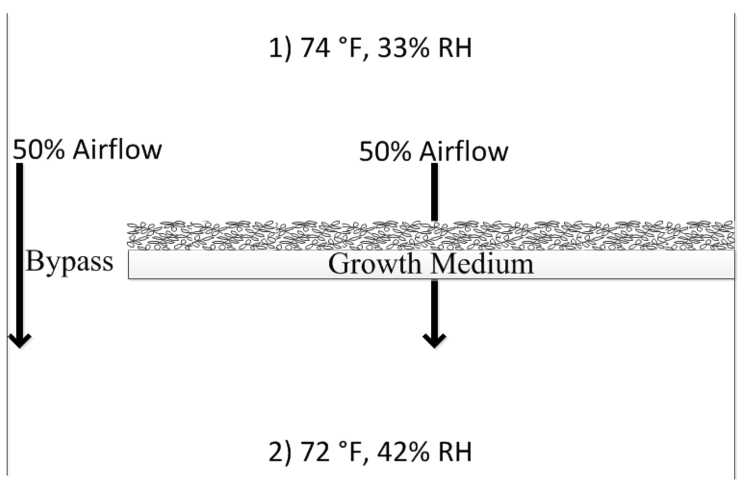

Figure 5: The Biowall's impact on temperature and humidity.

Equation 1 quantifies the bypass factor, which is the mass ratio of air flowing through the growth medium relative to the total volume of air. In this equation BP is the ratio of bypass around the filter, V_{bp} is the bypassed airflow and V_t is the total airflow. It was assumed that air density remained relatively constant across the filter, so only volumetric flow rates are included in equation 1.

$$BP = \frac{\dot{V}_{BP}}{\dot{V}_T} \tag{1}$$

The evaporative cooling for the Biowall was modeled using psychrometric equations for air/water mixtures to allow for the exchange between sensible energy and latent energy. In other words, air is passed over the wet growth medium and picks up moisture, causing a corresponding decrease in dry bulb temperature. This was quantified using wet-bulb effectiveness, which is a temperature ratio showing the amount of humidification achieved with respect to the maximum humidification possible. It can be expressed by equation 2:

$$\varepsilon = \frac{T_{1,DB} - T_{2,DB}}{T_{1,DB} - T_{1,WB}} \tag{2}$$

Where ε is the wet-bulb effectiveness, T is the temperature, state 1 is before the evaporative cooler, state 2 is after the evaporative cooler, DB denotes dry-bulb and WB denotes wet-bulb.

3.3 Biowall Analysis

Figure 6 summarizes a thermodynamic model of the Biowall that was developed to characterize its impact on temperature and humidity in ventilation air. Treating the Biowall as solely an evaporative cooler with a bypass is an oversimplification of its energy impact on an HVAC system because the device also has sensible energy from the lights and fan. Thus the overall model includes the inlet and outlet conditions (state points 1 and 2, respectively), the sensible heat gain by the lights, the moisture added by the biofilter, the bypass around the biofilter and the sensible heat gain by the fan.

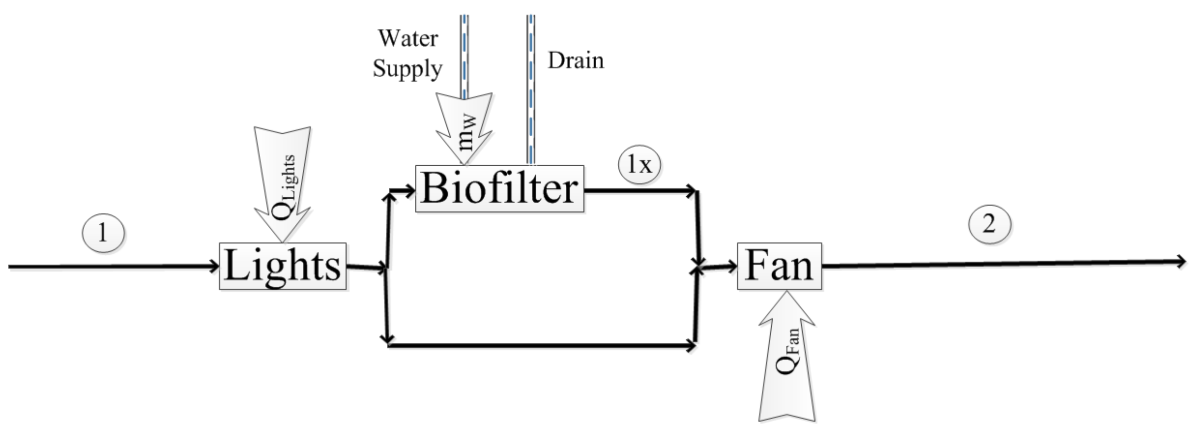

Figure 6: Energy diagram of Biowall components

The thermodynamic properties at the state points were determined using an engineering equation solver and equations based on conservation of mass and energy. The enthalpy at state 1x was determined using equation 3 below. In this equation Q_{lights} represents the sensible heat gain from the lights, $\dot{m}$ is the mass flow rate, h_1 is the enthalpy at the inlet, and h_{1x} is the enthalpy immediately following the biofilter.

$$Q_{lights} = \dot{m}(h_{1x} - h_1) \tag{3}$$

The sensible heat gain for the lights and fan were determined from the measured power readings and adjusted to account for the portion of electricity that became heat in the system. A similar approach was used for quantifying the sensible energy from the fan, except with state 1x as the inlet and state 2 as the outlet.

Equation 4 quantifies the latent load from the Biowall by the humidity ratio, where 2 is the outlet, 1 is the inlet, 1x is just after the biofilter, and BP is the bypass factor. The basis of this equation is a mixing process where conservation of mass is upheld. Once the humidity ratio and enthalpy at state point 2 have been determined, temperature and relative humidity can also be found using thermodynamic properties of air.

$$\omega_2 = (1 - BP)w_{1x} + BPw_1 \quad (4)$$

The thermodynamic model was calibrated by varying the wet-bulb effectiveness (ε) and bypass factor (BP). These values were adjusted until the model produced values for the temperature and relative humidity at state point 2 that were in reasonable agreement with direct measurements. The final wet-bulb effectiveness was found to be 0.70 and the bypass factor was 0.55.

Table 1 compares the calibrated model and the measured values for Biowall performance. The dry bulb temperature at the Biowall outlet was 72 ºF (22 ºC) and the modelled value was 72.6 ºF (22.6 ºC), which was less than 1% error. The relative humidity results were even more accurate. The measured relative humidity was 42%, the same as the modeled value.

Table 1: **Calibration of Biowall model**

Biowall Parameter	Measured	Modeled	Error
Outlet temperature, T_2 (ºF)	72.0	72.6	1%
Outlet humidity, RH_2 (%)	42	42	0%

Based on the low error values, the model was well calibrated in predicting the outlet conditions and can be used to analyze the Biowall's energy impact on an energy efficient home's HVAC system. The best way to summarize this potential impact is to consider the net heat load and moisture mass the Biowall adds to the system. Using the model these values were calculated to be approximately 300 Btu/hr (90W) and 0.4 lb/hr (0.2 kg/hr), respectively, or in other words the sensible heat ratio was 32%. The moisture mass added by the Biowall is very small; however the net heat load would have a significant impact on a residential HVAC system. Although in most applications more energy is spent heating a building annually than cooling it, so the Biowall could have a positive impact through its heat gain.

4. CONCLUSIONS

The Biowall has been shown to improve indoor air quality and have a positive impact on human health. Using toluene, a common VOC found in paints, adhesives and personal care products, the Biowall showed a three times faster reduction than not having a Biowall with a statistically significant dataset. This filtration has the potential to improve the life of the homeowner through increased productivity and decreased respiratory illness. Furthermore, the Biowall has been shown not to introduce additional allergens in the system so more homeowners can take advantage of this technology.

This Biowall project is significant because it closely aligns with efforts by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) and the United States Green Buildings Council (USGBC) to develop and promote performance based standards for indoor air quality. In other words, sensors in a building will measure contaminants in real time and adjust building performance accordingly to achieve a healthy balance.

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