# Optimization and Evaluation of a Botanical Air Filtration System in a Residence

Zhen Li
*Purdue university, United States of America*, li2215@purdue.edu

William Hutzel
*Purdue university, United States of America*, hutzelw@purdue.edu

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Zhen Li[1], William Hutzel[2]*

[1]School of Civil Engineering, Purdue University
West Lafayette, IN, USA
li2215@purdue.edu

[2] School of Engineering Technology, Purdue University
West Lafayette, IN, USA
hutzelw@purdue.edu

* Corresponding Author

## ABSTRACT

Studies have shown that plants are effective in removing indoor air contaminants to improve the Indoor Air Quality (IAQ). The Biowall is a botanical air filter which is designed to purify indoor air and improve IAQ through plant-assisted phytoremediation. Considering the development of high-performance building technology, the best solution may be to integrate plants into heating, ventilating and air conditioning (HVAC) systems. Using plants can reduce the energy consumption by decreasing the ventilation requirements. In addition, it also can provide moisture in the air, which can reduce the loads on the cooling equipment while delivering comfortable air quality. Earlier analyses for the Biowall showed it has the potential to remove contaminants and improve air quality. However, they were completed either in an environmental chamber or in another controlled environment and the Biowall was not connected with the HVAC system. Little research has been conducted on the performance of the Biowall in a residential setting to this date.

This paper evaluates the performance of the Biowall in a home, evaluates the control algorithms, and provides recommendations for long-term Biowall management. The Biowall system was installed in a research residence called the ReNEWW House, which is operated by Whirlpool Corporation and Purdue University and located in West Lafayette, IN. During the summer of 2016, a prototype Biowall was installed in the ReNEWW House. This paper evaluates the control strategies of the irrigation and fan system, presents a thermodynamic model of the Biowall, and shares results of the performance of the Biowall in terms of IAQ. The results suggest that the IAQ of the ReNEWW House was maintained well by the Biowall.

## 1. INTRODUCTION

The U.S. Energy Information Administration (EIA) data shows that residential buildings consume approximately 20% of the primary energy in the U.S. Roughly half of that total is for heating, ventilating, and air conditioning (HVAC) and is continually increasing. To reduce air infiltration and HVAC energy consumption, residential houses are increasingly being built more airtight. However, a well-insulated and tightly sealed building envelope also can have a negative effect on IAQ because it takes longer to dilute the contaminated air within the structure.

IAQ can significantly influence a person's health, comfort, and productivity. Past U.S. Environmental Protection Agency (EPA) studies indicated that Americans, on average, spend over 90 percent of their time indoors where the air may be two to five times more polluted than outdoors (EPA, 2016). Comparative risk studies performed by the EPA and the Science Advisory Board (SAB) ranked indoor air pollution among the top five environmental risks to public health. IAQ has been closely related to human productivity by other researchers. Wyon and Wargocki (2013) concluded that indoor environment quality affected the performance of their study participants in buildings. Specifically, they found that negative environmental air quality may reduce productivity in adults by 5% in laboratory settings, 10% in the field, and over 20 % in school children. Their review of 23 studies showed a linkage between typical building-related symptoms and productivity and that good indoor environment quality may promote less absenteeism. By using data from a call center, Niemela (2006) found a reduction of 10% in the prevalence of general symptoms (e.g., fatigue, headache, nausea, etc.) corresponded with a gain of 1.5% in performance.

Recent studies have shown that natural plants are effective in removing indoor air contaminants as they break down air contaminants into their fundamental elements and later use them as nutriment. In addition, through the process of photosynthesis, plants can absorb carbon dioxide from indoor air. As concern increases for the development of high-performance building technology, the best solution may be to integrate natural plants into HVAC systems.

Some case studies discussed performance of the biofiltration application and how it worked in buildings outside the test chamber. Dr. Alan Darlington from the University of Guelph investigated a living wall of plants. His team integrated this into an independent HVAC unit and the goal for this experiment was to examine the ability of a living plant wall to improve IAQ without a traditional ventilation system. This wall consisted of 150 different species of plants and was put in a 1,722 $ft^2$ air tight room at the Canada Life Assurance Co. headquarters building. The results showed that this living plant wall maintained acceptable IAQ without a traditional ventilation system (Darlington et, al., 2000). In 2004, they analyzed potential energy savings with living walls at several locations and showed that the living wall could save up to 60% of the energy used by ventilation (Darlington, 2004). A recent publication about a retrofit project for the Montreal-Pierre Elliott Trudeau International Airport terminal discussed the performance of the living wall. Compared to a steam humidifier, the living wall can be more economical and sustainable; and compared to an evaporator humidifier, the living wall can also improve the life quality for passengers and employees. This paper also analyzed the potential fresh air and energy consumption for the living wall (Peng, 2017).

A botanical bio filter called Biowall was designed by a team from Purdue University for the EPA Solar Decathlon in 2011. Since then, sets of experiments and analyses were conducted on the Biowall. The first stage study was in the Solar Decathlon House, the studies showed that the Biowall had the potential to decrease the temperature and increase the relative humidity (Rodgers, Handy, & Hutzel, 2013). Later, The Biowall was moved to an environmental chamber in the Applied Energy Laboratory, studies about the horticulture of the plants were conducted, which included the species of plants, growth media and irrigation frequency (Rajkhowa, 2016). Moreover, the performance of the Biowall in the environmental chamber was analyzed. The results of Alraddadi's (2016) study showed that in the same condition, the Biowall was more efficient compared to natural decay and he concluded that the Biowall had the potential to save energy in ventilation.

Although plants do improve the quality of indoor air, there have been few studies investigating the performance of plants in a residential environment. The function of the Biowall in a common residential house therefore needs to be evaluated and documented. To achieve this goal, The Biowall was installed in a residence in summer 2016. The next step for research aimed to test the performance of the Biowall in this residential house. Further research will focus on the benefits of the Biowall for improving IAQ and saving energy in a real residential house. Also, updates and control strategies are being implemented to make the Biowall more efficient.

## 2. SYSTEM SETUP

A new generation Biowall was installed in the Purdue University ReNEWW House in 2016, where the energy consumption, temperature and relative humidity were closely monitored by three graduate students from Whirlpool living in the house. Figure 1 is the street view of the ReNEWW House in West Lafayette, Indiana.

**Figure 1:** Street View of the ReNEWW House

The Biowall with its control system was installed in the ReNEWW House in May 2016. This installation included several steps: installing the body part of the Biowall, the watering system, and the lights and control system. Figure 2 shows the front view of the Biowall in the ReNEWW House. It faces the front door of the ReNEWW House. The white device to the left of the Biowall is the zone relative humidity and temperature sensor mentioned above. Beneath this sensor is a small doorbell switch that provides a local override to turn on/off the LED lights.

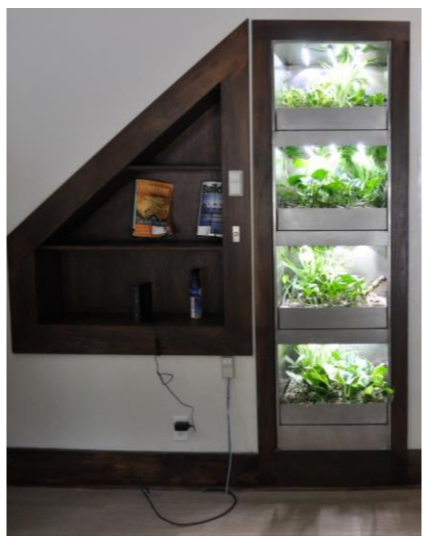

**Figure 2:** Front view of the Biowall in the ReNEWW House

Hidden from view, there is a Building Automation System (BAS) that adjusts the lighting, watering, differential pressure, and airflow to optimize air cleaning and plant health. The BAS is located in the closet as well. In this way, people can monitor the Biowall as well as access data like the temperature and relative humidity of the zone and the duct. The BAS was connected to the computer in the basement. By combining the sensors with the program, the controller can control the Biowall’s fan, lights, and watering schedule. Based on the data it collects, the trends of different parameters of the Biowall can be analyzed.

Equipping the Biowall with a controller, sensors, and programs provided automated control over its operation. Remotely monitoring the fan, lights, and watering system provides residents more operating choices for the Biowall. Through the control system, the Biowall system can be checked and monitored remotely.

# 3. METHODOLODGY

## 3.1 System Optimization

For the Biowall to function, it is connected to the HVAC system in the house when the fan of the HVAC system is running, it can provide air flow and extract and freshen air to the HVAC system to maintain better air quality. After the connection to the HVAC system was established, the air flow rate under different conditions through the duct was measured before collecting the IAQ data. When only the HVAC system was turned on, it generated a flow rate around 25 cfm. When the fan was on low speed with the running of the HVAC fan, 83 cfm were generated. These tests provided a foundation for the updates to the control algorithm to maintain the correct air flow.

Based on the previous research, the differential pressure across the growth media can indicate moisture levels in the soil. Preliminary data shows that 0.06 inch of water is a desirable level to maintain plant health. Combined with the pressure drop tests, a low speed fan is sufficient. The irrigation and fan operation algorithm were optimized in the control algorithm optimization. The duty cycle of watering was set to two minutes per day initially; and after weekly checking of the soil moisture, it was decreased to one minute per day. The moisture of the soil now is maintained at an acceptable level. Based on the earlier research of the Biowall, the fan duty cycle was set at 20% per hour for three weeks. The health and appearance of the plants were checked weekly. Another strategy in setting the fan code was demand control. The goal for the fan system is only working when the fan of the HVAC system in the house is on. To fulfill this, the fan status of the HVAC and ERV must be known through the BAS. Table 1 explains the different operation modes for the control system. In this table, the basic control mode for a point or unit is explained. The modes include on/off, duty cycle, and demand control.

**Table 1:** Control mode for the Biowall system

| Mode | On/Off | Duty cycle | Demand Control |
|---|---|---|---|
| Detail | If the point is set on, it runs all the time, until the operator changes it. If it is set off, it doesn't work until it is changed. | The duty cycle means this point is on for pre-set percentage in one hour. If the duty cycle is 50%, it runs 30 minutes each hour. | It means the status of this point is controlled by other signals. The other signals can energize the point through the control program. |

Current switches to monitor the status of the HVAC and the ERV in the ReNEWW House were wired to the BAS of the Biowall in December 2016. Prior to this, the Biowall's BAS could only collect approximate data for the status of the HVAC and ERV. However, the addition of these current switches provided the foundation for the demand control of the Biowall's fan. In other words, the Biowall fan was programmed to operate whenever the HVAC or ERV was on. Based on the data collected by BAS, the ERV runs with a 30% duty cycle (18 minutes per hour). The HVAC runs with this setting or when the ERV is working, and it is controlled by a NEST thermostat. The data was validated with the control system for the ReNEWW House.

## 3.2 Thermodynamic Model

In this study, a thermodynamic model for the airflow through the Biowall in the ReNEWW House was developed to evaluate the system performance. The air stream starts in the "zone," which is where the occupants are located. The fan of the HVAC or the Biowall pulls air from the zone, through the Biowall, and into the AHU to be conditioned. The air then recirculates back to the zone. Following are several assumptions made for the model. 1) The data was analyzed when the fan was running because the air in the Biowall was stagnant while the fan was off. As the HVAC had already been connected to the Biowall, the "fan" in this thesis means both the fan inside the Biowall and the fan of the HVAC/ERV system. 2) This model does not consider over-watering. There is some amount of direct evaporation of water from behind the Biowall when the fan is running. 3) The Biowall is treated as one integrated unit, not as individual trays. 4)There is no additional energy loss in the Biowall.

Figure 3 summarizes the energy model for the Biowall which connects to the central HVAC system. This schematic shows the air flow direction when the Biowall is working. If the HVAC or ERV system was used or the Biowall's fan was on, air would pass through the botanical air filter and then go through the air handling unit, and finally would be supplied back to the living room and other rooms in the house.

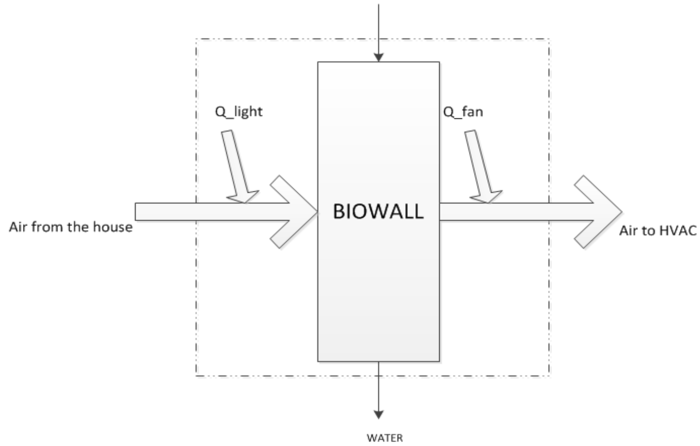


**Figure 3*:*** Schematic for the Biowall model

The rectangular box represents the Biowall in the house. The arrows with Q represent the energy consumptions of Biowall's light and fan. The other gray arrows are the air flow direction before and after the Biowall. The vertical black arrows show the water flow to the Biowall. Finally, the dashed line indicates the scope of the control volume of this thermodynamic model. This model was used to calibrate the experimental data, which is valuable for further research about the Biowall in residential houses.

From the process through the device, the air is forced across the Biowall, and the sensible energy decreases while the latent energy increases. The function of the Biowall in this model is like an evaporative cooler which can increase the moisture level and cool the air. Inputs for this point were the volume of air through the Biowall, WBE, pressure drop, and energy consumption for lighting and watering.

The WBE is the amount of moisture being supplied across the filter and is a function of the inlet temperature and outlet temperature. In this model, it represented the Biowall's effect. Equation 1 is the calculation for the WBE of the Biowall, $\varepsilon_{wb}$.

$$\varepsilon_{wb} = \frac{T_{z,db} - T_{BW,db}}{T_{z,db} - T_{BW,wb}} \tag{1}$$

The second calculations were based on the mass and energy balance for the control volume. In this calculation, the energy consumption of the light, fan and the controller of the Biowall system were considered. The mass balance yields equation 2. It shows the relationship of mass flow rate of air and water. These mass flow rates were used to calculate the energy consumption.

$$\dot{m}_{water} = \dot{m}_{air}(\omega_{BW} - \omega_z) \tag{2}$$

The last two equations were based on the energy balance, the first one was for the latent energy and the second one was for the overall energy. For the energy loss, here only considered the heating loss of the light.

$$\begin{aligned} \dot{Q}_{latent} &= \dot{m}_{water} h_{fg} \\ \dot{Q}_{latent} + \dot{Q}_{light} + \dot{Q}_{fan} &= \dot{m}_{water}(h_{BW} - h_z) \end{aligned} \tag{3}$$

For this research, the thermodynamic model was built by using the EES, which can compute any property of a fluid once the state is determined. This model outputs the temperature and relative humidity for the air after the Biowall, but due to the flexibility of the model, it can also output other defined properties.

### 3.3 Experiment Procedure

With the experimental setup in place for the Biowall, the next step was to provide an experiment procedure to test the IAQ. During the test, three students with one dog lived in the house. The experiments began in March 2017 after the updates of the control algorithm of the fan and watering. The experiments concluded in May 2017. As the experiment was conducted after the spring break and ended before the summer break, the residents had regular weekly schedules. Two students normally lived in the house every day while the third student with his dog usually lived there Monday through Thursday. During this time, the residents seldom opened the windows.

This test used two devices to measure the parameters of the IAQ besides the BAS of the Biowall; one was the Fluke 975 air meter test tool (Fluke 975) and the other was the Multi RAE gas detector, this was a photo-ionization detector (PID). This Multi RAE was used to detect the toluene in the house. The Fluke 975 was placed on the kitchen countertop during the test period, which was at the center of the main occupied zone of the house. It measured five parameters of IAQ: dry bulb temperature (˚C), relative humidity (RH, %), carbon monoxide concentration (CO, ppm), carbon dioxide concentration (CO2, ppm), and dew point temperature (˚C). The Multi RAE was used to measure VOCs levels and located on the shelf of the living room on the right side of the Biowall. The researcher uploaded the data to the computer every fourth day, which led to several time slots for each test phase.

During the experiment period in 2017, both the Fluke 975 and Multi RAE collected data over the entire period at five-minute intervals. The light schedule for the Biowall was normally from 8:00 am to 8:00pm. These data could help to validate the data collected by the commercial grade sensors permanently installed in the house. Table 2 summarizes several operations that were used while gathering data during the Biowall's experiment. The variations were based on the schedule of the Biowall's fan. The outdoor weather conditions and activities of the occupants were not controlled. For each condition, the duration of data collection was constant.

**Table 2.** Experimental schedule

| Test | Date | Fan |
|---|---|---|
| Preparation | March 14-18 | tests |
| 1 | March 23-April 11 | off |
| 2 | April 11-April 25 | 20% low speed |
| 3 | April 25-May 15 | Auto |

There was a one-week preparation phase with three tests and each test was measured around two weeks. The preparation phase was during Spring Break and no students were in the house so the IAQ device was tested and the relative humidity sensor was fixed for the zone. During that time, the fan of the Biowall was tested, and the schedule of fan depended on the test. The first test measured the IAQ when the fan was locked off and the other two measured the IAQ in different fan modes. These tests could help to decide which mode of the fan schedule is better. Percentage (%) represents the duty cycle of the fan, 20% means running 12 minutes per hour.

# 4. RESULT

## 4.1 Model Validation

The WBE, which characterize the cooling effect of the Biowall, was firstly calculated for the model validation. As the fans of the system run according to the chosen setting and the irrigation system waters the Biowall once per day, the overall tendency of the WBE is constant for one day. Some slight decreases can be caused by the changing moisture level of the substrate with time.

Based on the data collected, the WBE was related to the status of the fans. When the fans were on, the WBE increased and vice versa because moisture was being extracted from the Biowall when the fans were on and the air was being cooled. The WBE increased when water was added to the Biowall. However, the WBE significantly decreased when the light was on as the light heated the air when it passed through the Biowall. The duct air temperature therefore was higher than when the light was off. The WBE changed 30 minutes after the status of the light changed which means there was a delay. To minimize the effect of light, the model was calibrated to correct the WBE computations with the heating generation of the light. Figure 4 show the WBE before and after the calibration.

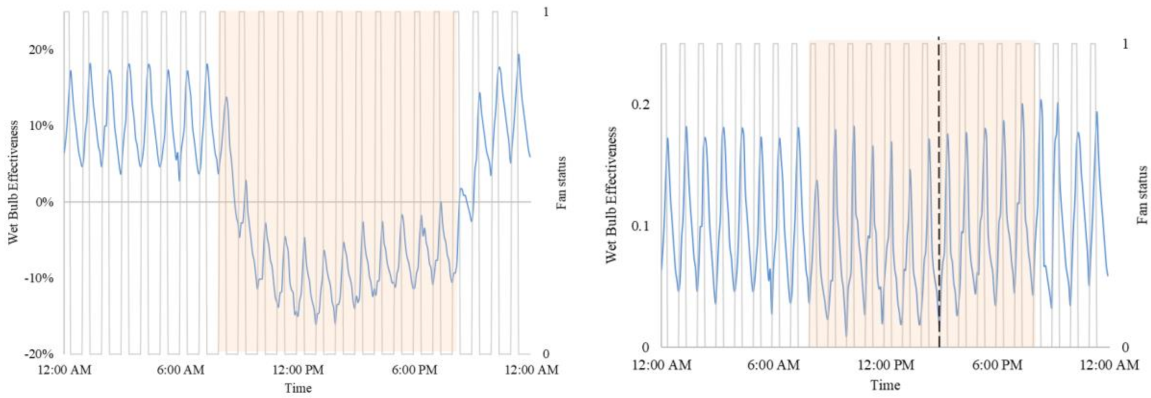


**Figure 4:** Trend for wet bulb effectiveness (WBE) (left: origin, right: calibrated)

To determine the value for WBE, data were collected and calibrated for several typical days, from which the average WBE value that would validate the thermodynamic model was determined. Overall, when the Biowall's fan was off and the HVAC fan was on, the WBE was 5%; and when the Biowall's fan was on and set at 20% duty cycle, the WBE was 10%. When the Biowall's fan was demand-controlled, it could not use an average number to represent the mode because it is very dependent on the operation of the HVAC system. During the experiment, on some days the HVAC system was turned off for the whole day and the WBE was a negative number, which was meaningless for the Biowall's model.

After obtaining the WBE, the model for the Biowall was validated. Figures 5 compares the actual data to the model's results for April 15 when the fan was on duty cycle. The figures represent the temperature and relative humidity of the Biowall's duct for one typical day. Note that the data was analyzed only when at least one fan was working. In left side of figure 5 is the temperature data. The solid line represents actual temperature data gathered by the BAS system. The dashed line represents the duct temperature based on the model. The rectangular dotted line shows the trend for the duct temperature after calibrating the model. Besides the time when the light was on, the duct temperature difference was around 0.5 °C. The temperature determined from the model was smoother than the actual value because the zone temperature only changed slightly while the model used a constant WBE with the zone temperature to generate the duct temperature. As discussed before, the light can provide energy for heating the air result; and as a result, the actual duct temperature was higher than the model predicted.

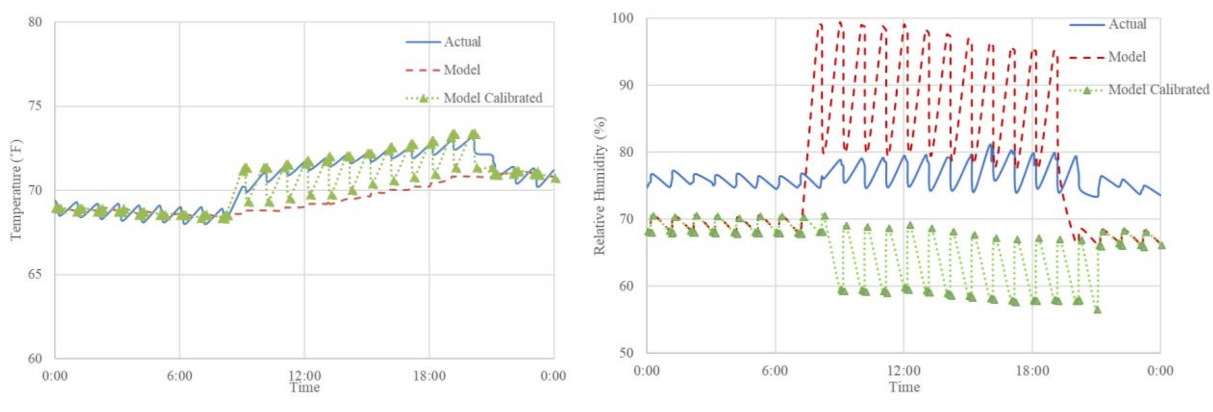


**Figure 5:** Biowall outlet parameter (left: temperature, right: relative humidity)

Compared to the experimental data, the models had similar trends with the actual temperature. The temperature difference also was minimized when the light was on. In addition, this result can reflect that the assumed heating energy and temperature difference are reasonable.

For the relative humidity, the model data and actual data increased and decreased simultaneously. Compared to the actual data, the model results were around 7% lower when the light was off and were much higher (20%) when the light was on. Compare the actual data with the calibrated data, they have different variation. The reason is the sensible heating of light has a lag phenomenon. After calibration, the model value always lower than the experimental value, one possible reason is the current water system is not well insulated, which causes the duct of Biowall always contain saturated water. As the relative humidity is a temperature-dependent variable and the model was not considering the heating effect of light, the relative humidity results were unexpected. There are several possible explanations for the unexpected relative humidity trend. First, the actual relative humidity is difficult to measure as it is based on a wide dynamic range of moisture. Second, the model ignored the heating impact of the lights. Third, the Biowall's current irrigation system is not well insulated so the duct can hold water during watering, which may have caused the Biowall duct to retain saturated water.

## 4.2 Indoor Air Quality

The IAQ was evaluated using five indicators: temperature, relative humidity, CO, CO2, and toluene. The data sampled from the units reflected the results from the ReNEWW House and the characteristics of its environment. All the experiments included three different conditions, but the operation modes of the Biowall did not have a significant impact on the concentration of indoor air pollution in the house. One typical week was chosen to illustrate the result.

First, the overall statistical analysis for concentration of $CO_2$ was conducted, which included analyzing the average and peak values of $CO_2$. For the overall analysis, there were around 11,500 sampling points with a five-minute sampling rate. As there were several time gaps, the data were collected for 46 days. The average $CO_2$ level during the experiments was 556 ppm; 93% of the time the $CO_2$ concentration was under 750 ppm; and 99.6% of the time it was under 1000 ppm. During the test period, the highest value was 1088 ppm and the lowest was 374 ppm. These values show the $CO_2$ level in the room was acceptable for a typical residential house.

Figure 6 shows one typical week data for the level of $CO_2$ during the test period from April 14 to 21. The trend line is the concentration of $CO_2$, the range is 400 ppm to 1000 ppm. The dotted line represents 750 ppm, and this number is a reference level for $CO_2$. Ambry (2015) used this level for the "evaluated" value for $CO_2$ when analyzing the IAQ in the ReNEWW House.

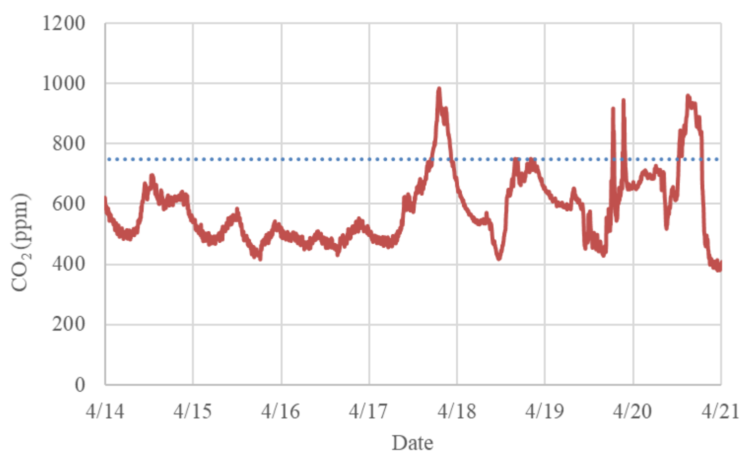


Figure 6: $CO_2$ concentration in the living room

Since the $CO_2$ correlates with human metabolic activity and activities in the house, there was no typical trend for the concentration of $CO_2$ in Figure 4, but it is obvious that the $CO_2$ decreased during the night and increased during the day. The spikes usually were attributed to a large gathering of the occupants near the sensor or cooking activities based on the data gathered during the weekend of April 15 and 16. Also, one resident went home so the $CO_2$ level was lower than the other days.

From the ASHRAE standard (2016), humans may be exposed to health risks when the $CO_2$ is at a high level, such as 5000 ppm. As the outdoor $CO_2$ level is around 300-500 ppm, the maximum accepted indoor $CO_2$ level ranged from

1000 ppm to 1200 ppm, which is 700 ppm higher than the outside air. An evaluated level of $CO_2$ is not dangerous, but it may cause humans to feel stifled. Based on the standard, The $CO_2$ level was acceptable during the example week, the $CO_2$ was below 1000 ppm all of the time, and just a small part of it was above 750 ppm.

Finally, a peak analysis was conducted for the $CO_2$ analysis to determine the probability of different levels of CO2 concentrations (O'Connor, Kleyner, & Wiley, 2011). Figure 7 is for the extreme value probability of CO2, the x-axis is the CO2 concentration, and y-axis represents the cumulative probability with 95% confidence level based on the peak ranking. A strong correlation with the $R^2$ value of 0.96 can be seen, which means this method can reflect the probability of extreme CO2 concentration. The low concentration level is not a problem for human health, thus 1030 ppm is the extreme value and would have a 2% chance of happening each day. During the experiment, there were only four days above the extreme value.

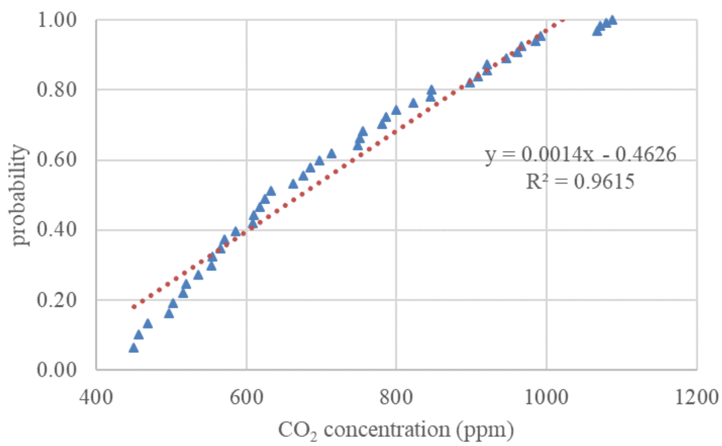


**Figure 7:** $CO_2$ extreme value probability

CO and toluene were also measured. Based on the study by the U.S. EPA, the average levels of CO in a house without gas stoves may vary from 0.5 ppm to 5ppm. Thus, the CO was not an IAQ problem for this house. The level of CO maintained a stable value and never reached above 4 ppm for the entire period of time even during the cooking and party events in the house. The average CO concentration was 0.28 ppm and was zero for 72% of the time. Similar results were obtained for toluene and it also is not an indoor air problem for the house. The recommended long-term maximum exposure limit for toluene is 0.6 ppm while the level of toluene in the house was always below 0.1 ppm.

The zone temperature and relative humidity were also recorded and analyzed. In terms of temperature, the Biowall has the potential to save energy by pre-cooling. As for the relative humidity, the Biowall does not extremely change it in the house even during the watering process. Overall, the Biowall helped to keep the relative humidity of the house mostly in the range of 45% to 55%, which is the recommended by ASHRAE. $CO_2$, CO, and toluene dropped to recommended levels with the Biowall. In addition, the residents were not complaining about unpleasant odors from the Biowall.

## 5. CONCLUSIONS

This study demonstrated the use of Biowall in a real residential house for maintaining a heathier indoor environment. The plants and IAQ results showed that the Biowall performed well in the Purdue University ReNEWW House in West Lafayette, Indiana. Control and management updates helped the Biowall operate in a more efficient way. A mathematical model for the Biowall was created but still needs further developments. As this study was the first time that the Biowall was installed and monitored in a real house, it provided valuable fundamental data and results for later research. Based on this analysis, several updates and tests are needed to ensure the satisfactory operation of the Biowall.

## NOMENCLATURE

| | | |
|---|---|---|
| $\varepsilon_{wb}$ | wet bulb effectiveness | (-) |
| T | temperature | (°C) |
| $\dot{m}$ | mass flow rate | (kg/s) |
| ω | humidity ratio | (-) |
| h | enthalpy | (kJ/kg) |
| $\dot{Q}$ | power | (kJ/s) |

**Subscript**

| | |
|---|---|
| BW | Biowall |
| z | zone |
| db | drybulb |
| wb | wetbulb |

## REFERENCES

Ambry, S. (2015). Indoor air quality analysis of ReNEWW. Unpublished manuscript, West Lafayette: Purdue University. Alraddadi, O. (2016). *Investigating the toluene removal of a botanical air-filter with a loose packed growth medium for potential energy savings.* West Lafayette: Purdue University.

ASHRAE. (2016 b). *ASHRAE Standard 62.2: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential.* Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers.

Darlington. (2004). *An Integrated Indoor Air Biofiltration System for Municipal Infrastructure.* Guelph, ON: Air Quality Solutions Ltd.

Darlington, A., Chan, M., Malloch, D., Pilger, C., & Dixon, M. A. (2000). The biofiltration of indoor air: Implications for air quality. *Indoor Air, 10*, 39-42.

Niemelä, R., Seppänen, O., Korhonen, P., & Reijula, K. (2006). Prevalence of building-related symptoms as an indicator of health and productivity. *American journal of industrial medicine*, *49*(10), 819-825.

Peng, R. A. (2017). Living Wall Retrofit. *ASHRAE Journal*, *59*(4), 72.

Rajkhowa, B. (2016). *Establishing and Improving Control Strategies that Sustain Plant Health in a Botanical Bio-Filter.* West Lafayette: Purdue University.

Rodgers, K., Handy, R., & Hutzel, W. (2013). Indoor Air Quality (IAQ) Improvements Using Biofiltration in a Highly Efficient Residential Home. *Journal of Green Building*, *8*(1), 22-27.

U.S. EPA. (2016) Why Indoor Air Quality is Important to Schools? Washington, DC: Indoor Environment Division, U.S. Environmental Protection Agency, https://www.epa.gov/iaq-schools/why-indoor-air-quality-important-schools

Wyon, D. P., & Wargocki, P. (2013). How indoor environment affects performance. thought, 3(5), 6.

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