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Dhanurja De Silva
Purdue University

Yalin Lu
Purdue University

Siqi He
Purdue University

See next page for additional authors

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Cover Page Footnote

We thank our writing mentor William Hutzel and community partner Melissa Freed from the West Lafayette Public Library. We are grateful for the support from Vincent Schutz and Jan Aynes from the Purdue Facilities Service Building for working with the team in building and assembling the biowall. Thanks to also to Whitman Jerman, Hailey Benfield, and Swapnil Umap, who were part of the team early on, for their support.

Authors

Dhanurja De Silva, Yalin Lu, Siqi He, Ajay Dalal, and Bill Hutzel

BIOWALL DEVELOPMENT FOR THE WEST LAFAYETTE PUBLIC LIBRARY

Dhanurja De Silva *(School of Engineering Technology)*, Yalin Lu *(Lyles School of Civil Engineering)*, Siqi He *(Mechanical Engineering Technology)*, Ajay Dalal *(Mechanical Engineering Technology)*, and William Hutzel *(Professor of Mechanical Engineering Technology)*

STUDENT AUTHOR BIO SKETCHES

Dhanurja De Silva is a master's student at Purdue University with research interests including indoor environmental quality and high-performance buildings. After completing his master's degree, he hopes to pursue a PhD to work in academia in the future. Dhanurja is from Sri Lanka and completed his undergraduate studies at Southeast Missouri State University. He has been leading the Biowall project since August 2022. In this essay he discusses his master's research project and how it will benefit the West Lafayette Public Library and the West Lafayette community.

Yalin Lu is a visiting scholar at Purdue University and a graduate student at City University of Hong Kong. She has been working in the advanced air distribution and indoor air quality of patient wards since 2019. Yalin joined the Biowall project in September 2022 as a lab technician. She plans to work in academia in the future.

Siqi He is currently an undergraduate junior majoring in mechanical engineering technology at Purdue University. She has been part of the Biowall project since September 2022 as an undergraduate assistant, and she continues her research this semester as part of the Undergraduate Interdisciplinary Research Internship program. Siqi has experience in CAD software such as SolidWorks 2021, NX 12, and Autodesk Inventor 2022.

Ajay Dalal is a dual-major junior in mechanical engineering technology and automation and systems engineering technology from North Brunswick, New Jersey. He has shown experience in the manufacturing industry as well as in energy efficiency. Ajay has been part of the Biowall project since December 2022 as part of a research fellowship.

INTRODUCTION

A multidisciplinary student team has designed, tested, and installed a Biowall for the new children's wing of the West Lafayette Public Library. The goals of this partnership are to educate the public about the importance of indoor environmental quality (IEQ) and technologies that can improve IEQ.

INDOOR ENVIRONMENTAL QUALITY

People in the United States spend 90% of their time indoors (US Environmental Protection Agency, 1989). Therefore, IEQ is an important factor in people's health, productivity, and well-being (Heinzerling et al., 2013). The indoor environment has pollutants from indoor sources such as cleaning products, flooring, furniture, and curtains (Centers for Disease Control and Prevention, 2016). These indoor pollutants include volatile organic compounds such as toluene, benzene, and formaldehyde. Without proper ventilation, the pollutants will accumulate and be toxic to occupants.

Household air pollution is identified as a cause of over 3.8 million deaths globally (World Health Organization, 2022). There are also concerns about particulate matter (PM) from outdoor air, which can transport to the indoor environment. Inhalable particles such as PM_{10} and $PM_{2.5}$ can be deposited on the human respiratory tract and lead to health risks. Recently, the COVID-19 pandemic again stimulated the public's focus on indoor air quality.

The heating, ventilation, and air conditioning (HVAC) systems in buildings control indoor air quality and thermal conditions and consumes a lot of energy. In 2021, about 235 billion kWh of electricity was consumed because of the cooling for residential buildings in the United States, which was about 16% of total residential-sector electricity consumption and 6% of total US electricity consumption (US Energy Information Administration, 2022).

For indoor air quality control, fresh outdoor air is conditioned and supplied to the indoor environment to dilute and exhaust the contaminant; the higher the indoor air to outdoor air ratio, the better the indoor air quality. However, there is a trade-off between indoor air quality and energy consumption when outdoor air has more entropy or unavailable heat energy than indoor air.

IEQ incorporates more than just clean air. It refers to a holistic evaluation of the built environment and usually covers factors such as air quality, thermal conditions, acoustics, lighting, and nonlight visual conditions. Humans are most comfortable and productive when subtle parameters such as light quality, background noise, and ventilation have been addressed (Fisk & Rosenfeld, 1997). The different aspects of IEQ can affect occupants' cognitive functions, including attention, perception, memory, language function, and higher-order cognitive skills (Wang et al., 2021). For example, it was found that a 10-ppb increase in annual ozone can decrease cognitive performance in adults, equivalent to 3.5–5.3 years of decline because of aging (Chen & Schwartz, 2009). Another study showed that increased indoor CO_2 concentration increases the reaction time of school children ages 10–11 (Ko et al., 2020).

WHAT IS A BIOWALL?

A biowall, also known as a living wall or green wall, is an air filtration system that uses plants to purify indoor air. The concept of biowalls originated in the 1980s when NASA scientist Dr. Bill Wolverton began researching the ability of plants to remove pollutants from the air. The plants used in biowalls are chosen for their ability to remove toxins and pollutants from the air. Examples of commonly used plants include spider plants, snake plants, peace lilies, and English ivy. As air flows through the biowall, it passes over the plants' leaves and roots. Microbes surrounding the roots absorb and break down harmful chemicals and particles in the air. This process is called phytoremediation and has been shown to be effective in removing a wide range of pollutants, including volatile organic compounds, formaldehyde, and benzene (US Environmental Protection Agency, 2012). The air is then released back into the room, creating a natural and refreshing environment.

Biowalls can be used in commercial and industrial settings, such as offices, hospitals, and airports, as well as in residential settings. One of the benefits of using biowalls is their ability to improve the aesthetic appeal of a space. They can be designed to incorporate a wide range of plants and greenery, creating a visually pleasing and calming environment. Additionally, exposure to plants and greenery can have a positive impact on mental health and well-being.

Biowalls also improve energy savings by reducing the need for conditioning outdoor air. In hot and humid climates and dry and cold climates, humans spend a lot for energy in cooling and heating outdoor air to meet the conditions set indoors. Using a biowall, indoor conditioned air can be cleaned and recycled, thus reducing the need for heating and cooling and therefore saving energy. A biowall can also be used with an energy recovery system and with ultraviolet cleaners to further improve cleaning and energy savings.

Another advantage of using biowalls is the reduction of single-use air filters; using plants to clean indoor air pollution is a more sustainable approach compared to single-use air filters. Air filters in buildings are typically made of media that traps contaminants and reduces airflow over time. The filtering process renders the filter useless over time, requiring it to be thrown out after being used once. Even though single-use filters can last a long period of time, a biowall generates less waste compared to current air filters, as contaminants are absorbed into the plants.

Purdue has created two earlier versions of a biowall. The first generation was created in 2011 for a home that was built for the US Department of Energy's Solar Decathlon competition. This first biowall was a vertical wall of philodendrons that was grown in a thick filter media without any soil (Figure 1a). Although the biowall had a good overall appearance initially, it was difficult to maintain the plants over time. The second-generation biowall addressed these concerns by using a porous growth media for the plants. The second-generation biowall is operational in a local research home called the ReNEWW House (Figure 1b).

The new biowall that students have designed for the West Lafayette Public Library has many of the same features as the second-generation biowall in the ReNEWW house. The generation of the biowall for the library features a new self-watering system that disperses the water into the soil to allow all plants to receive equal amounts of water. The biowall also features sensors that will track and display air quality. Limitations at the library, including the lack of a constant water supply and access to a return duct of the HVAC system, made the project more challenging.

The objective of the biowall for the West Lafayette Public Library project was to improve on the previous generation of the biowall and showcase the technology to the public. The previous generation of the biowall proved that the technology was feasible and that indoor air quality can be improved. Research on the previous generation showed an imbalance in watering between the plant trays, and the airflow between them proved to be unbalanced. The new generation of the biowall aims to improve watering and airflow distribution while also making it engaging to the public. As the new biowall is designed to be placed in the children's section of the West Lafayette Public Library, the goal is to engage children in science, technology, engineering, and mathematics (STEM) from an early age.

Figure 1. The Generation of Biowalls Made by Purdue University

BIOWALL DEVELOPMENT AND METHODOLOGY

Partnership with the West Lafayette Public Library

During the end of 2021, the West Lafayette Public Library was going through renovations and was adding a children's wing to the main building. The new wing was

Figure 2. Images of the Biowall Space for the West Lafayette Public Library's Children's Division

designed to engage children to see and learn about new things in the world. The library was interested in showcasing the biowall technology in one of these showcase spaces and reached out about the possibility of installing a biowall to showcase sustainability.

Figure 2 shows the space in the children's wing of the library (2a) and a rendering of the biowall (2b). The space is roughly 5 feet tall, 4.5 feet wide, and 1.5 feet deep. The space is about 4 feet above ground level, which is helpful for keeping young children away from the plants. Additional information about the biowall is presented on a website, and a reserved reading list was created for children who want to learn more about the exhibit.

The Children's Services department head for West Lafayette Public Library was the main contact between the library and the team working on the project. When asked about how the library heard about the biowall, the library contact responded that the "deputy director saw it in the Whirlpool House [ReNEWW House] and suggested it for the new alcove in the children's area." The project team was also excited to hear that the Children's Services Department head had "a background in plant sciences . . . [and] felt it would be well received by our patrons and offer a great STEM learning experience to visitors" (personal communication with De Silva, March 1, 2023).

The Biowall team also asked the library contact about future events that would involve the biowall and the community. The contact replied, "All our front desk staff will be receiving regular questions about it. It will have interaction from passersby which I hope will be supported by informative signage and possibly a QR code linking to a video." The contact also added that "my colleagues and I are very pleased to have this awesome addition to our library. We are confident that it will be another asset that sets us apart and that supports the STEM interests of our community."

The Biowall team is sincerely grateful to have been able to work with the Children's Services department head and would not have been able to succeed without assistance from the West Lafayette Public Library staff. The team communicated with the library over emails and in

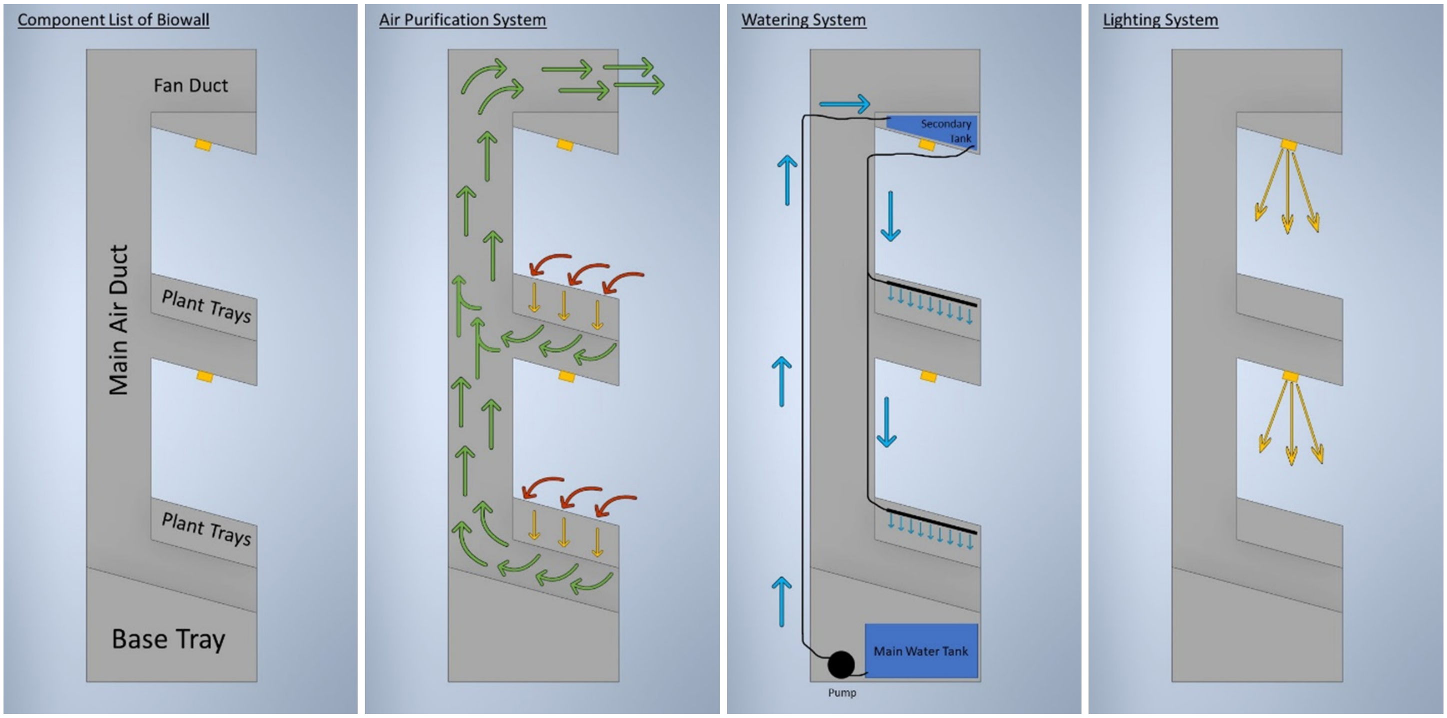

Figure 3. The Design of the Biowall

person over a time span of about a year. The library was presented with virtual renderings, 3D prints in 1/20th scale, and images of the device as it was being built.

Biowall Components and Considerations

The biowall was designed to fit the space available at the library, with four plant trays placed at a 15-degree angle to allow for children to see the plants in the trays. Based on the measurements of the space available in the library, the design of the biowall was completed using Autodesk Inventor. As shown in Figure 3, the biowall consists of an air purification system, a watering system, a lighting system, and an electronic and control system.

The air purification system includes a main duct, a fan duct, a fan, and four identical plant trays. Two plant trays are at a higher level, and two are at a lower level. The fan pulls air slowly through the growth media in the plant trays, where it is cleaned and then supplied back into the room from the fan duct. The key for the air purification system is to maintain even and low air velocity through four trays. Low air velocity allows for the highest cleaning efficiency and the low possibility of noise from airflow. To achieve this, a computational fluid dynamic (CFD) simulation using Autodesk CFD software was conducted to decide the thickness of the growth media and the fan parameters. Figure 4 shows the air velocity field of the sectional plan of the biowall.

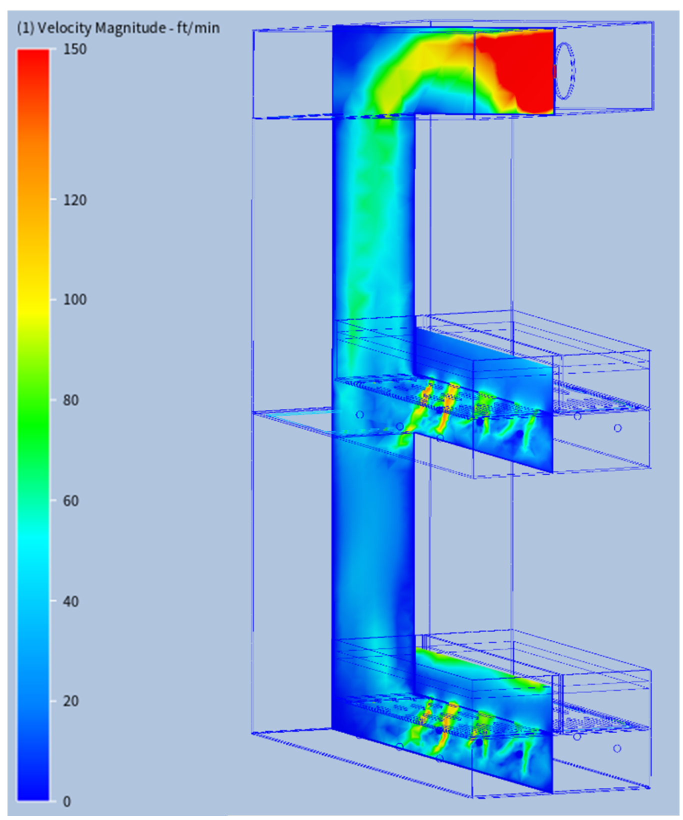

Figure 4. CFD Simulation Made on Autodesk CFD

The airflow rate through each plant tray is about 15 cubic feet per minute.

Given the lack of a constant water supply and the location of the available space being out of reach without a ladder, a watering system needed to be designed to provide water to the plants. The watering system uses a pump to deliver equal amounts of water to two identical secondary tanks at the top of the biowall from the main water tank and at the base of the biowall. The pump head needed to be at least 6 feet to overcome gravity, so a diaphragm pump was used to pull water from the main tank.

Each secondary tank is connected to the drip irrigation setup in each plant tray at higher and lower heights. The water is distributed using a tubing, with holes drilled every inch, placed inside each plant tray. The watering system can equally distribute water between the plant trays at high and low heights by splitting the water between tank before gravity pulls water down to different heights. Calculations were done using the transpiration rate of plants, the ability of the growth media to hold water, and the wet bulb effect of air flow through the growth media at the designed air flow rate. For four plant trays, the needed water amount is one gallon per week. Thus, the water tank holds one and a half gallons, leaving enough space for accidentally overfilling the container.

The lighting system consists of LED grow lights capable of producing 85 $\mu mol/m^2s$ at 8 inches from the light. The measurement of photosynthetic photon flux density with $\mu mol/m^2s$ units allows for measuring how much lighting is needed to keep the plants alive. Based on the plants chosen for the biowall, 85 $\mu mol/m^2s$ or greater was needed to keep the plants alive and healthy. Two sets of these lights are used per plant tray to provide enough energy for the total area in each tray.

The electronics and the control system are in the base tray. The electronics are controlled using a Wi-Fi Smart switch that can turn on and off AC power to equipment based on user input and timers. The timer feature is used to turn on the lights from 10 a.m. to 8 p.m. every day to mimic sunlight inside the library while the space is open. The timer feature is also used to turn on the fan for 20 minutes every two hours and to provide power to the watering system and the push buttons.

Commissioning and Results

After the designing and manufacturing of the biowall, each component was tested in the Environmental Chamber of Applied Energy Lab located in the Knoy Hall of Technology at Purdue University. The lights, watering, and airflow were tested to make sure they functioned as designed. Table 1 summarizes the equipment used during the commissioning of the biowall. Air velocity and temperature measurements were key to identify the balanced airflow and watering in the new design of the biowall. The luminous flux meter provided the data needed to confirm if the installed lights worked as advertised.

Table 2 presents the results from the commissioning process with the measured variables and locations in the biowall, with the designed parameter in the second to last column and the actual measurement in the last column. The designed parameters also consist of an error range to allow for real-world measurement errors and broader design validation. A successful commissioning would be to measure all parameters within the design requirement error ranges.

The clean air delivery rate featured in Table 2 is an important metric for assessing IEQ. The rate was determined by a laboratory test that compared the rate of volatile organic compound removal with and without a biowall. As reflected in Table 2, laboratory testing showed that the small biowall in the library generated the equivalent of 10 cubic feet per minute of fresh outdoor air.

COMMUNITY IMPACT

One of the primary goals of the Biowall project is to enhance reciprocity, meaning that both the community partner and the student can benefit from this initiative. The biowall is expected to spark the interest of library

Table 1. Equipment Used in Commissioning of the Biowall for the Library

<table>
<tr><th>Equipment</th><th>Variable</th><th>Range</th><th>Accuracy</th></tr>
<tr><td rowspan="2">TSI VelociCALC 8386A Anemometer</td><td>Air velocity</td><td>0 to 9999 ft/min</td><td>±3% of reading or ±3 ft/min</td></tr>
<tr><td>Temperature</td><td>14–140 F</td><td>±0.5°F</td></tr>
<tr><td>Apogee MQ-306 Quantum meter</td><td>Luminous flux</td><td>410 to 655 nm</td><td>± 5%</td></tr>
</table>

Table 2. Results from the Commissioning of the Biowall

Component	Item	Requirement	Measurement
Air purification system	Air flow rate of bottom duct	30 cfm (±20%)	26 cfm
	Air flow rate of top duct	60 cfm (±20%)	60 cfm
	Clean air delivery rate	> 0 cfm	10 cfm
	Fan is quiet at 2 ft from fan	< 50 dB	42 dB
Watering system	Pump moves water up 6 ft	True	True
	Primary tank is emptied when pump shuts off	True	True
	Water is equally distributed between two secondary tanks	Within 100ml	True
	Tanks are dry after a couple of hours	No standing water	No standing water
Lighting system	Lights are bright at plant height	> 80μmol/m2s @ 8in	80–135 μmol/m2s
Electronic and control system	Pump turns on when water is present in primary tank	True	True

visitors, particularly children, in STEM programs and in air quality and environmental issues. In this way, the project has the potential to inspire curiosity and learning among the library's patrons.

To ensure that the project's legacy endures, all designs, reports, and instructions related to the biowall have been saved in a shared folder. This enables students who are interested in future research on the biowall to access information about the project's successes and challenges. While it is difficult to conduct assessments on the biowall's effectiveness in a public space due to ethical considerations and data safety, the hope is that this project will inspire other institutions to embark on similar initiatives and further research in sustainable energy practices.

STUDENT IMPACT

During the spring 2023 semester, both undergraduate members of the project participated in Purdue University's Discovery Undergraduate Interdisciplinary Research Internship (DUIRI) program. As part of the program, they were given the opportunity to work alongside the graduate team lead and the visiting scholar and gain valuable experience working on a research team. Additionally, one of the undergraduate members leveraged this project to conduct research for their fluid dynamics class, focusing specifically on the watering system and gaining a deeper understanding of topics such as dripping irrigation, pump pressure, and water level. Overall, the DUIRI program allowed the undergraduate students to expand their skill sets and knowledge base while contributing to the research team's goals.

The master's student leading the project used this experience to improve his research, presentation, community collaboration, leadership, and teamworking skills. The Biowall project involved the successful collaboration of many teams, with timely communication between teams and clear exchange of information being as important as any major project in the workplace.

The visiting scholar working on the project was able to apply their knowledge from their master's and PhD programs to the real world with the Biowall project. The project provided everyone with the opportunity to work on real-world components and the ability to test different designs and learn about the complicated process of commissioning a project.

Student Collaborations

The Biowall project would not be possible without the collaboration of many organizations and much assistance from interested parties. Table 3 lists a few of the student organizations that were involved in the project. Two student organizations, the American Society for Heating, Refrigeration and Air Conditioning Engineers and the Boiler Green Initiative, were involved in planning and generating funds for the beginning of the project. The Office of Engagement also provided funds for the Biowall project through the Service-Learning Grant. The Office of Undergraduate Research provided funds for two student researchers who contributed their time to the Biowall project through the DUIRI.

A senior-level HVAC design class, MET 421, assisted the Biowall project by helping commission the components. Students made temperature, pressure, airflow, and light intensity measurements to ensure that the device was operating as intended. The students also benefited

Table 3. Overview of Purdue Organizations Involved in the Biowall Project

Purdue Organization	Contributions
Student Organizations: American Society for Heating, Refrigeration and Air Conditioning Engineers the Boiler Green Initiative	Technical support and Student Organization Grant Allocation board
Office of Undergraduate Research: Undergraduate Interdisciplinary Research Internship	Student researchers
Office of Engagement: Service-Learning	Service-learning grant
MET 421, "Air Conditioning & Refrigeration"	Commissioning report
Purdue Students for Sustainability	Publicity and general interest

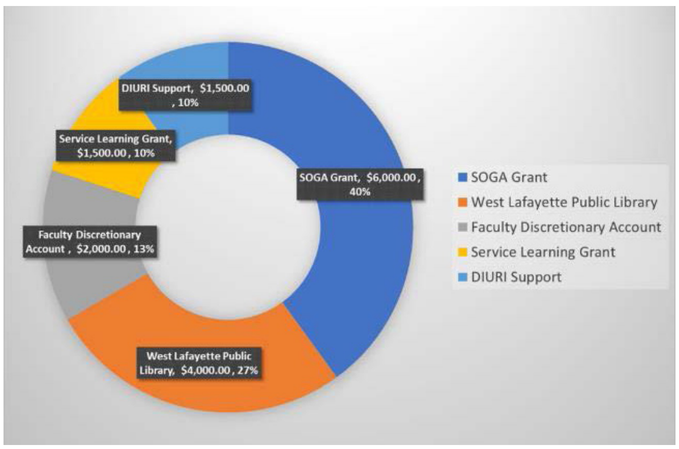

Figure 5. Summary of Project Expenditures

from learning how a biowall works and seeing the assembly in person.

A summary of the funding for the Biowall project is presented in Figure 5. The total project cost was approximately $15,000. The biggest contribution was from the Purdue Student Organization Grant Allocation board, which funded the American Society for Heating, Refrigeration and Air Conditioning Engineers for the project's successful completion. The next biggest sponsor was the West Lafayette Public Library, which modified their bookshelf to support the nearly 200 lb. weight of the Biowall and added a power outlet for the biowall. The Office of Undergraduate Research and the Office of Engagement also supported this project. Without the support of every individual and organization involved in the Biowall project, this project would not be as successful as it turned out to be.

Figure 6. The Biowall Installed in the West Lafayette Public Library

Installation

Figure 6 is a close-up of the biowall, which was installed in the library with the assistance of Purdue Facilities Services staff. The base of the biowall features push buttons to light up separate sections, while the center space also contains an Android tablet to display IAQ data to provide more information. The QR code located to the right of the biowall front panel sends patrons to the website on biowalls from Purdue University (https://www.purdue.edu/biowall/), which contains more information on the current and previous generations of biowalls as well as how they work.

CONCLUSION

The completion of the Biowall project will allow the West Lafayette community and the public to learn about IEQ and the process of using plants to clean indoor air. The technology is being presented in a highly visible public space, which allows people to see it in person while also being able to learn more information by accessing the website, which presents more information.

Another expected outcome of this project includes the learning experiences for the students involved in the project. The students received hands-on experience in designing, building, and assembling the biowall. This industry-equivalent experience is valuable in the students' future, and working with a client as important as the West Lafayette Public Library was a great opportunity in itself. The public library is visited by many people on any given day, and being able to represent technology developed at Purdue University is an immense opportunity.

The biowall will be maintained at the library with the help of the library staff and the staff at the Applied Energy Lab. The project can be further improved in the future with newer plants, fans, and different plant tray designs. Given the modular aspect of the biowall, new components can be installed while easily removing older components. More research can be conducted in plant health, airflow characteristics, and engagement surveys in the future. An online form can be shared at the library to measure the interest generated from the biowall.

The future of the project allows for more collaborations between the university and the public library, with more potential for service-learning projects that benefit the community. The bond made from this Biowall project benefited the students involved and the community, as the students were able to display their skills, and the community gets to learn about current and future technologies.

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