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The Durability of Plant-Based Air Filtering Systems in Buildings: From an Air Quality and Energy Reduction Perspective

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Abstract. *After the oil crisis, all the commercial and residential buildings were designed with tightly sealed envelopes to minimize the air leakage through the building to save energy. Since buildings were no longer able to breathe naturally, indoor air quality problems started to occur. Currently, there is still a dilemma between these two parameters inside the buildings. To address IAQ issues and reduce the energy loads in mechanical conditioning systems, the plant-based air filtering system is designed. The proposed system is a hydroponic system (plants growing without soil) that is composed of a mixed bed of activated carbon adsorbents and porous glass stones that capture and filter the toxins in the air. HVAC-integrated plant walls that include growth media are designed to support the plants and capturing toxins. These toxins are then metabolized by the plants which can create a self-regenerating filtration system that requires less outdoor air being fed into the building, thereby reducing the conditioning costs associated with HVAC. This paper is focused on the durability of the design and fabrication of a plant-based air filtering system from an air quality and energy reduction perspective.*

Keywords: *Filter, Indoor Air Quality, Mechanical Conditioning Systems, HVAC, Hydroponics.*

1 Introduction

Buildings and construction operations are responsible for about 40% of the final energy consumption and generation of energy-related carbon dioxide (UN, 2017) In mechanically ventilated buildings, most of the energy consumption is related to the heating and cooling outdoor air and distributing it internally (Chan, 2010; Hughesa, 2011). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has designated of the health of the occupants and energy consumption profiles of the buildings (Roth, 2002) as the two key contributing factors in assessing the indoor air quality (IAQ) in ASHRAE standards. However, after 40 years of research and practical experiments in the field, finding a satisfactory solution to reduce building energy consumption while mainlining high indoor air quality remains a challenge. Even though HVAC filtration systems seem to be among the best solution for IAQ, they are mostly ineffective for volatile organic compounds (VOCs) and mostly contaminate the air instead of filtering it by infrequently changed filters (Bluyssen, 2003; Schleibinger, 1999).

Indoor air can be more contaminated than outdoor air and may lead to serious health problems related to the length of exposure (Liu, 2007). People, particularly living in urban areas, spend up to 90% of their time in indoor environments (Klepeis N.E., 2001; Robinson, 1995; USEPA, 2002). In the US alone, the annual economic losses related to IAQ is between $40 billion and $160 billion (Fisk, 1997; Lomborj, 2002), the cost which is associated with the loss of productivity and medical costs for the individuals who suffer from asthma, sick building syndrome and allergies caused due to poor IAQ (Guo, 2009). Passive techniques like increasing ventilation in buildings can improve IAQ. However; they are not suitable for many climate conditions due to the increasing energy expenditures of HVAC systems related to the heating and cooling loads (Kibert, 2008). Since filters are also not efficient to remove most of the cancerogenic pollutants like formaldehyde and benzene, efficient filters need to be designed to protect building occupants from indoor air pollutants. There is a clear need for the design of a system that can address the IAQ concerns in the buildings and reduce the energy load from the HVAC systems at the same time. The successful design of such a system would have significant impacts on the urban environment and sustainability.

Plants can improve IAQ by metabolizing airborne pollutants such as formaldehyde, benzene, and xylene (Wolverton, 1993; Yoo, 2006; Aydogan, 2011). The utilization of the root zone (rhizosphere) of the plant is paramount to achieving high purification ability. There have been numerous applications of plants in buildings and the most relevant to our work is the integration of the plants into buildings to improve the quality of life in the indoor environment (Blanc, 2012). However; this system does not take advantage of the full cleaning capacity of plants, especially the root zone. Therefore, they do not sufficiently remediate pollutants within an indoor environment, nor do they incorporate their performance with the commercial buildings HVAC systems. For that reason, air remediation capacity, maintenance, energy savings and the cost of the system is lower than building-integrated systems. Building-integrated botanical air filtration systems are integrated into the building's conventional air handling units to save energy and provide a filtration system for the entire building. These systems take advantage of root zone of the plants which were the direct agents of toxin removal (Wolverton, 1993; Wang, 2014; Wolverton, 1993; Wood, 2002; Orwell, 2006). Building-integrated botanical air filtration systems have been recommended by the U.S. Department of Energy's Building Technologies Program for industrial-scale research, development and demonstration to improve air quality, energy efficiency and public health (USDOE, 2010).

The proposed botanically-based air purifying system constitutes plant-based air remediation strategies. It is a hydroponic system (plants growing without soil) that is composed of adsorbents and porous glass stones to capture and filter the toxins in the air. Plant-associated microbes in the rootzone convert these toxins to nutrients, which are then consumed by the plants. Through this, a self-regenerating filtration system is created. Significant work in plant-based filtering systems has been completed (Aydogan et al., 2016; Aydogan and Tardos, 2017) In continuation of earlier works of the author, this paper is focusing on the durability of the prototype design, fabrication, and assembly of an alternative filtration system by utilizing plants to clean indoor air and reduce energy consumption.

The paper is outlined as follows. In section 2, a discussion on the methods and the material used for the design is presented. Section 3 presents the results of the analysis, and section 4, concludes the paper by discussing the potential future developments of the system.

2 Materials and Methods

2.1 Materials

The prototype of the plant-based air filtering system is composed of three main parts: *(1)* a cassette holding the mesh, *(2)* a mesh holding the plants and growing media, and *(3)* a structure holding the cassettes together. The system components are shown in the exploded diagram in Figure 1. The heaviest elements of the prototype are the base and water basins (for watering the plants), which provide structural stability when located on the bottom.

The design of the modular system utilizes a series of cassettes that are repetitive and arranged to form a wall system. Through this design, natural channels are created on the back of the cassettes to allow the air pass through and circulate back to the environment by the fans on each side of the panel prototype (Figure 2a). Each cassette holds the mesh containing lightweight growing media and the plants, LED lighting and drip irrigation tools (hose and drippers) (Figure 2b). The LED lighting system, which aids photosynthesis, is designed to be hidden within the three sides of the cassettes' lids. The irrigation is a closed-loop system, where the water flow is controlled using a timer. This allows the exact amount of water to drip and reach to the plants' roots without excess water overflowing in the prototype system. Five 0.25 gallons per hour drip emitters are aligned to be used in each of the cassettes. The pumps are located at the bottom of the prototype inside the water basins and the hoses of the drippers are hidden (on the back) between the cassettes (Figure 3a).

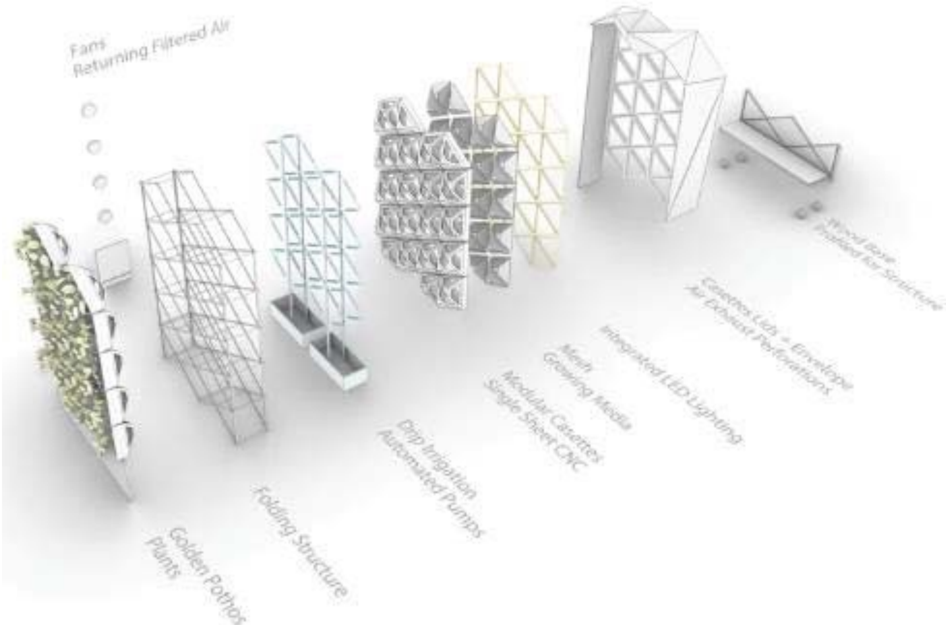

Figure 1. Exploded diagram of plant-based air filtering system.

In the design of the structure, steel bars with the dimension of 1/2" (width) x 1/8" (depth) are used. Since the prototype is double-sided (plant cassettes on both sides), the structure is designed to be versatile with easy and fast assembly by creating pockets that cassettes settle in. The bottom of the bars is embedded in the groves created in the wooden base that are profiled for the flat steel bars.

A mesh that holds the plants and growing media is designed by using a three-dimensional reinforcement mat (Enkamat7020), commonly used for erosion control on the slopes in the urban scale applications. This material is selected due to its performative features. It allows airflow to pass through the growing media and plants without creating additional pressure on the surface, it doesn't absorb moisture, it is UV resistant and holds the growing media with plants in place even it is installed vertically (Figure 3b).

Figure 2. a. The double-sided prototype of plant-base air filtering system; b. Components of plant-based air filtering system.

Figure 3. a. Folded cassettes and dripper attachments**;** b. 3d mesh holding growing media and plants.

Growing media used in this system is composed of a mixed bed of activated carbon (4 × 8 Coconut Shell Granular) adsorbents and porous glass stones (GS2 Soil Aerator) that capture and filter the toxins in the air. The role of activated carbon in this mix is to capture toxins whereas porous glass stones are used for creating an environment for roots to grow. The porous surface on the glass stones makes it ideal for the roots to get water and climb.

Different kinds of plant species can be used in indoor environments and, essentially, depending on the specific functions that they can serve. Additional knowledge of the conditions that are required for their growth such as lighting requirements, watering, and maintenance are also vital factors. However, the most important principle for this project is their toxin degradation capacity through their rhizosphere. Golden Pothos (*Epipremnum aureum)* and English Ivy (*Hedera Helix*) are the two plants that are used in this prototype, based on the results of the toxin removal capacity that was discovered through our previous studies (Aydogan, 2011).

2.2 Methods

In this prototype, different materials and techniques of fabrication are investigated. Emphasis is placed on designing a lightweight and collapsible scissor structure, which allows the project to be easily transported and assembled. Subtractive manufacturing methods are selected to be used to conduct the base and the cassettes of the prototype. Computed-numerically-controlled (CNC) machine is used to cut the 1” wood base and sides. Precise 3/4” deep grooves are routered on the interior faces of the base so that the steel structure would snap into its designated shape. The structure’s geometry is designed to hold two abutting cassettes per one parallelogram (Figure 4a and Figure 4b). While the base’s hidden grooves and inserted cassettes hold the metal scissor structure’s geometry in place, it is the 1” plywood walls on both sides that provide support against shear stresses. These sidewalls are holding the fans that are used to distribute the air, which was cleaned by the plant cassettes.

Figure 4. a. Assembly of the prototype; b. Plant assembly of the prototype.

17 sheets of HDPE are used to CNC cut the cassettes of this prototype. A total of four cassettes are cut from a 49” × 96” sized sheet. The cassettes are designed and assembled by folding technique (Figure 5).

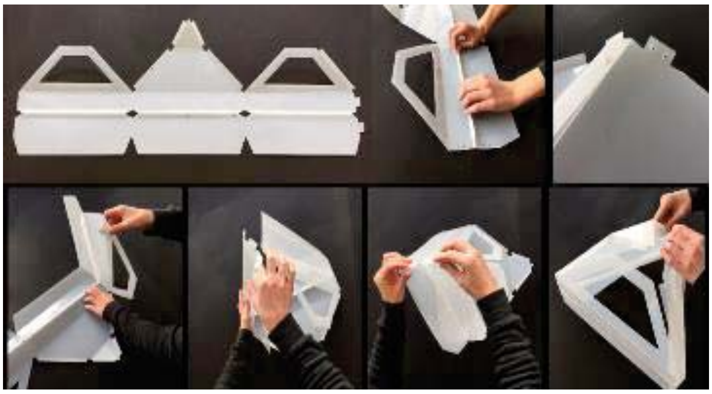

Figure 5. Cassette assembly by folding.

Cutout sheets are used to cut the mesh and create individual mesh holders. It is designed to fold and sewed a zipper in the seams, which makes planting easier. Three zippers are used in the mesh, two of them on the sides and one in the middle, which are preventing the growing media to fall and holding plants in place. In plant-based filtering systems, porous glass stones and activated carbon have different particle sizes and creates opportunities for settling in the planters. This creates a loss of active adsorption area in the cassettes. To prevent this problem two growth media are granulated (bonded together).

3 Results

In this project, a prototype containing 68 modules was designed and fabricated (Figure 6a and Figure 6b). Folding technique for the structure and cassettes seemed to be a practical solution, however; due to connection problems on the corners, the fabrication technique needs to be revisited for the cassettes. Using CNC for cutting the material was not the ideal solution due to time-inefficient and waste of material concerns. Two different solutions were generated to solve this problem.

Figure 6 a and b. The plant-based air filtering system prototype.

Those solutions are either using different fabrication techniques as traditional die cutting to cut the HDPE sheets for the cassettes or changing the folding technique to a different design so that more cassettes can be generated through one sheet of HDPE. 1/8” thick HDPE is also found not to be practical for reusing after disassembly of the cassettes and it can easily crack. Instead of HDPE, more flexible materials are recommended as Styrene, Vinyl or Polypyrene.

The structural scissor system is a practical technique to allow the ability to open and fold easily with lighter elements that carry the cassettes and growing media. The prototype generated valuable feedbacks on the structure by showing arising potential problems.

The mesh holding the plants worked very well with the media. Zippers around the perimeter of the mesh and sleeve create easiness for the assembly of the growing media and planting. Since the system is designed on the premise of flexibility and modularity, the mesh can be easily replaced for the maintenance without shutting the whole system, which allows the durability of the system in the long run.

4 Conclusion and Future Potentials

The durability of the plant-based filtration system is investigated by exploring the design, fabrication and installation properties of the materials. Most of the plant-based integrations in the field do not take advantage of the root zone (rhizosphere) cleaning capacity and have limited applicability in terms of modularity, scalability, flexibility, disassembly /reassembly and life cycle factors. In this paper, the project focused on the design and prototyping of the system to analyze the ways to minimize the maintenance cost and maximize the durability of the system by demonstrating the constructive feasibility of the modular, durable, easily transportable, flexible, adaptable approaches that can be efficiently mounted in indoor spaces. The conclusion of these investigations is showing that especially the structural scissors system and mesh holding (the growth media and plants) has a high potential to be applied to the plant-based filtration system.

Full-scale implementation of plant-based air filtering system is an alternative filtration solution that provides fresh air through the purification of recirculated air. In addition, by this system, end-use energy efficiency will be obtained due to the reduced outdoor air intake and recirculated indoor air. The proposed plant-based air filtering system would provide crucial support for building air handling systems.

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