The 16th Conference of the International Society of Indoor Air Quality & Climate
ONLINE | From November 1, 2020
Paper ID ABS-1222

Experimental Tests of CAM Plants and Hydrogels for Outdoor Air Pollutant Filtration Systems

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SUMMARY
Water and plants absorb 55% of the carbon dioxide and pollutants introduced by humans into the atmosphere (Riebeek, 2011). This study hypothesizes that outdoor air filtration systems consisting of combinations of specific plants and saturated hydrogels are effective in increasing indoor air quality (IAQ) by decreasing airborne pollutants coming in via outdoor urban environments. Various plant types are analyzed to compare their efficiency in reducing air pollutants. From these, the Crassulacean Acid Metabolism (CAM) type plants were found to be the most efficient. Saturated hydrogels configured in a matrix to allow air to pass through were also found to absorb volatile organic compounds (VOCs) and particulate matter (PM_{10} and $PM_{2.5}$). The study was conducted in a hot arid climate in Tucson, Arizona, USA. The results revealed a lowering of dry-bulb temperature in the daytime hours via evaporative cooling, an increase in relative humidity levels to 46% on average, and reduction in daytime levels of VOCs, CO_2, and PM_{10} and $PM_{2.5}$. This study, therefore, has significant implications for the future design of outdoor air filtration systems that can be combined with natural ventilation strategies for optimum IAQ.

KEYWORDS
indoor air quality (IAQ), hydrogel filters, CAM plants, air quality monitoring, natural ventilation

1 INTRODUCTION

In the United States of America, people were found to spend 90% of their time inside built environments (Wallace, 1987), a finding which makes health and wellbeing key considerations when designing indoor environments. Built environments are also essential to create comfortable and healthy habitats for humans by providing shelter from harsh outdoor conditions. Indoor Air Quality (IAQ) is a key feature of a healthy indoor spaces. IAQ refers the air quality levels inside built environments which impact human health and comfort. Indoor air pollutant levels, in fact, are usually two to five times higher than the outdoor air because of inadequate pollution control and air flow via natural ventilation strategies (Wallace, 1987). We need better natural ventilation solutions, therefore, to improve IAQ, particularly in urban areas.
Water and plants absorb 55% of the carbon dioxide and pollutants that humans introduce into the atmosphere. This process which involves the absorption of carbon dioxide and the production of oxygen is in fact, the most massive operation in nature (Riebeek, 2011). This study is inspired by this natural phenomenon. It aims to use natural materials (water and plants) to purify indoor environments from airborne pollutants which enter indoor environments through natural ventilation systems from polluted urban spaces. In this study, different plant

types are analyzed to compare their efficiency in absorbing air pollution. Hydrogels are used as filters and microcontainers for water to capture pollutants while air passes through.

Plants absorb air pollutants through two processes: photosynthesis and the Calvin cycle. Photosynthesis is a chemical reaction of three interacting substances (carbon dioxide, water, and sunlight), which produces oxygen and glucose to supply the plant with the energy it needs to survive (Owens, 2016). Calvin cycle is a process of converting carbon dioxide that occurs in plants to produce energy and oxygen. It is part of the photosynthesis process, but it does not require light and is therefore known as a dark reaction (Gunther, n.d.). There are three types of Calvin Cycles: C3, C4, and CAM, which are further explained below.

Figure 1: a) Canna indica, C3 Calvin Cycle (left); and b) Echinocactus grusonii, CAM Calvin Cycle (right) (by author).

C3 (three-carbon molecule) is the process of fixation of carbon dioxide in a 3-carbon molecule. Carbon dioxide passes through the leaves' pores and then, interacts with an enzyme called Rubisco to produce oxygen and energy for the plant. A reverse reaction called Photorespiration, however, occurs in this process which reduces the efficiency of oxygen production (Sage, 1999). Photorespiration is a wasteful reaction which occurs when one of Calvin cycle enzymes (Rubisco) reacts with oxygen instead of CO_2 (Stéphanie Arrivault, 2019). This reverse process cannot be avoided unless the plant is in an atmosphere containing zero oxygen (Sage, 1999). One example of a C3 plant which is also used in this study is Canna indica (Figure 1a). It is originally from and native to Australia, New Zealand, southern USA, southern and eastern Africa, Hawaii and several other Pacific islands (Lusweti, n.d.).

C4 (four-carbon molecule) plants contain a PEP enzyme which reacts with CO_2 before reaching the Calvin Cycle cell. The PEP enzyme converts CO_2 into a liquid called Malate, and then sends it to Calvin Cycle cells to produce oxygen and energy. This plant type, therefore, does not produce a wasteful reaction (Sage, 1999). Rice plants are examples of C4.

Crassulacean Acid Metabolism (CAM) plants have a type of Calvin cycle which is the same as C4 plants described above. This plant type, however, closes its pores when it is extremely hot outside or when the water in its leaves decreases. This type of Calvin cycle is commonly found in desert plants (Sage, 1999). The Golden Ball Cactus (Figure 1b) is one example of a CAM plant and is used in this study. Its botanical name is Echinocactus grusonii and it is originally from, and native to Mexico (Cactus & Succulents Plants, n.d.)b

The hydrogel is a polymer capable of absorbing large quantities of water which swells due to its hydrophilic groups and its physical components (Bahram, 2015). Based on the configuration of saturated hydrogels within a matrix, air can be allowed to pass through, which in turn gives them the ability to absorb VOCs and particulate matter. The average hydrogel pore sizes is 10 nanometers (nm) to10 micrometers or microns (μm) (Verma, 2016). The size of Particulate Matter 10 – commonly known as PM_{10} – is 10 micrometers (μm) or less, and the size of Particulate Matter 2.5 – commonly known as $PM_{2.5}$ – is 2.5 micrometers (μm) or less (Particle Pollution, 2017). Since they are smaller than a hydrogel's pores, they are able to enter a hydrogel membrane and get absorbed by the water.

2 MATERIALS/METHODS

To test the ability of plants and saturated hydrogels to absorb pollutants and improve IAQ, a scaled physical model of a building with a solar chimney as one of the natural ventilation strategies, was designed and constructed (Figure 2). The solar chimney, as shown in figure 3 below, is a glass wall supported with a black layer directed towards the sun's radiation to absorb thermal radiation which in turn heats the air and makes it rise and move out through the chimney, thereby creating a continuous air flow inside the room. The design of this model was based on a previous study by Mathur (2006). In this study, the chimney's efficiency can was tested in a scale model of 1 cubic meter. An adjustable air gap (10 – 70 cm) was created in the chimney outlet. A 30 x 30 cm window was used as an air inlet. The chimney along with these openings was found to generate a continuous airflow inside the space (Mathur, 2006).

Figure 2 Model for a solar chimney (by author).

The model (Figure 2) is representative of a small-scale building with a solar chimney for natural ventilation. The model dimensions are 30 x 22 x 17 inches, and it is made of plywood. The air gap (outlet) in the chimney is 2.5 x 17 x 4.5 inches in size. The interior of the chimney has a black iron absorber of 10 x 17 inches, and the chimney exterior wall has a 17 x 14-inch glass wall to allow solar radiation to enter and heat the air. A window inlet is introduced in a side near the bottom of the model to make the airflow more efficient with displacement via temperature and pressure differentials. The window size is 4x12 inches. The model is covered by 2 inches of 6.0 R-value insulation. The model was sealed with glue and tape to make it as airtight as possible. This model was tested in Tucson, Arizona, in the Spring season, at the end of March 2020. The model was placed alongside a main street so as introduce urban pollutants to the air-stream. The experiment was carried out on seven consecutive days for four hours per day in the afternoon from 12:30 pm until 4:30 pm. On the first day, the model was placed next to the main street to with the window open to record baseline measurements of outdoor and indoor air quality. On the third day, the hydrogel filter was introduced, and installed in the window. On the fourth day, CAM plants were placed directly outside the window. On the fifth day, the hydrogel filter and CAM plants were put in the window and outside it, respectively. On the sixth day, the hydrogel filter was removed, and CAM plants were replaced with C3 plants placed outside the window. On the seventh day, hydrogel filters were added back C3 plants and the hydrogel filter were put together, and the sensors were placed in and outside the model in all experiment's days.

To measure air quality in and out the model, Mentor Pro：6-in-1 Smart Air Quality Monitor (8096-AP) was used. It has a temperature Sensor: Range: 0°C ~ 80°C, humidity Sensor: Range: 0 ~ 100%, particulate Matter Sensor: PM2.5 Range: 0 ~ 300μg/m3, PM10 Range: 0 ~ 300μg/m3, TVOC Gas Pollution Sensor: Range: 125 ~ 3500 PPB, and CO2 NDIR Sensor: Range: 400 ~ 2000 PPM.

3 RESULTS

The results of this study, classified as per the natural ventilation strategy tested and measured in the physical model, are as follows:

a. Baseline results: There is a relationship between the quality of the outdoor air and the quality of the indoor air due to natural ventilation via an open window in the room which brings pollutants into the space from the outside.

b. Hydrogel filter results: The introduction of the hydrogel filter in the window opening increases the humidity inside the model up to 60% [Figure 4], and on average, 46% throughout the day. The solar chimney helps to increase the airflow coming from the outside the window by absorbing heat and creating differential air pressure inside the space, thereby also increasing the release of moisture inside the model from the hydrogel. Due to the exhaust of vehicles and cars, the percentage of particulate matter increase in the outdoor environment. The hydrogel filter, however, demonstrates the ability to absorb them before they enter the prototype, decreasing them by 10 – 80% [Figure 7,8] on the inside, throughout the day. The rate of carbon dioxide (CO_2) inside the model also decreases by up to 12% as compared to the outside [Figure 6]. Additionally, there is a 36% reduction in volatile organic compounds (VOCs) inside the model [Figure 9]. VOCs may have been introduced inside the model due to the glue and wall insulation materials used, and we assume that introducing natural ventilation reduces this amount.

c. CAM plants: The CAM-type desert plants lose the least amount of water through their pores. The outside air; therefore, does not cool down when passing through this type of plant before entering through the window . There is no significant impact on temperature [Figure 5] and humidity levels either [Figure 4], inside the model. VOC levels outside and inside are almost the same throughout the day, indicating that CAM plants do not have the ability to absorb VOCs [Figure 9]. These plants, however, are successful in reducing CO_2 levels inside [Figure 6], in the range of 50 to 56 ppm throughout the day. This is probably due to the fact that this type of plant produces oxygen all the time (i.e. 24 hours a day) and does not perform photorespiration.

d. Combination of CAM plants and hydrogel membrane: Since CAM plants were found to be more effective in improving IAQ than C3, only CAM plants were combined with hydrogel membrane in this step. The indoor temperature reduced by up to two Celsius degrees (2° C). The humidity inside the model increased by up to 60%, and averaged 46% throughout the day. Particulate matters (both $PM_{2.5}$ and PM_{10}) remained at 0 – 10 $\mu g/m^3$ and their levels decreased from 10-80% as compared to the outside, throughout the day. CO_2 levels were also consistently reduced inside the model by an average of 60 ppm as compared to the outside levels, throughout the day. The combination of plants and hydrogel in this step, therefore, revealed an overall increase in IAQ levels.

e. C3 plants: Placing C3 plants in the model just outside the window reduces the indoor temperature by up to 10% throughout the day [Figure 6]. This could be because C3 plants do lose water through their pores, but the amount of water loss varies from time to time. The density (i.e. the number) of plants also plays a role in affecting humidity and temperature. The higher the density of plants, the more the humidity and lower the temperature. Although these plants are a significant source of oxygen and absorb carbon dioxide. they are not as efficient in reducing CO_2 as CAM plants. C3 plants were found to be 6% less effective in reducing CO_2 than CAM plants [Figure 6].

f. Combination of C3 plants and hydrogel membrane: The results of this step were found to be similar to the previous step, except for an additional increase in humidity (up to 60%) and a reduction in air temperature (2° C). The overall improvement in IAQ with regards to CO_2, VOCs, and particulate matters, however, was not as significant as step d (CAM plants + hydrogels).

4 DISCUSSION

The combination of plants and hydrogel filters tested in this study as natural filtration strategies successfully reduces three types of air pollutants which have a negative impact on individual health: VOCs)up to 35%, $PM_{2.5}$ up to 80%, PM_{10} up to 78%, , as well as levels of CO_2 up to 17%, the build-up of which negatively impacts cognition and human performance. The efficiency of the solar chimney was also found to be key in increasing the inside air flow and reducing pollutants in the model.

Additionally, climate and weather patterns have a strong influence on the solar chimney as cloudy days reduce the efficiency of the indoor airflow created by the solar chimney via air temperature and pressure differentials. The chimney was found to be more efficient in sunny days, since the airflow is stronger and faster as the air heats up and moves upwards, also making the hydrogel filter more efficient in releasing moisture, cooling the air entering the model and absorbing air pollutants in its pores.

Materials used to construct the model were also found to influence IAQ. Wood, insulation, glue and tape are all sources of VOCs that increased the level of VOCs up to 37% inside the model. The percentage of VOCs, therefore, was found to be higher in the model on the first day and it gradually reduced every day, since no new sources of VOC were found to be introduced from the outside air.

5 CONCLUSIONS

This study found an overall improvement in IAQ via a combination of CAM plants and hydrogels used at a source of outdoor air entry i.e. a window, and a solar chimney at the roof. Indoor air is often polluted five times more than the outdoor air (Wallace, 1987), therefore, the application of this passive system leads to efficient natural ventilation and an overall improvement IAQ. The results of this research proved that a combination of hydrogels and plants, along with a solar chimney can improve IAQ by a 17% reduction in CO_2 levels, 79% in PM_{10}, 82% reduction in $PM_{2.5}$, an increase in humidity levels by 60%, 15% reduction in temperature, and 36% reduction in VOCs. As per previous studies, these IAQ improvements would significantly improve the health of the human respiratory system, heart, eyes, and skin. In addition, they would reduce the incidence of cancer caused by air pollution. In addition, these strategies have the ability achieve human thermal comfort by raising humidity and reducing temperature in hot arid climates.

Many studies demonstrate the influence of plants on IAQ, however, not all plant types are equally efficient in producing oxygen and absorbing CO_2. CAM plants in this regard, were found to be particularly efficient. This study was carried out in a hot arid desert area, which is a suitable environment for CAM plants to grow; it may not be feasible, therefore, to use these plants in other types of environments. Also, the hydrogel membrane, a source of cooling and moisture, may be most efficient in hot and dry areas where evaporative cooling strategies are effective. Using them in hot humid regions may increase pathogens and air pollution from increased humidity. It is also important to note that hydrogels do not introduce contaminants during manufacture which is important for environmental sustainability and health considerations (Bahram, 2015).

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