International Conference on Applied Energy 2021
Nov. 29 - Dec. 2, 2021, in Bangkok, Thailand
Paper ID:920

Plant-based Green Wall in Office Environment-Part 1: Real-Time Experiments

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ABSTRACT

Indoor greenery is an energy-efficient and sustainable solution for living spaces thanks to its positive impacts on indoor air and environmental quality. This study presents experimental research to see the impact of a living green wall based on vegetation systems on the removal of total volatile organic compounds (TVOCs). The living space is a real office environment with a number of 15 people while the outdoor environment is a tropical climate. The study collects continuous and long-term TVOC data using Demand Based Biological Air Purification System (DBBAPS) supported by cloud-based data storage. Sensors are located in various parts of the office and the results show that the present green wall can remove TVOCs up to 95% over a five-week period.

Keywords: green wall, vegetation systems, indoor greenery, indoor environment, air quality, volatile organic compounds

1. INTRODUCTION

Indoor air quality (IAQ) has a pivotal role in people's daily life since nearly 80% of their time[1] is spent in indoor places such as offices, homes, etc., while the share of time is even above 80% in developed countries [2, 3]. Fjeld and her colleagues[4, 5] pointed out a similar fact which stated that the impact of indoor air quality on human health may be more significant than the outdoor air quality due to the fact that people spend most of their time in indoor activities. As a result of poor indoor air quality, various health problems can occur in humans like chemical sensitivity and sick building syndrome [6]. The most known indoor air pollutants are particulate matter (PM), volatile organic compounds (VOCs), and volatile inorganic compounds (VICs) like carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_X). The term VOC covers a broad range of gas pollutants with low boiling points and vapor pressure [7]. Besides these pollutants, González-Martín et al. [8] informed that ozone (O_3) is another VIC that is generated by electronic devices in office environments. To minimize the poor indoor air quality, mechanical ventilation, which provides fresh air to the indoor environment, is a well-established solution [7, 9, 10]. Mechanical filtration is also a well-known approach especially for indoor environment with cooking facilities. Material characteristics of filters, particle types, filter specifications are the main criteria for the best filtering efficiency [11, 12]. Other methods to reduce indoor pollutants are electronics filtration, adsorption (especially via carbon and zeolites), membrane-based separation (removal of pollutants via flow in semipermeable membranes), non-thermal plasma, photocatalytic oxidation, and ultraviolet photolysis. More details on different approaches can be found in Refs. [7, 8].

Apart from mechanical ventilation and other filtration solutions, biological-based IAQ improvement systems are recently being promising alternatives to reduce pollutants. Biological-based air purification systems consist of plants or microorganisms (e.g. biofilms) that use the gas pollutants as their carbon & energy sources [8]. Hereby, we can observe pollutant degradation at remarkable levels. The utilization of the indoor pollutants in biological processes usually occurs by means of the gas-cell (plant or microorganisms) or the gas-water interfaces [8, 13]. Since the biological-based

Selection and peer-review under responsibility of the scientific committee of the 13th Int. Conf. on Applied Energy (ICAE2021).

systems are less energy-intensive systems than the conventional mechanical solutions and relevant filtration processes, they are also known as energy-efficient approaches. Besides, considering the psychological factors of people, they can provide additional aesthetic improvements according to Moya et al. [14]. González-Martín et al. [8] listed the biological-based air purification systems as follows: membrane bioreactors, capillary bioreactors, biofilter & biotrickling filter, microalgae reactor, and plant-based systems. Except for the plant-based systems, biological-based air purification systems are mostly based on microorganisms so that their operating costs can be high due to potential biological hazards and smells even though they reduce the energy consumption compared to mechanical solutions. The plant-based systems include small plants instead of microorganisms so that they have both aesthetic views and easy-to-replace/maintenance processes. The plant-based systems are also called green wall/ vegetation systems/ greenery systems [14]. Following the above-mentioned trends and the advantages of the green wall systems in IAQ performance improvement applications, this study conducts real-time experiments to reduce total VOCs (TVOCs) with a proposed green wall structure in a real office environment in the tropics.

2. EXPERIMENTAL SYSTEM

The experimental study is performed with an active green wall system located in the Surbana Jurong-Nanyang Technological University (NTU) Corp. Lab office, NTU, Singapore. The office has an L-shaped layout with a total area of 160 m^2 and a height of nearly 3 m. The office layout can be seen in Fig. 1.

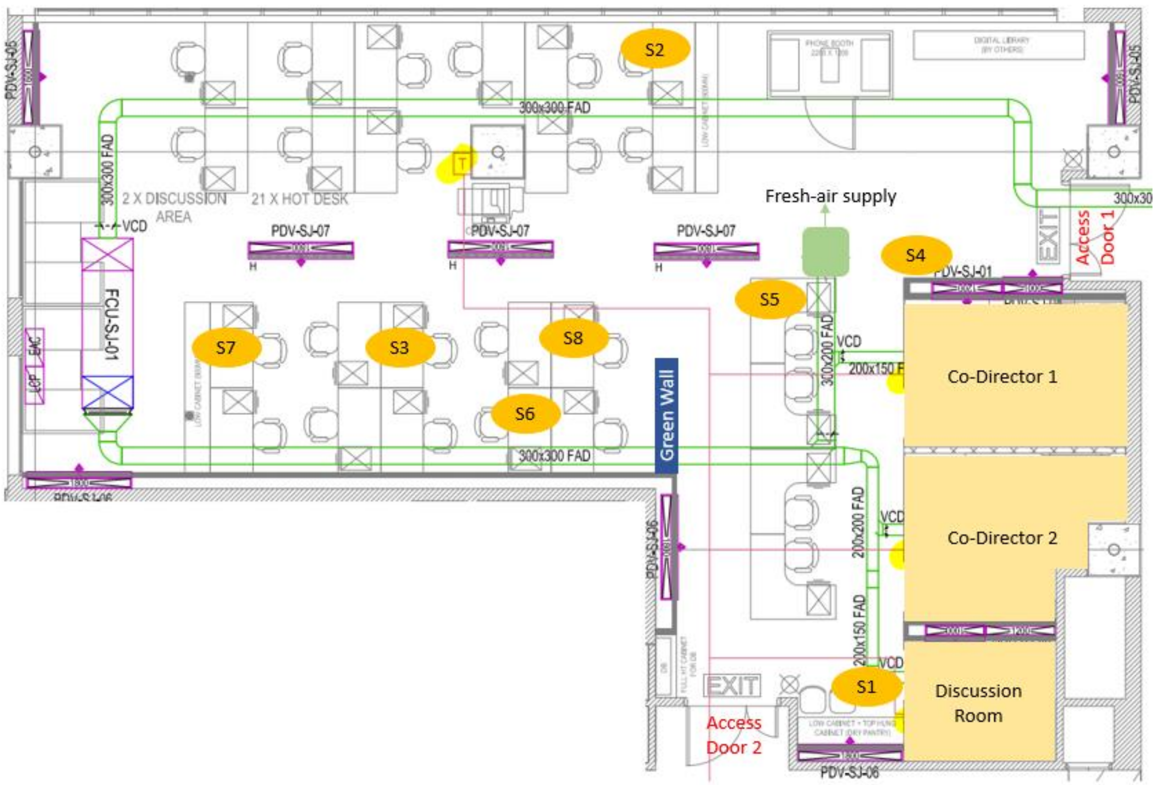

Fig. 1. The layout of the office (S: sensors for indoor air quality).

The office environment is an open environment for occupants except for rooms (champagne-colored) designed for co-directors 1 & 2 and discussion purposes. There are two access doors (red-colored) and eight passive displacement ventilation units (PDVs) (purple-colored) with the cooling capacity of 3000 W (each of them has 375 W). Windows are airtight and always closed in the office. The only fresh air input is provided by a fresh air supply duct (green-colored) with an airflow rate of 236 l/s, a flow velocity of 1.7-1.9 m/s, and an air temperature of 16°C. The supplied fresh air system is a part of the automatically-controlled air conditioning system of the whole building, Academic North Building of NTU. The office temperature is kept constant at 23°C. Even though there are 26-30 seating places of employees, the average number of employees is 15 where each of them has a thermal load of 70 W. Assuming a desktop computer for each employee, the thermal load of each desktop is assumed 100 W that making the total thermal load (people and computers) 2550 W. Apart from the fresh air supply via ducts, additional fresh air exchange occurs via access doors from their gaps between their bottom surface and the floor and during the opening/closing. The green wall is located in the internal corner of the L-shaped office (blue-colored in Fig. 1), and its details are shown in Fig. 2.

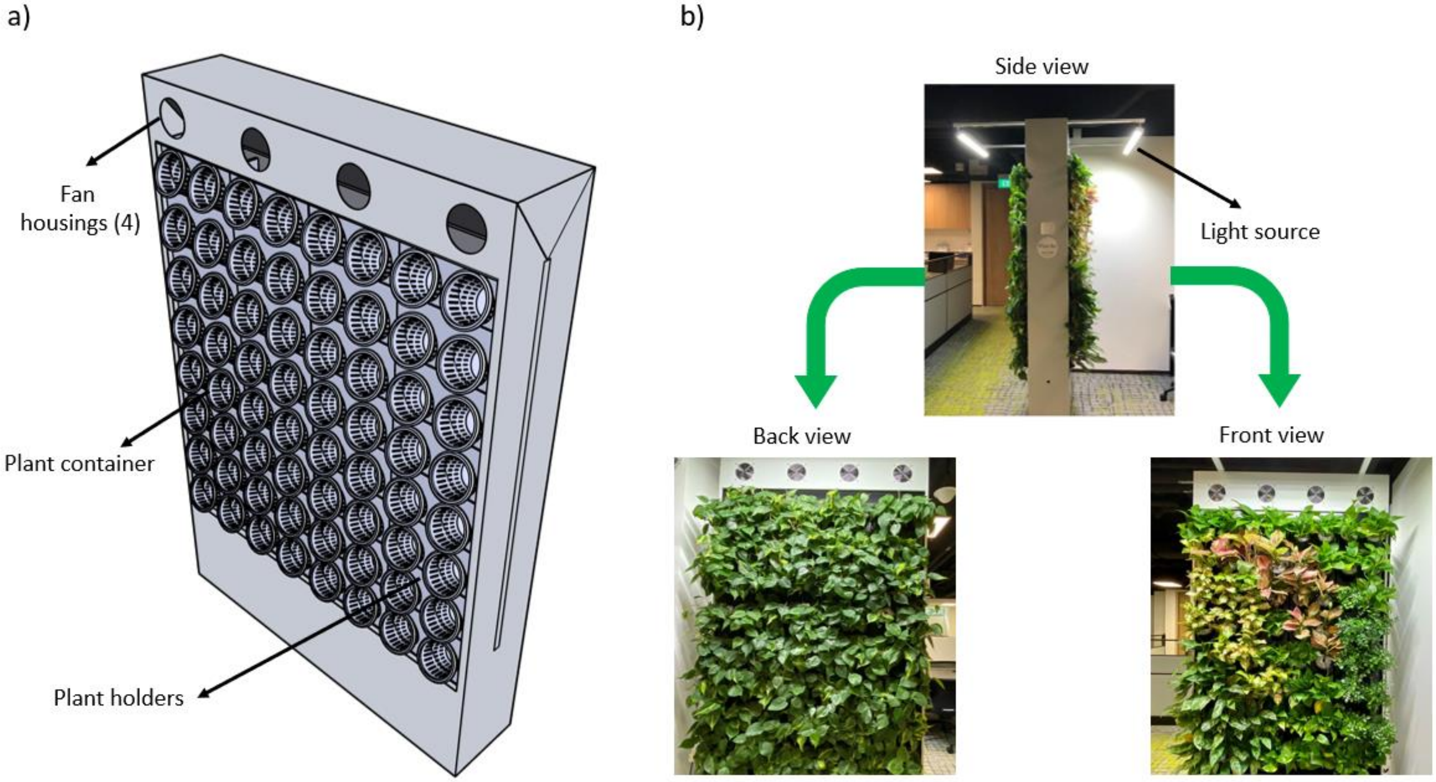

Fig. 2. The green wall in the office; a) isometric CAD view and b) real setup.

Each face has four fans, which are placed in the fan housings (Fig. 2a) to ingest the air from the indoor environment, and sixty-four plants, which are placed in the plant containers (Fig. 2a). All the plant containers are vertically held via plant holder plates (Fig. 2a). The setup is known as an active and double-sided green wall system, known as Flora Aer developed by Greenology Pvt Ltd. The setup is capable to carry different types of plants as shown in the front-view of the system (Fig. 2b) or includes a single type of plant as shown in the back-view of the system (Fig. 2b). In the experimental study, we used a single plant type instead of different plant types. The green wall dimensions are 2×0.35×1.2m and it is fully automated with irrigation. Also, the lighting system (side-view of Fig. 2b) is fully automated in order to meet the growing demands of the plant during day and night while it helps to light demands of the indoor environment. The total active green area is 70% during the experimental study with a total fan capacity of 800 m^3/h. The system ingests the indoor air with fans and pushed the air down through the plants; hereby, the sucked air interacts with the plant roots and is purified while passing through the plants (from interior wall volume to the indoor office) as the treated air.

The indoor air quality is measured at eight different locations using commercially available sensors (Awair IoT sensors), which are recommended by the Buildings Construction Authority (BCA) Singapore to match the highlighted standards by the Singapore Standards (SS554) [15]. Sensors are capable of collecting data for temperature, humidity, CO_2 (ppm), TVOC (ppb), and Particulate Matter (PM) (μg/m^3). In this experimental work, we focus on TVOC measurement since the green walls are biological-based systems for TVOC reduction in the indoor environment as mentioned in Section 1. The sensor data is recorded every fifteen seconds; then, it is stored in Awair's cloud that provides us with quick access to data via a user-friendly dashboard. The locations of sensors are shown in Fig. 1.

Through the cloud-based data storage capabilities of sensors, we also implement a Demand Based Biological Air Purification System (DBBAPS). DBBAPS is based on *If This Then That* (IFTTT) protocol that allows IAQ sensors to trigger mechanical systems such as fans in this case. It makes the system active and passive at the same time while being situationally aware when to alternate between the two modes. Hence, DBBAPS transforms an ordinary green wall into a “smart” one. This concept brings a whole array of commercially available smart systems to interact with the green wall. In this way, according to the need and availability, a variety of systems can be used to control the green wall. DBBAPS provides a way to quantify the efficacy of the system in space. This quick reference technique not only helps size up the system but also provide a realistic picture of air quality in a space. Fig. 3 illustrates the developed concept.

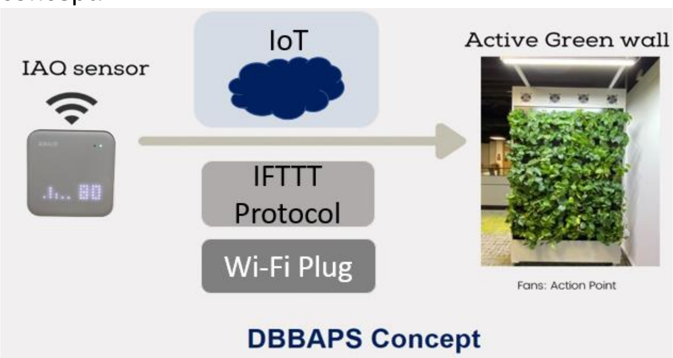

Fig. 3. Demand Based Biological Air Purification System (DBBAPS) based on IFTTT triggering protocols.

3. RESULTS AND DISCUSSION

Fig.4 presents the TVOC trends before and after implementing the green wall in the office environment. The whole period is nine-week period. The first four weeks were a “no green wall” case in the office. It is worth mentioning that the observed low TVOC values in the figure represent weekends in the office because the number of occupants was zero or 1-2 during weekends. Thus, TVOC trends saw minimum values at weekends. The TVOC concentration was at high values before implementing the system with the highest TVOC value of 441 ppb, but it started to decrease just after operating the green wall. The decrement rate increased over time because the plants took some time to acclimatize to the indoor environment. For example, the maximum TVOC value was 296.1 ppb after implementing the green wall, which was recorded just after the implementation. At the end of five weeks, the minimum TVOC value was recorded as 22.9 ppb. That is, the TVOC values decreased nearly by 92% at the end of five weeks, which was a period between just after implementing the green wall and the end of the measurement. In addition to the given TVOC trends, the sensor 8 data (S8 in Fig. 1) is not plotted in Fig. 4 since it is dynamically affected by velocity contours near the green wall volume.

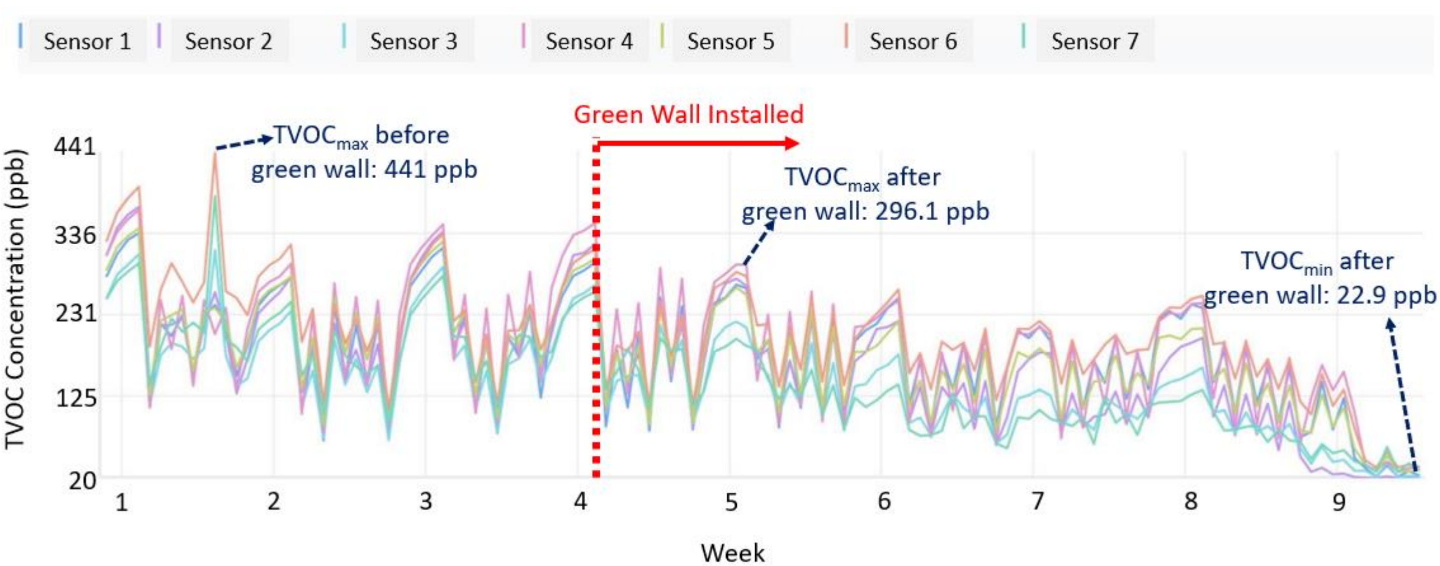

Fig. 4. Changes in TVOC trends in the office space before and after implementing the green wall.

Soon after the installation was completed, the green wall fans were automated to run 12 hours a day from 7:00 pm to 7:00 am. This coincided with the cut-off of the fresh air supply inside the office environment. Therefore, the green wall replaced the fresh air supply. The volume of lab space was approximately 540m^3 and the fans circulated air up to 800m^3/h. The green wall recirculated air up to 1.48 times/ h for 12 hours a day. As observed in Fig. 4, before the installation of the green wall, the TVOC concentrations inside the space increased every night after the fresh air supply was cut off. When the TVOC concentrations are compared between before and after implementing the wall, it is seen that the TVOC decrement was up to 95%. This implies that the green wall played a dominant role to bring down the TVOC levels to acceptable/safe standards. The mitigation of

TVOC by plants through phytoremediation, which refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment, was observed dynamically and it was in good agreement with the well-documented studies in the literature [16]. The DBBAPS concept was also investigated with dynamic observations. Fig. 5 presents the results of the testing of the system according to the DBBAPS concept.

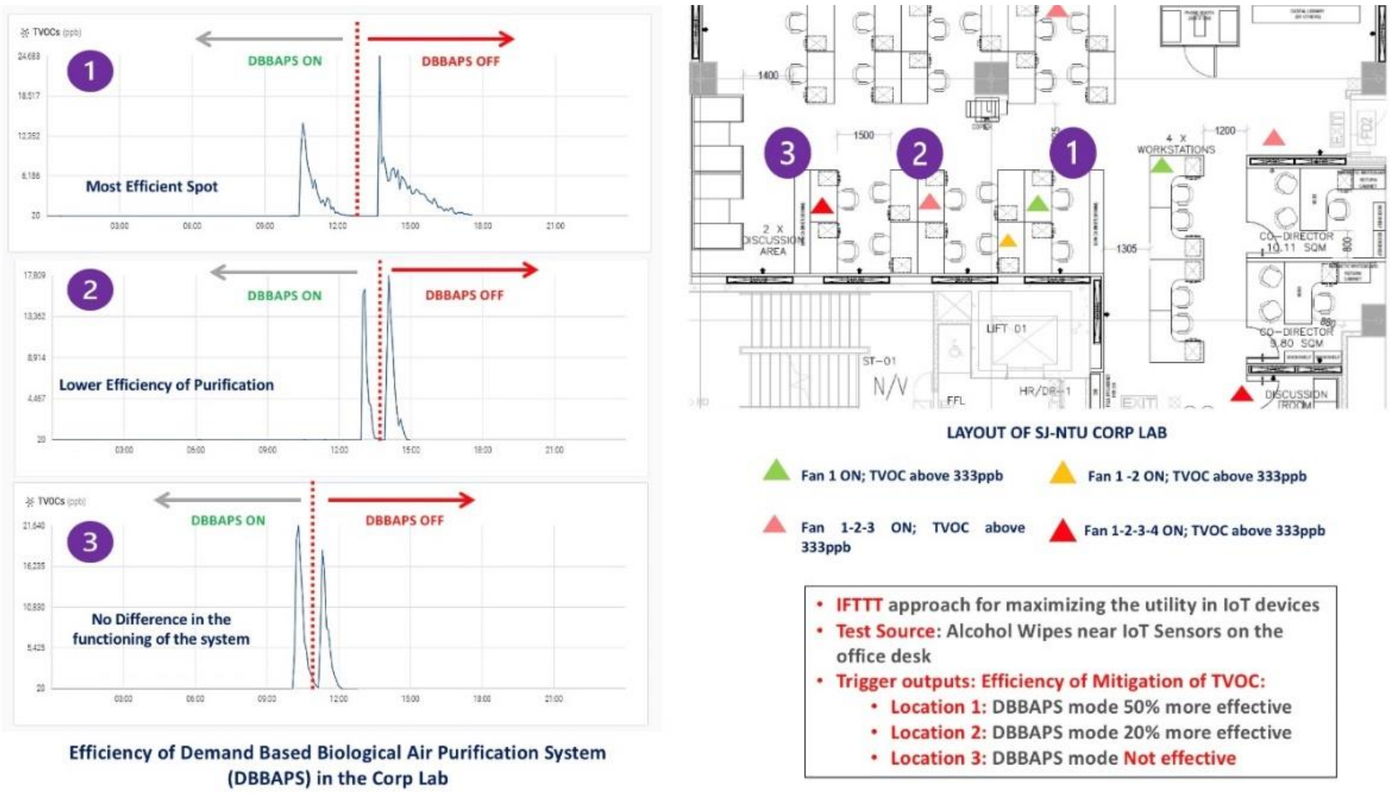

Fig. 5. Testing of the green wall system using the DBBAPS concept.

The distance-based tests result in decreasing efficacy of the air purification by the green wall, as the sensors move away from it. Each sensor's trigger was varied which was again based on the surroundings and distance from the green wall. TVOC were chosen as the triggers since there has been extensive literature on their mitigation using plants [16]. The difficulty to bring pristine sources of TVOC and the complexity of real-life TVOC made it an intricate experiment. Alcohol wipes were used to increase the TVOC levels in local space (Points 1, 2, 3 from Fig. 5) and present a safer alternative to locally increase the TVOC of the space without disturbing the occupants in the space. It is also a realistic way to approach an increase in TVOC of the space as there has been an increased awareness of using alcohol to sanitize surfaces and hands.

Points 1, 2 & 3 were chosen as test points. Each point displays its distance from the green wall. While Point 1 is the closest to the green wall, Point 3 is the farthest. Hence the closest point (Point 1) was assigned to trigger one set of fans accounting for a 200 m^3/h flow rate of air being drawn in for purification; Point 2 triggered 2 sets of fans accounting to 400 m^3/h of flow rate and finally Point 3 triggered 3 sets of fans accounting to 800 m^3/h of air drawn in for purification. Point 3 was the uttermost point from the green wall and was assigned to turn all the fans (up to 800m^3/h) on to mitigate the TVOC around its space. This logic provided us with the efficacy of mitigation of TVOC with respect to the distance from the green wall. The efficiencies in each scenario were calculated from their rise-peak-decay times and full width at half maximum (FWHM) values of the data. The graphs provided in Fig. 5 allowed to test the DBBAPS concept providing the most efficient spot for the green wall (Point 1). Point 1 presented 50% more effectiveness to mitigate TVOC when DBBAPS was triggered. DBBAPS was only 20% effective at Point 2 as the air circulation took longer to mitigate (dilute & remove) the TVOC around its space. Point 3 had a negligible impact of DBBAPS on the space. The decay time of the TVOC was similar when the DBBAPS was not functioning. This implied that the space was closer to be a dead zone for air circulation or more time was required to dilute/remove the TVOC from the air, in that spot. The drop in efficacy of DBBAPS with distance noticed in the experiment was in line with the logical understanding of airflow dynamics in space. While the problems of airflow at farther ends of the space remain, the efficacy of the system in mitigating the toxins from the air due to local fluctuations is almost nothing. This points out the drawback in the system's ability to efficiently recirculate the air to the farthest ends of the test space.

4. CONCLUSIONS

The presented study performed an experimental investigation of a green wall in the office environment in order to reduce the TVOC concentration. A plant-based green wall was implemented in an office space. The TVOC concentration was measured by indoor air quality sensors and the data was able to be stored in a cloud environment. The results showed that the green wall was capable of reducing the TVOC concentration up to 95%. The DBBAPS concept showed the impact of distance between the green wall and any location in the office on the TVOC trends. The data was successfully stored and processed in the cloud environment so that it was seen that the dynamic green wall operation could be operated as a smart solution. The DBBAPS results were in good agreement on the fact that the impact of the green wall was very small at the uttermost right-side of the office. To this end, it was proven that the implementation of the green wall increased the air quality from the standpoint of TVOC removal, but its impact strongly depended on the shape and area of the office. Following the experimental findings, future studies can focus on more effective designs of the green wall and its relevant energy consumption studies including the effect of lighting. Furthermore, the location of the green wall can be investigated anywhere in the office environment.

ACKNOWLEDGEMENT

This study is supported under the RIE2020 Industry Alignment Fund – Industry Collaboration Projects (IAF-ICP) Funding Initiative, as well as cash and in-kind contributions from Surbana Jurong Pte Ltd. B.B. Kanbur is the Mistletoe Research Fellow of the Momental Foundation.

REFERENCE

[1] (WHO) WHO. WHO guidelines for indoor air quality: selected pollutants. Geneva, Switzerland: WHO; 2010.

[2] Commission E. Indoor Air Pollution: New EU Research Reveals Higher Risks than Previously Thought. 2003.

[3] Marć M, Śmiełowska M, Namieśnik J, Zabiegała B. Indoor air quality of everyday use spaces dedicated to specific purposes—a review. Environmental Science and Pollution Research. 2018;25:2065-82.

[4] Fjeld T. The Effect of Interior Planting on Health and Discomfort among Workers and School Children. HortTechnology horttech. 2000;10:46.

[5] Fjeld T, Veiersted B, Sandvik L, Riise G, Levy F. The Effect of Indoor Foliage Plants on Health and Discomfort Symptoms among Office Workers. Indoor and Built Environment. 1998;7:204-9.

[6] Burge PS. Sick building syndrome. Occupational and Environmental Medicine. 2004;61:185-90.

[7] Luengas A, Barona A, Hort C, Gallastegui G, Platel V, Elias A. A review of indoor air treatment technologies. Reviews in Environmental Science and Bio/Technology. 2015;14:499-522.

[8] González-Martín J, Kraakman NJR, Pérez C, Lebrero R, Muñoz R. A state–of–the-art review on indoor air pollution and strategies for indoor air pollution control. Chemosphere. 2021;262:128376.

[9] Chenari B, Dias Carrilho J, Gameiro da Silva M. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. Renewable and Sustainable Energy Reviews. 2016;59:1426-47.

[10] Leung DYC. Outdoor-indoor air pollution in urban environment: challenges and opportunity. Frontiers in Environmental Science. 2015;2.

[11] Harriman L, Stephens B, Brennan T. New Guidance for Residential Air Cleaners. ASHRAE Journal. 2019;61:14-23.

[12] Tang X, Wei J, Kong Z, Zhang H, Tian J. Introduction of amino and rGO into PP nonwoven surface for removal of gaseous aromatic pollutants and particulate matter from air. Applied Surface Science. 2020;511:145631.

[13] Soreanu G. 12 - Biotechnologies for improving indoor air quality. In: Pacheco-Torgal F, Rasmussen E, Granqvist C-G, Ivanov V, Kaklauskas A, Makonin S, editors. Start-Up Creation: Woodhead Publishing; 2016. p. 301-28.

[14] Moya TA, van den Dobbelsteen A, Ottele M, Bluyssen PM. A review of green systems within the indoor environment. Indoor and built environment. 2019;28:298-309.

[15] Committee BaCS. SS 554: Code of practice for indoor air quality for air-conditioned buildings. Singapore: Singapore Standardisation Programme; 2016. p. 65.

[16] Soreanu G, Dixon M, Darlington A. Botanical biofiltration of indoor gaseous pollutants – A mini-review. Chemical Engineering Journal. 2013;229:585-94.

