A dynamic botanical air purifier (DBAP) with activated carbon root-bed for reducing indoor carbon dioxide levels

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Abstract. Indoor Air Quality (IAQ), is important in buildings because it can affect an occupant’s health and productivity. Carbon Dioxide (CO₂) is a main indicator of IAQ. 4 decades ago, researchers discovered the potential for indoor plants to remediate indoor air pollutants via photosynthesis. This study investigates the CO₂ removal rate when a *Maranta Leuconeura* is paired with activated carbon (AC), as well as a mechanical ventilation system that draws air into its root-bed making it an active system (DBAP). The results were compared to passive systems i.e plant with AC, potting soil etc. The study was conducted in a 0.7 m³ Plexiglas chamber with initial CO₂ concentrations of 1500±100 ppm while initial temperatures ranged between 24 ± 2°C for a duration of 6 hours continuously. Results showed, the DBAP reduced CO₂ levels by 40.90% while a passive plant with AC only, was able to lower CO₂ levels by 15.20%. The other passive systems did not reduce CO₂ levels. All systems were able to raise humidity and reduce temperature in the chamber, with the exception of the DBAP, which slightly increased the temperature in the chamber.

1. Introduction
On average worldwide, 80% of the lives of people today are spent indoors. This increases the risk of exposure to harmful indoor air contaminants [1]. The level of indoor air pollutants can range from two to five times and occasionally 100 times higher than outdoor levels and recently indoor air pollution is ranked as the top five environmental risks to public health [2]. In addition, buildings nowadays are significantly riskier than in the past due to the buildings being more air-tight to cut cost and save energy on air-conditioning, leading to accumulation of pollutants. The rise in accumulation of pollutants will lead to a phenomenon known as Sick Building Syndrome (SBS) [1].

Carbon dioxide (CO₂) is one of the major constituents or compounds found among indoor air pollutants mainly derived from occupant respiration [3]. CO₂ gas is colourless with a density 60% higher than dry air and is widely used as an indicator of the adequacy of fresh air supply in a room whereby a concentration of less than 1000 ppm indicates adequate fresh air supply [4]. CO₂ is a metabolic product that indicates the overall level of air pollution and the need for ventilation in an occupied space [5]. Normally carbon dioxide is non-toxic however, if at elevated levels, it has been associated with sick building syndrome (SBS) [6]. Inhaling CO₂ becomes toxic at levels of 5% (50000 ppm) and above, at which it can kill in a couple of minutes [7]. If indoor CO₂ levels are many times higher than ambient or outdoor levels, symptoms of the mucous membranes and lower respiratory tract may manifest [8]. Besides that, the overall performance both at workplaces or academic establishments have been known to decrease with increased CO₂ levels [9].
In Malaysia, the range of acceptable IAQ parameters and allowable levels of contaminants are stated in the Department of Safety and Health (DOSH) Industrial Code of Practice (ICOP) 2010 as shown in Tables 1 and 2.

**Table 1.** The acceptable range of specific indoor air physical parameters [10]

| Parameter          | Acceptable Range |
|--------------------|------------------|
| Air Temperature    | 23 – 26 °C       |
| Relative Humidity  | 40 – 70 %        |
| Air Movement       | 0.15 – 0.50 m/s  |

**Table 2.** List of indoor air contaminants and the acceptable limits [10]

| Indoor Air Contaminants | Acceptable Limits |
|-------------------------|-------------------|
|                         | ppm | mg/m³ | cfu/m³ |
| Carbon Monoxide         | 10  | -     | -      |
| Formaldehyde            | 0.1 | -     | -      |
| Ozone                   | 0.05| -     | -      |
| Respirable Particles    | -   | 0.15  | -      |
| Total Volatile Organic Compounds | 3     | -     | -      |
| Total Bacterial Count   | -   | -     | 500    |
| Total Fungi Count       | -   | -     | 1000   |
| Carbon Dioxide          | 1000 | -     | -      |

Replacement and total removal of the source of CO₂ is normally not a viable option as it is a direct product of human respiration thus it could not be fully omitted from interior spaces. This brings attention to the method of mechanical ventilation. Ventilation is the most widely spread technology used nowadays. It is the best method to remove indoor air pollutants efficiently however it comes with many negative cost implications [11]. Ventilation allows for the air pollutants in a building to be diluted and removed from the building. However, this method is also possible for introducing more pollutants from outside if the air outside is heavily polluted.

Therefore, when emission sources cannot be controlled or reduced for technical or financial reasons, air-cleaning devices need to be used [12]. The technology behind such devices ranges from simple filters to hybrid treatment systems. The four types of best-selling air cleaners are photo-catalytic, activated-carbon, negative ion, and ozone air cleaners [13]. Air cleaning technologies are now being extensively researched to find ways to reduce indoor air pollution with minimal power consumption.

Earth has its natural lungs called plants. They produce oxygen that supports all life. Not only that, they add precious moisture to the atmosphere as well as filter toxins. Common indoor houseplants may provide a valuable weapon in the fight against rising levels of indoor air pollution [14]. It was suggested that if man is to move into closed environments on earth or in space, he must take along nature’s life support system [15]. Studies proposed that plants are the most efficient, most cost-effective way to remove toxins from air [16]. It also has been stated that several plants are able to add aesthetic and biological comfort to interior spaces [3].

Since then, a multitude of tests and studies on the usage of plants to alleviate indoor air quality problems have been carried out, with different applications for various indoor air pollutants as well as their efficiencies in different conditions, as summarized in Table 3.
Table 3. Prior Chamber Test Results on the Ability of Various Plants to Remove CO₂

| Plant                          | Light Intensity (Lux) | Temp. (ºC) | Initial Conc. (ppm) | Duration (hours) | Removal   | Source |
|-------------------------------|-----------------------|------------|---------------------|------------------|-----------|--------|
| Peace Lily (Spatiphyllum sp.) | 20000                 | 25         | 2000 ± 200          | 12               | 361.2 ppm/hr | [17]   |
| Dumb Cane (Dieffenbachia sp.) | 20000                 | 25         | 2000 ± 200          | 12               | 216.5 ppm/hr | [17]   |
| Ficus Benjamina (Ficus sp.)   | 20000                 | 25         | 2000 ± 200          | 12               | 407.6 ppm/hr | [17]   |
| Janet Craig (Dracaena sp.)    | 18919                 | 25         | 1000 ± 200          | 0.8              | 13.6 mg/hr  | [11]   |
| Golden Pothos (Epipremnum sp.)| 300                   | 25         | 454                 | 8                | 28.33 ppm (6.5%) | [18]   |
| Syngonium sp.                 | 300                   | 25         | 454                 | 8                | 19 ppm (3.1%) | [18]   |
| Prayer Plant (Maranta sp.)    | 300                   | 25         | 1000±10             | 8                | 154.6 ppm (14.4%) | [19] |
| Kadaka Fern (Asplenium sp.)   | 300                   | 25         | 458.67              | 8                | 21.34 ppm (4.65%) | [18] |
| Anthurium sp.                 | 300                   | 25         | 452                 | 8                | 5 ppm (1.1%) | [18]   |
| Table Palm (Chamaedorea sp.)  | 18919                 | 25         | 1000 ± 200          | 0.8              | 118 mg/hr  | [11]   |
| Areca Palm (Dypsis sp.)       | 18919                 | 25         | 1000 ± 200          | 0.8              | 139 mg/hr  | [11]   |

Although plants seem remarkable at first, some researchers claim it is non-beneficial as the number of plants that must be used is far more than what the indoor space could accommodate [20]. Most research has focused on traditional potted indoor plants; however, newer developments in horticultural technology, specifically green wall systems, have received far less research, with much recent research focused on exploring other aspects of the indoor environment including cooling potential and humidity regulation [21]. A biological purifier is a term to describe any devices that include a biological component either botanical or microbial for pollutant removal. Examples of such real-life applications can be seen in bio-wall technology which is essentially a type of green wall, bio-scrubbers and bio-trickling filters [22]. Although there is a range of biological purifiers out in the market, only a few focus on the assimilation of plants and activated carbon. Examples of such assimilation of activated carbon in the root-bed of plants are demonstrated in the Dynamic Botanical Air Filter [23]. There had been tests that utilized activated carbon in the root zone of potted plants however they are mostly focused on the laboratory test chamber results and not for real-life applications. It is still too early to dismiss the potential of plants as the experiments made on plants are only mainly focused on passive ability alone. Studies can still be made to determine whether mechanically assisted plants can put plants back in the spotlight in the quest for better indoor air quality [24].

2. Method
A Prayer Plant (Maranta Leuconeura) was used in this study based on recommendations by prior research [19]. A matured plant with dark green foliage was chosen. It was grown in a pot of 17 cm diameter and 25 cm height with a ratio of 2:2:1 (Garden Soil, Compost and Perlite). Plant care was done accordingly to the methods suggested [25]. The plant was acclimatized indoors for two weeks and watered a day before tests were conducted. An air-tight Plexiglas test chamber (0.7 m x 0.7 m x 0.7 m) with a removable lid was fabricated and it houses a 12V PC fan to mix the air in the chamber homogeneously. It was tested and was found to be able to maintain CO₂ concentrations, temperatures and relative humidity levels constantly. CO₂ was introduced into the chamber by means of a chemical reaction between sodium bicarbonate and 5% acetic acid. To ensure that the concentration of CO₂ produced in the chamber is replicable within a range of 1500±100 ppm, simple stoichiometry was done beforehand to ensure the correct ratio of reactants is achieved. It was found that 1 g of sodium
bicarbonate reacts with 20 mL of acid to raise the CO$_2$ concentration in the chamber from an ambient level of 600±100 ppm to 1500±100 ppm. It was normalized for half an hour before tests began. During the test, ambient light levels of 1000 lux were achieved in the chamber by placing it near to the windows where it could receive adequate sunlight as well as artificial lights from the fluorescent lighting in the room.

Each test ran for a duration of 6 working hours. Each parameter was recorded with a YESAIR 8-Channel IAQ Monitor with data logging after every one-minute interval from the time the CO$_2$ has been introduced into the chamber and the internal fan has been turned on. The tests were conducted to identify the parameters (the temperature, relative humidity, and CO$_2$ concentrations) in three controlled conditions and one variable condition as summarized in Table 4, with the variable test being the DBAP. Triplicates were taken for each stage of the control tests by repeating each test three times on three separate days throughout a week. The equipment was located away from the direct blow of the PC fan to avoid inaccuracy.

Quantitative measures were taken to assess the data obtained through the observations. The data for the control and variable tests were recorded in tabular format. A series of triplicates were averaged to give the most accurate results. It is then synthesized into a graphical format with respect to time. The graphs show a clear trend in the changes in CO$_2$ levels in the chamber and were used to compare with other results from other papers to draw for any significant findings. The graphs were compared among each other, to see if there are any significant changes between the control tests as well as the variable tests. Statistical tests such as the ANOVA and T-Test was carried out to determine the significance of the data. The setup of the experiment is as shown in Figures 1, 2, 3 and 4.

| Test       | Growth Media | 250g AC | Plant | PC Fan |
|------------|--------------|---------|-------|--------|
| Control 1  | ✓            | -       | -     | -      |
| Control 2  | ✓            | ✓       | -     | -      |
| Control 3  | ✓            | ✓       | ✓     | ✓      |
| Variable (DBAP) | ✓        | ✓     | ✓      | ✓      |

Table 4. Prior Chamber Test Results on the Ability of Various Plants to Remove CO$_2$
3. Results
Table 5 shows the comparison of percentage changes of parameters between the various test calculated by comparing the difference between initial and final readings and averaging the triplicated results. A negative percentage change signifies a reduction and vice versa. From the table, it is shown that all the test were able to reduce the temperature in the chamber slightly except for the DBAP as the mechanical fan converts some of the electrical and kinetic energy into heat. In terms of relative humidity, the DBAP contributed the highest rise. This can be due to the fan which blows air directly into the root-zone of the plant. More moisture could be released into the chamber when the growth media is constantly blown by a fan. The CO₂ percentage change in the chamber for control tests 1 and 2 both recorded a slight increase. This could be contributed by the respiration of microorganisms in the growth media as the growth media is primarily made up of soil and compost. Control test 2 recorded a lower increase than control test 1 due to the adsorbing properties of the AC. However, the study failed to show that it is very efficient in removing the CO₂ in the chamber through passive adsorption without any form of mechanical aid to stream air into the AC. However, both the control test 3 as well as the DBAP managed to record a significant decrease in CO₂ concentration in the chamber.

Table 5. Average Percentage Change of Parameters and the ANOVA p-Value for Each Test

| Parameters          | Test   | Average % Change | SD   | ANOVA P Value |
|---------------------|--------|------------------|------|---------------|
| Temperature (°C)    | Control 1 | -2.40            | 0.85 | 0.054184 (>0.05) |
|                     | Control 2 | -3.08            | 2.09 | 0.141572 (>0.05) |
|                     | Control 3 | -4.12            | 1.38 | 0.304164 (>0.05) |
|                     | DBAP    | 1.97             | 3.29 | 4.84 x 10⁻¹¹ (<0.05) |
| Relative Humidity (%) | Control 1 | 22.00            | 1.60 | 0.972014 (>0.05) |
|                     | Control 2 | 21.79            | 1.28 | 0.757139 (>0.05) |
|                     | Control 3 | 16.29            | 1.35 | 0.881328 (>0.05) |
|                     | DBAP    | 37.52            | 3.84 | 0.554729 (>0.05) |
| CO₂ Concentration (ppm) | Control 1 | 1.62             | 0.67 | 7.88 x 10⁻⁹ (<0.05) |
|                     | Control 2 | 0.70             | 0.64 | 1.81 x 10⁻⁵ (<0.05) |
|                     | Control 3 | -15.20           | 2.15 | 0.166884 (>0.05) |
|                     | DBAP    | -40.90           | 6.98 | 0.265384 (>0.05) |
The difference of results from this study with prior studies could be attributed to various factors such as the leaf area of the plant, which is a predominant factor on the rate of photosynthesis [18]. The current study also incorporates AC which may serve to slightly increase the rate of removal of CO\textsubscript{2} from the chamber. Not to mention, the initial CO\textsubscript{2} concentration in this study is also higher than in the previous study which may explain the increase in removal rates of CO\textsubscript{2} from the chamber. Plants exhibit higher rates of photosynthesis in CO\textsubscript{2} rich environments particularly in ranges from 1300 ppm to 1500 ppm which explains the increase in removal rates of CO\textsubscript{2} in this study compared to the prior studies [11].

An ANOVA (Analysis of Variance) test is conducted to find out if there are any significant differences within or between each set or groups of data. For both control tests 1 and 2, the p-value exceeds 0.05 for the temperature and relative humidity parameters indicating that both the systems have a significant effect on both the parameters. However, they do not affect the CO\textsubscript{2} concentration significantly. Control test 3 as well as the DBAP both recorded a significant difference with the p-values exceeding the alpha value for all the tests except for the temperature parameter in the DBAP test. This indicates that the systems were effective in reducing the parameters tested with an exception of the DBAP not being able to reduce the temperature inside the chamber.

4. Conclusions and Recommendations

Results from this study concluded that the DBAP had the best capability of reducing CO\textsubscript{2} concentration (40.90% reduction) and was able to humidify the chamber. However, it was not able to cool the temperature in the chamber. It has shown an improved removal of CO\textsubscript{2} as compared to the passive plant with AC in control test 3 which had an average removal of CO\textsubscript{2} of 15.20%. Control tests 1 and 2 did not reduce CO\textsubscript{2} levels significantly, however they reduced temperature and was able to humidify the air in the chamber. Although the DBAP was able to reduce CO\textsubscript{2} under a closed system, further tests should be carried out on actual field conditions via pilot tests in real world conditions of various buildings. Tests that are done in field conditions can be more accurate and will show whether the system is truly applicable in real life situations. The durations of the test should be longer and more frequent if possible. A longer duration means that the long-term efficiency could be assessed and optimised to find out what time throughout a day is most suitable for this system to operate as well as how long the system could run before maintenance is needed. The DBAP should be tested for its ability to not just reduce CO\textsubscript{2}, but other harmful gasses as well such as VOCs and Formaldehyde.

References

[1] An et al. 2012 Indoor formaldehyde removal over CMK-3 Nanoscale Research Letters 7:7. doi: 10.1186/1556-276X-7-7
[2] US EPA 2007 Testing for Indoor Air Quality section 01 81 09.
[3] Suhaimi MM, Leman AM and Safii H 2016 Indoor Plants as Agents Deterioration of Gas Pollutions ARPN Journal of Engineering and Applied Sciences 11:10944–9.
[4] Alberts WM 1994 Indoor air pollution : NO , NO\textsubscript{2} , CO , and CO\textsubscript{2} Tampa, Florida: 1994;94:289–95.
[5] Luengas A, Barona A, Gallastegui G and Elias A 2015 A Review of Indoor Air Treatment Technologies Rev Environ Sci Biotechnol 14:499–522 doi:10.1007/s11157-015-9363- 9.
[6] Seppanen and Fisk OA 2004 Summary of human responses to ventilation Indoor Air, Supplement 14:102–18. doi: org/10.1111/j.1600-0668.2004.00279.x
[7] Ekaterina P. 2014 Comparison of indoor air and outdoor air contaminant concentrations.
[8] Erdmann C and Apte M 2004 Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset Indoor Air 14(s8):127–34. doi: 10.1111/j.1600-0668.2004.00298.x
[9] Shaughnessy R et al. 2006 A preliminary study on the association between ventilation rates in classrooms and student performance Indoor Air 16(6):465–468. doi:10.1111/j.1600-0668.2006.00440.x.
[10] Department of Occupational Safety and Health Malaysia (DOSH) 2010 Industry Code Of Practice On Indoor Air Quality (JKKP DP(S) 127/379/4-39).

[11] Torpy F, Irga P and Burchett M 2014 Urban Forestry & Urban Greening Profiling indoor plants for the amelioration of high CO₂ concentrations. Urban Forestry and Urban Greening 13(2):227–33. doi:10.1016/j.ufug.2013.12.004.

[12] Ayoko GA and Wang H 2014 Volatile Organic Compounds in Indoor Environments. P. Pluschke and H. Schleibinger (eds.), Indoor Air Pollution 2 doi:10.1007/698.

[13] Tseng C, Hsieh C and Chen S 2005 The Removal of Indoor Formaldehyde by Various Air Cleaners Proceedings of the Air & Waste Management Association’s 98th Annual Conference; Paper no.457.

[14] Wang Z, Pei J and Zhang JS 2012 Modeling and simulation of an activated carbon-based botanical air filtration system for improving indoor air quality. Building and Environment;54:109–15. doi:10.1016/j.buildenv.2012.02.011.

[15] Wolverton 1984 Interior Landscape Plants For Indoor Air Pollution Abatement Economic Botany 38(2) 224-228. doi: 10.1007/BF02858837

[16] Dai X, Liu J, Yin Y et al. 2018 Modeling and controlling indoor formaldehyde concentrations in apartments : On-site investigation in all climate zones of China. Building and Environment 127:98–106. doi:10.1016/j.buildenv.2017.10.036.

[17] Sevik H, Cetin M, Guney K, et al. 2017 The Influence of House Plants on Indoor CO₂ Polish Journal of Environmental Studies 26(4) 1643-1651 doi:10.15244/pjoes/68875.

[18] Mahathir M, Leman AM, Hariri A et al. 2016 Profiling of Indoor Plant to Deteriorate Carbon Dioxide Using Low Light Intensity MATEC Web of Conferences 78 01011. doi: 10.1051/matecconf/20167801011

[19] Suhaimi M, Leman A., Afandi A et al. 2017 Effectiveness of Indoor Plant to Reduce CO₂ in Indoor Environment MATEC Web of Conferences;103:05004. doi:10.1051/matecconf/201710305004.

[20] Girman J, Phillips T and Levin H. 2009 Critical Review: How Well Do House Plants Perform as Indoor Air Cleaners? Buildings :9–12.

[21] Pérez-urrestarazu L, Fernández-cañero R, Franco-salas A, et al. 2016 Vertical Greening Systems and Sustainable Cities Vertical Greening Systems and Sustainable Cities Journal of Urban Technology 22(4) 65-85. doi:10.1080/10630732.2015.1073900.

[22] Torpy FR, Zavattaro M, Irga PJ. 2017 Green wall technology for the phytoremediation of indoor air : a system for the reduction of high CO₂ concentrations Air Quality, Atmosphere and Health 10(5) 575-585. doi:10.1007/s11869-016-0452-x.

[23] Wolverton BC, Mcdonald RC and Watkins EA. 1984 Foliage plants for removing indoor air pollutants from energy-efficient homes Economic Botany 38:224–8. doi:10.1007/BF02858837.

[24] Zhang Y, Mo J, Li Y, et al. 2011 Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review Atmospheric Environment 45:4329–43 doi:10.1016/j.atmosenv.2011.05.041.

[25] Pennisi BV 2017 Growing Indoor Plants With Success. Bodie V. Pennisi Extension Floriculture Specialist Retrieved from http://athenaeum.libs.uga.edu/handle/10724/12395.