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Using Active Green Wall Systems for both Saving Energy and Improving Indoor Air Quality in Classrooms

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Abstract. University classrooms in Thailand normally use air conditioners to enhance thermal comfort for building occupants. Classrooms with many students are often found to exceed standard concentration levels of carbon dioxide (CO_2). This research aims to study the benefits of active green wall systems in two aspects. They are energy consumption and the ability to reduce CO_2 of plants. The green walls in this research are divided into two systems, which are active green wall (AGW) and passive green wall (PGW). The experiments took place in an air-conditioned classroom with ten occupants. The room temperature was set at 25 °C for all experiments. The data collected for all experiments are CO_2, temperature, and energy consumption. The results showed that two active green wall panels with a single plant of *Epipremnum aureum* is the optimal model for improving air quality in classrooms, when compared to other experiments. It can reduce the CO_2 concentration by 35% and use less energy than the no green wall experiment at 26%.

1 Introduction

University classrooms in Thailand normally use air conditioners to enhance thermal comfort for building occupants. The CO_2 concentration in classroom increases as students enter and it starts to decay after dismissal [1]. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) guideline 36-2021 recommends that the CO_2 setpoint for ventilation system in lecture classroom is 1,305 ppm [2]. Increasing the ventilation rate to alleviate high concentrations of CO_2 is costly [3]. Growing plants in numbers and organised in a suitable pattern could reduce the load on ventilation systems. Shao et. al. [4] studied vertical farming in 30 m^2 office with 1-3 occupants and discovered that building ventilating energy consumption could be reduced by 12.7%–58.4%. Constructing a green wall is an option for reducing concentration rates of CO_2 without employing ventilation fans. Green walls which occupy 1% of a rooms volume can reduce CO2 concentration [5]. Light intensity and the angle of light on a green wall are important

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factors in CO_2 absorption efficiency [6]. Pérez-Urrestarazu et al. [7] found that an active green wall can reduce the temperature in a hall by 0.8 to 2.3 °C at a measurement distance of 0.6 m. Al-Kayiem et. al. [8] found that installing green wall and rooftop shading can reduce the cooling load by the air conditioning causing less amount of energy consumption for 18.3%. However, details concerning the energy consumption of implementing active green walls to improve air quality improving in air-conditioned room are less known. Therefore, this research is interested in studying minimizing energy consumption to improve air quality in classrooms with green walls.

2 Material and Methods

2.1 Material

The green walls in this study are divided into two types, mixed plants and single plants. Three ornamental plants were put on a green wall in the mixed plants condition. They were 28 pots of *Epipremnum aureum*, 28 pots of *Spathiphyllum spp.*, and 28 pots of *Ficus Lyrata*. Only *Epipremnum aureum* was put on a green wall in the single plant condition due to its well known ability to reduce CO_2 from previous research [9, 10, 11]. Each plant pot had a size of 25 x 11 x 11 cm. The green wall panel was made of angle steel and covered by a clear acrylic sheet to allow the natural light necessary for plant growing. The panel had a size of 2.00 (W) x 1.80 (H) x 0.40 (D) meters. Six fans with a diameter of 15 centimeters were installed on the top and bottom of the panel to exchange polluted air in the room with fresh air inside panels, as shown in Figure 1. Two LED daylight (125W) were installed on the side of the panel to increase the active green wall ability to reduce CO_2 in the room.

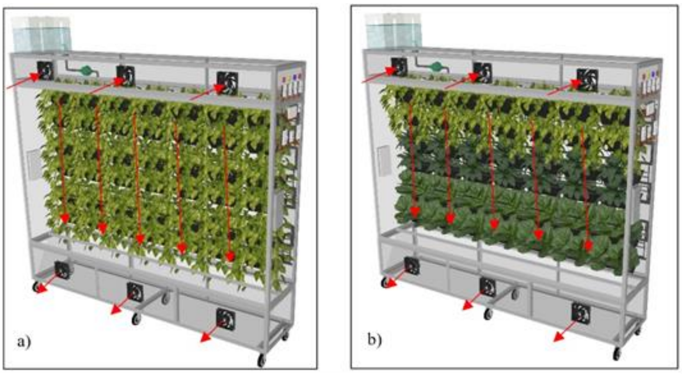

Fig. 1. Green wall panels - a) single plant condition and b) mixed plants condition.

2.2 Methods

Energy usage for the LED and ventilation systems on the green wall panel were recorded in kWh by a ZMAi-90 sensor connected to the Wi-Fi via a Tuya Smart application. Air conditioning energy consumption was measured by a MAIB Dds576 energy meter. The CO_2 concentration and temperature were measured by IQAir AirVisualPro connected to Wi-Fi via an AirVisual application. The light intensity was recorded using a Xiaomi Mijia GZCGQ01LM.

3 Methodology

This research was conducted in an air-conditioned university lecture classroom. A classroom with a size of 28.2 m^2 with a ceiling height and volume of 3.50 m and 99.0 m^3, respectively. One exhaust fan with a of diameter of 8" and a 36,000 BTU air conditioner were installed in the classroom. The room temperature was controlled and set at 25 °C. The green wall was installed inside the classroom with its back facing the window. Watering was set automatically at 17:00 PM for two minutes per day. Data collection started at 8:00 am and ended at 12:00 pm, or a test duration of 240 minutes. The teaching period was 120 minutes. Nine students with average age of 20 years old were present in the classroom with one teacher. An average artificial light intensity of 4,500 lux was used during the experiments. Figure 2 shows the measurement of light intensity at night time. A total of ten experiments were conducted in this study. They are labelled and shown in the first and second columns of Table 1. NGW means no green wall, PGW means passive green wall, and AGW denotes active green wall.

Table 1. Ten situations in the experiment.

No.	Experimental name	Exhaust fan in room	LED on green wall panel	Ventilation fan on green wall panel	Plants species			Number of green wall panels
					Epipremnum aureum	*Spathiphyllum spp.*	*Ficus Lyrata*	
1	NGW	off	-	-	-	-	-	-
2	NGW / turn on exhaust fan	on	-	-	-	-	-	-
3	1 PGW mixed	off	off	off	✓	✓	✓	1
4	2 PGW mixed	off	off	off	✓	✓	✓	2
5	1 AGW mixed	off	on	on	✓	✓	✓	1
6	2 AGW mixed	off	on	on	✓	✓	✓	2
7	1 PGW single	off	off	off	✓	-	-	1
8	2 PGW single	off	off	off	✓	-	-	2
9	1 AGW single	off	on	on	✓	-	-	1
10	2 AGW single	off	on	on	✓	-	-	2

* Note: The ✓ sign is yes and the - sign is no.

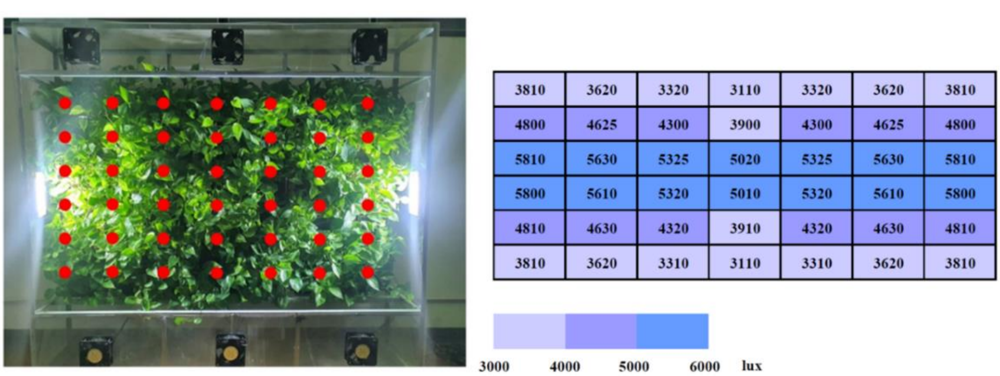

Fig. 2. Artificial light intensity measurement.

4 Results

4.1 CO_2 concentration

The CO_2 concentration for the ten experiments when all ten persons entered the room is shown in Figure 3. It was found that the CO_2 concentration increased when the classroom started being used and decreased when classes ended. None of the experiments have CO_2 exceeding the ASHRAE guideline [2]. The NGW / turned on exhaust fan experiment had the best control in terms of CO_2 levels. It was able to reduce the CO_2 concentration from 1,158 ppm to 732 ppm. The second most effective was 2 AGW single plants, this was able to reduce the CO_2 concentration from 1,158 ppm to 735 ppm. The green walls had different natural light intensities on different testing days, as shown in Column 4 of Table 2.

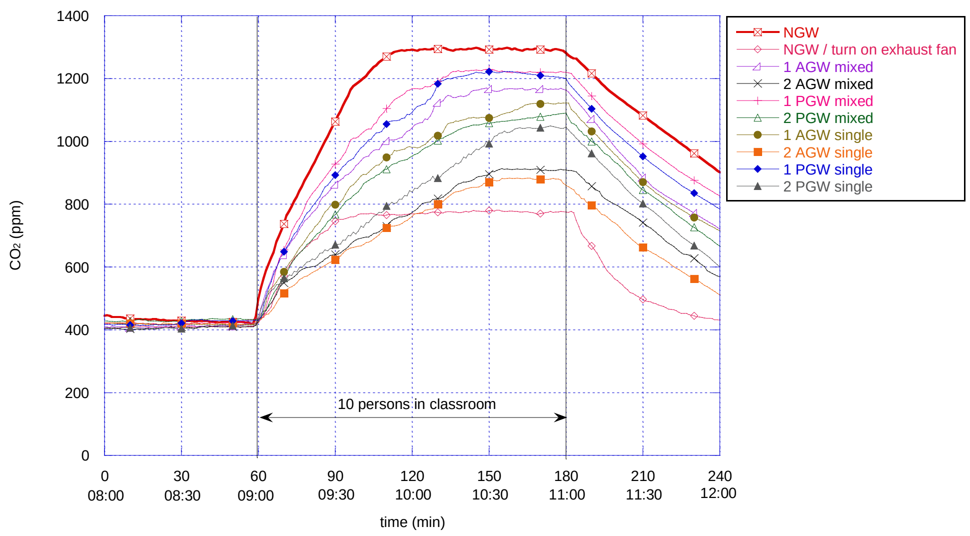

Fig. 3. The CO_2 concentration of each experimental model.

Table 2. The average CO_2 concentration and light intensity received by the green wall during 9-11am.

Experimental name	Average outdoor CO_2 (ppm)	Average indoor CO_2 (ppm)	Average natural light intensity (lux)	Average artificial light intensity (lux)
NGW / turn on Exhaust fan	410	732	-	-
2 AGW single	408	735	7,019	4,500
2 AGW mixed	403	758	7,103	4,500
2 PGW single	405	826	6,812	-
2 PGW mixed	404	899	6,962	-
1 AGW single	415	927	6,835	4,500
1 AGW mixed	405	989	6,790	4,500
1 PGW single	404	1,029	6,805	-
1 PGW mixed	401	1,054	6,879	-
NGW	402	1,158	-	-

4.2 Energy consumption

The energy consumption of air conditioning, exhaust fan, and green wall panels of the ten experiments are summarized in Table 3. Energy consumption from the exhaust fan was 0.1 kWh which was for NGW / turned on exhaust fan experiment only. While energy consumption from active green wall panels were different according to different experiments. The furthest right column shows the values of total energy consumption for all experiments. It was found that 1 AGW single plant experiment consumed the lowest energy in order to improve classroom air quality. To improve classroom air quality by turning on the exhaust fan incurred the most energy usage.

Table 3. The average CO_2 concentration and light intensity received by the green wall during 9-11am.

Experimental name	Air conditioning energy (kWh)	Exhaust fan energy (kWh)	Green wall panel energy (kWh)	Total energy consumption (kWh)
NGW	9.1	0.0	0.0	9.1
NGW / turn on exhaust fan	9.7	0.1	0.0	9.8
1 AGW mixed	5.5	0.0	0.4	5.9
2 AGW mixed	5.6	0.0	0.9	6.5
1 PGW mixed	7.9	0.0	0.0	7.9
2 PGW mixed	7.0	0.0	0.0	7.0
1 PGW single	7.8	0.0	0.0	7.8
2 PGW single	6.8	0.0	0.0	6.8
2 AGW single	5.3	0.0	0.9	6.2
1 AGW single	5.6	0.0	0.4	6.0

5 Determining the Best Plant in Terms of CO_2 Absorption and Energy Consumption

5.1 Normalizing the light intensity impact

Since the natural light intensity in different experiments varied on different testing days. The ability of plants to reduce CO_2 in the classroom, therefore, was affected by natural light intensity [12, 13]. Thus, the CO_2 levels of each experiment were normalized to the same light intensity. The 2 AGW single plant experiments were selected to be recorded twice for use as a base case for normalizing purposes, as shown in Table 4. The natural light intensity that the green wall received were 7,019 and 6,996 lux for 2 AGW single 1 and 2 AGW single 2, respectively. While the average indoor CO_2 levels were 735 and 732 ppm for 2 AGW single 1 and 2 AGW single 2, respectively. The natural light intensity of 1 PGW mixed plant experiment was chosen as a base for normalization at 6,879 lux, as shown in column 4 of Table 4. This value was closest to the mean value of all experiments. To normalize, for example, 1 AGW mixed experiment which has an average natural light intensity at 6,790 lux. The natural light intensity of 1 AGW mixed is lower than the mean value for 6,879 - 6,790 or 89 lux. Therefore, the CO_2 levels of 1 AGW mixed should be lower than 989 ppm for $(\frac{735\text{-}732}{7{,}019\text{-}6{,}996}\times 89)$ = 12 ppm. As a result, the normalized value of CO_2 levels is 977 ppm, as shown in column 5 of 1 AGW mixed row. Other values of indoor CO_2 levels were normalized in the same manner and shown in column 5 of Table 4.

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Table 4. CO_2 concentration in classroom and natural light intensity for before and after normalization.

Experimental name	Recorded data or before normalization processes		CO_2 after normalizing natural light intensity at 6,879 lux		Average outdoor CO_2 (ppm)	Difference in CO_2 concentrations between outdoor and indoor (ppm)
	Average natural light intensity (lux)	Average indoor CO_2 (ppm)	Average natural light intensity (lux)	Average indoor CO_2 (ppm)		
NGW	-	1,158	-	1,158	402	756
NGW / turn on exhaust fan	-	732	-	732	410	322
1 AGW mixed	6,790	989	6,879	977	405	572
2 AGW mixed	7,103	758	6,879	787	403	384
1 PGW mixed	6,879	1,054	6,879	1,054	401	653
2 PGW mixed	6,962	899	6,879	910	404	506
1 PGW single	6,805	1,029	6,879	1,019	404	615
2 PGW single	6,812	826	6,879	817	405	412
2 AGW single 1	7,019	735	6,879	753	408	345
2 AGW single 2	6,996	732	6,879	747	406	341
1 AGW single	6,835	927	6,879	921	415	506

From column 5 of Table 4, it was found that the NGW / turned on exhaust fan experiment has the best ability to improve air quality. It has the lowest CO_2 concentration at 732 ppm or 37% lower the NGW experiment at 1,158 ppm. The second rank was 2 AGW single plants of *Epipremnum aureum* experiment at 747 ppm from column 5. This value was 35% lower the NGW experiment at 1,158 ppm. Pichlhöfer et. al. [14] found that the green wall of *Epipremnum aureum* had the ability to reduce the CO_2 concentration better than other plants. It can decrease the CO_2 concentration in the classroom by 13% when compared to no plants. Estupiñan et. al. [9] found that *Epipremnum aureum* was highly efficient in eliminating CO_2 indoors. This conclusion has been revealed in other research. Thus, by using the active green wall system developed in this research together with *Epipremnum aureum* plants would represent an effective recommendation for improving indoor air quality. From all the experiments shown in column 5 of Table 4, passive and active green wall panels in this research were able to decrease the CO_2 concentration in classrooms for 9% to 35% comparing to no green wall experiment. The average outdoor CO_2 from 11 experiments in Table 4 is 406 ppm. Therefore, an acceptable indoor CO_2 concentration should be less than 1,106 ppm. Thus, only the no green wall experiment was found in this category.

5.2 Normalizing the outdoor air temperature

The outdoor temperature in different experiments varied on different testing days. This affects the energy consumption of air conditioners in the classroom. Therefore, the air conditioning temperature of each experiment was normalized to the same outdoor temperature at 30.9 °C or the mean temperature from all experiments. The NGW experiments were tested twice for normalization purposes. Outdoor temperatures were 33.1 and 32.5 °C for NGW1 and NGW2, respectively. While energy consumption was 9.1 and 8.9 kWh for NGW1 and NGW2, respectively. The mean temperature of all experiments was 30.9 °C. This value which is used for normalizing air conditioning energy in kWh. For example, consider the NGW / turned on exhaust fan in Table 5 which has an average outdoor at 32.1 °C. The temperature of NGW / turned on exhaust fan is higher than the mean value for 32.1 - 30.9 or 1.2 °C. Therefore, energy consumption of NGW / turned on exhaust fan should be lower than 9.7 kWh for ($\frac{9.1\text{-}8.9}{33.1\text{-}32.5} \times 1.2$) = 0.4 kWh, as shown in column 5. As a result, the normalized energy consumption is 9.3 kWh. Other values of air conditioning energy consumption were normalized in the same manner and shown in column 6 of Table 5. Energy consumption from the exhaust fan was 0.1 kWh. While energy consumption from the active green wall panel was 0.4 and 0.9 kWh for one active green wall panel and two active green wall panels, respectively. Combining all energy consumption from columns 6 to 8, total energy consumption during two hour experiments were obtained. It was found that 1 AGW single plant experiment consumed the lowest energy. It used 29% less energy than the NGW experiment. While turning on the exhaust fan in the classroom consumed the most energy consumption. It consumed more energy to improve air quality by 12% compared to the NGW experiment. Meanwhile, it consumeds more energy than 2 AGW single at 75%, while yielding better air quality by 2 %, as shown in Table 6.

Table 5. Energy consumption and outdoor temperature before and after normalization.

Experimental name	Recorded data or before normalization		Energy consumption after normalizing at 30.9 °C temperature					
	Average outdoor Temp. (°C)	Air conditioning energy (kWh)	Diff. Temp. from the mean value at 30.9 °C	Adjusting energy usage due to Diff. Temp. (kWh)	Air conditioning energy (kWh)	Exhaust fan energy (kWh)	Green wall panel energy (kWh)	Total Energy (kWh)
NGW1	33.1	9.1	2.2	0.7	8.4	0.0	0.0	8.4
NGW2	32.5	8.9	1.6	0.5	8.4	0.0	0.0	8.4
NGW / turn on exhaust fan	32.1	9.7	1.2	0.4	9.3	0.1	0.0	9.4
1 AGW mixed	30.2	5.5	0.7	0.2	5.7	0.0	0.4	6.1
2 AGW mixed	30.9	5.6	0.0	0.0	5.6	0.0	0.9	6.5
1 PGW mixed	29.8	7.9	1.1	0.4	8.3	0.0	0.0	8.3
2 PGW mixed	29.2	7.0	1.7	0.6	7.6	0.0	0.0	7.6
1 PGW single	30.3	7.8	0.6	0.2	8.0	0.0	0.0	8.0
2 PGW single	29.7	6.8	1.2	0.4	7.2	0.0	0.0	7.2
1 AGW single	30.9	5.6	0.0	0.0	5.6	0.0	0.4	6.0
2 AGW single	30.9	5.3	0.0	0.0	5.3	0.0	0.9	6.2

Table 6. Comparing 2 AGW single plants with exhaust fan experiments

Experimental name	Before normalization		After normalization	
	Air conditioning energy (kWh)	Average indoor CO_2 (ppm)	Air conditioning energy (kWh)	Average indoor CO_2 (ppm)
NGW / turn on exhaust fan	9.7	732	9.3	732
2 AGW single	5.3	732	5.3	747
		Difference	4	15
		% Difference	75%	2%

6 Discussions

To be considered as good air quality, an alternative has to have less than 1,106 ppm of CO_2 concentration. Figure 4 presents the average CO_2 level in the classroom and the energy consumption of each experiment from when the classroom started being used to when the classes is ended. Where the y axis is the average CO_2 level (ppm) and x axis is energy consumption (kWh) The lower left area of Figure 4 means good air quality with the least cost of energy which represents an optimum alternative. In this research, four alternatives are located in this favorable area of the graph. They are one and two active green walls for both single and mixed. These alternatives can help save energy by 23% to 29% comparing to the no green wall option. The upper right area of Figure 4 means bad air quality and high energy costs, denoting the unfavorable area. The no green wall experiment is located in this area of Figure 4. Meanwhile, the lower right area means good air quality with high energy costs. In this case, no green wall with turning on the exhaust fan experiment can be found. This represents the common condition found in Thai classrooms. The upper left area of Figure 4 offers bad air quality with low energy costs. No alternative was found in this area. The last area is in the middle of Figure 4 is a moderate area neither expensive, nor possessing bad air quality. Four alternative are found here. They are passive green walls. One passive green wall single and mixed, two passive green walls single and mixed are located in this area. These alternatives can help save energy by 1% to 14% compared to the no green wall option, while offering good air quality based on the tested room conditions.

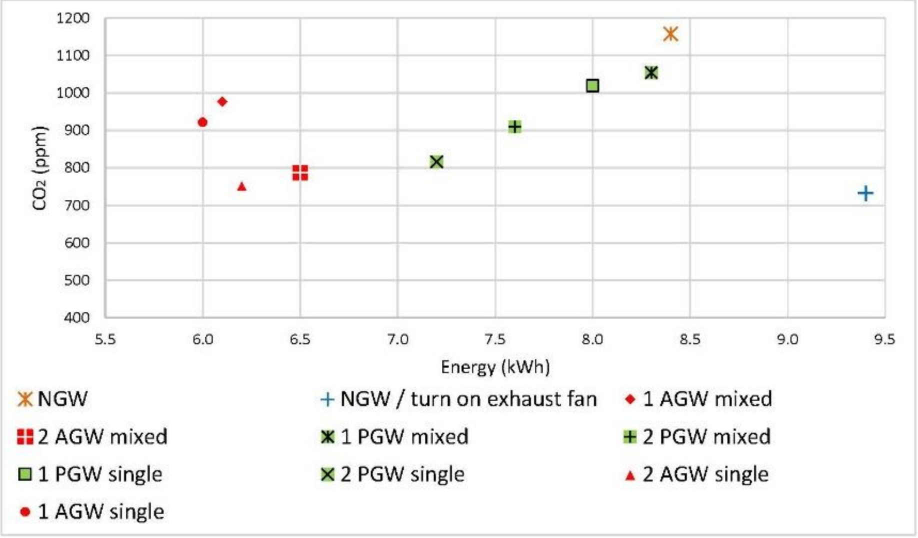

Figure 4. CO_2 levels and energy consumption in the classroom of the each experiment.

7 Conclusions

An alternative to improve indoor air quality in classrooms while minimizing usage of energy was found in this study. It is the two active green wall panels with single plants. The AGW green wall panel is more effective in improving air quality than PGW green wall panels. Two active green walls with *Epipremnum aureum* can reduce the CO_2 concentration by 35% and use less energy than the no green wall experiment at 26%. This research recommends the installation of two active green walls with *Epipremnum aureum* plants to save energy consumption and improve indoor air quality in a 28 m^2 classroom with ten occupants case.

References

1. Kabirikopaei, A., and Lau, J. (2020). Uncertainty analysis of various CO2-Based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems. *Building and Environment*, **179**, 107003.
2. ASHRAE Guideline 36-2021 (2021). *High-Performance Sequences of Operation for HVAC Systems*.
3. Taheri, S., and Razban, A. (2021). Learning-based CO2 concentration prediction: Application to indoor air quality control using demand-controlled ventilation. *Building and Environment*, **205**, 108164.
4. Shao, Y., Li, J., Zhou, Z., Hu, Z., Zhang, F., Cui, Y., and Chen, H. (2021). The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings. *Building and Environment*, **195**, 107766.
5. Tudiwer, D., and Korjenic, A. (2017). The effect of an Indoor Living Wall System on humidity, mould spores and CO2 concentration. *Energy and Buildings*, **146**, 73-86.
6. Dominici, L., Fleck, R., Gill, R. L., Pettit, T. J., Irga, P. J., Comino, E., and Torpy, F. R. (2021). Analysis of lighting conditions of indoor living walls: Effects on CO2 removal. *Journal of Building Engineering*, **44**, 102961.
7. Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco, A., and Egea, G. (2016). Influence of an active living wall on indoor temperature and humidity conditions. *Ecological Engineering*, **90**, 120–124.
8. Al-Kayiem, H.H., Effendy, M., Riyadi, T.W.B., Kurnia, J.C., and Morganadus, A. (2020). Influence of Life Green Wall and Roof Shedding on the Internal Thermal Condition of Buildings: Case Study in Malaysia. *Proceeding of the 7th International Conference on Production, Energy and Reliability (ICPER 2020) Borneo Convention Centre*, 35-45.
9. Estupiñan, Y. M. M., Ruiz, C. P. T., Garcia, N. M. S., and Rincon, M. V. S. (2021). Growth analysis and CO2 absorption capability of epipremnum aureum. *Proceeding of the 8th Congreso Colombiano y Conferencia Internacional En Calidad De Aire y Salud Publica*, CASAP 2021 – Proceedings, 1-4.
10. Torpy, F., Zavattaro, M., and Irga, P. (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.
11. Zuo, L., Wu, D., Yuan, Y., Li, H., and Yu, L. (2020). Effect of arrangement and quantity of epipremnum aureum on work efficiency and subjective perceptions. *Environmental Science and Pollution Research*, **27**(15), 17804-17814.
12. Taemthong, W. (2021). Air quality improvement using ornamental plants in classrooms. *Journal of Green Building,* **16**(2), 201–216.
13. Bondarevs, A., Huss, P., Gong, S., Weister, O., and Liljedahl, R. (2015). Green walls utilizing Internet of Thing. *Sensors & Transducers,* **192**(9), 16-21.
14. Pichlhöfer, A., Sesto, E., Hollands, J., and Korjenic, A. (2021). Health-Related Benefits of Different Indoor Plant Species in a School Setting. *Sustainability*, **13**(17), 9566.