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The Impact of Biowall on Human Multisensory in Tropical Landed Dwellings

Currently, forest therapy is a new trend with various limitations. Biowall is the other form of mini forest therapy that brings plants into the built environment. This research offers the novelty of a human multisensory approach to investigating how biowalls, as a forest therapy, affect the environment. It's essential because humans perceive a comfortable environment through multiple sensory inputs simultaneously, including thermal (touch), visual (sight), respiratory (smell and lung), and auditory (hearing) conditions. To achieve the research objectives, data were measured from various variables, including temperature and humidity (for the thermal sensor), light intensity (for the visual sensor), CO2, VOC, HCHO, and PM2.5 concentration (for the respiratory sensor), as well as noise reduction (for the auditory sensor) in the family room with and without biowalls.

Furthermore, descriptive statistical methods with daily measurement averages were used to analyze the measurement variations. The results showed that a module of biowalls planting pot system with a leaf area of 10 m^2 improved thermal (temperature and humidity), visual (light intensity), and auditory (noise reduction) conditions by 0.20 % and 2.54 %, respectively, for medium and high frequencies of 4.87 % and 6.87 %. They also could reduce the quality of respiratory conditions by 13.55 %. In conclusion, the findings suggested that biowalls can enhance the human multisensory conditions in the family rooms of tropical landed dwellings. This fact aligns with the main concept of forest therapy, which is to build a multisensory experience in the natural environment.

Keywords:
Biowall; Multisensory; Family Room; Comfort

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INTRODUCTION

Forest therapy is defined as a conscious human effort to build multisensory experiences in the natural environment to improve health and wellness (Clifford, 2018). In the modern era, human limitations provide opportunities to bring forests and nature into their built environment. Biowalls as a small-scale forest therapy alternate, is expected to provide positive multisensory impacts.
The concept of multisensory conditions is based on the sensors in the human body, such as touch, vision, smell, and lungs, as well as hearing sensors for thermal, visual, respiratory, and auditory conditions, respectively. In urban dwellings, it is important to plan for these conditions to ensure the comfort of the occupants. However, despite these efforts, comfort in urban dwellings still falls short of expectations.
According to a 2016 study, the use of fans for improving thermal comfort in Indonesia was 75.6%, with air conditioning reaching 14.9% and 1.8% in urban and rural areas, respectively. In terms of visual conditions, a lack of shading trees in urban areas results in excessive direct sunlight entering dwellings. Regarding respiratory conditions from WHO's data, the death rate in 2016 due to household and ambient air pollution was 112.4/100.000 people, whereas unintentional poisoning, including air poisoning, was 0.4/100.000 population. For auditory conditions, according to WHO data, Indonesia has exceeded the noise quality standards during both day and night by 55 dB(A).
Based on this phenomenon, the community needs a comprehensive lifestyle change. One potential solution is the implementation of biowalls, which refer to any type of vegetated walls. These can include vertical vegetation growing on or near vertical surfaces, particularly interior walls. Biowalls are generally placed on exterior vertical walls. The term also applies to interior walls and is synonymous with other terms such as green walls, vertical vegetation, vertical gardens, and living walls (Andadari, 2021). Biowalls come in several types, including linear, modular, and continuous (Medl et al., 2017). This study is being conducted in-situ on tropical landed dwellings without any special treatment and not in a controlled laboratory setting.
The preceding discussions indicate that conversations regarding biowalls are typically limited to a singular sensor, such as thermal, visual, respiratory, or auditory. When discussing thermal conditions, biowalls are primarily linked to temperature and humidity levels (Peng et al., 2019). For visual conditions, biowalls are associated with light intensity (Kristanto et al., 2021). In respiratory conditions, they are linked to CO_2 (Shao et al., 2021), Volatile Organic Compound (VOC) (Suárez-Cáceres et al., 2021), Formaldehyde (HCHO) (Suárez-Cáceres & Pérez-Urrestarazu, 2021), and Particulate Matter (PM2.5) (Pettit et al., 2017). Meanwhile, for auditory conditions, biowalls are associated with noise reduction (Lunain et al., 2016). The state of the art of this research is clearly to determine the influence of biowalls on human multisensory, including thermal, visual, respiratory, and auditory conditions within tropical landed dwellings with a daily measurement average method, in-situ on the family-room walls.

METHODOLOGY

This study was conducted in Ungaran City, Central Java, Indonesia, within the geographical coordinates of 7°11'01" to 7°16'81" South Latitude and 110°36'04" to 110°41'25" East Longitude. This region experiences dry and rainy seasons at an altitude ranging from 321 to 573 masl, with average temperatures of 25°C to 26°C.

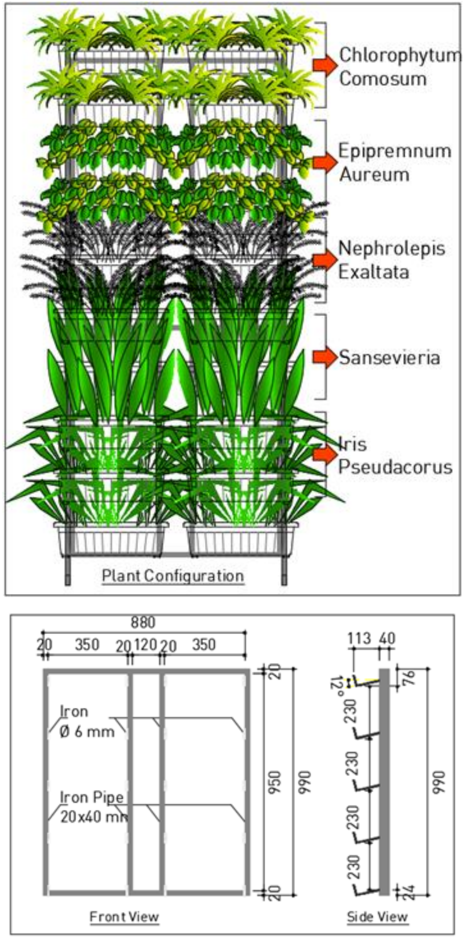

Fig. 1 - Planting Pot System Biowall In Family Room

The object is a tropical landed dwelling in Indonesia with an area of about 45 m², featuring family rooms measuring 2600 mm x 3000 mm, excluding corridors (see Figure 2). This describes the general condition of the family room in Indonesia. The type of biowalls used is the planting pot system made of an iron frame hung by plants

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in the potting media and arranged according to the desired design shape. The frames and dividers are made of (20 x 40) mm^2 steel tubing, with the overall dimensions of each module being (940 x 190 x 2370) mm^2, as shown in Figure 1. Each module contains 20 pots. Each pot measures (490 x 175 x 150) mm^2 and holds approximately 0.055 m^3 of substrate, containing soil, roasted, and manure in a ratio of 1:2:0.25.

Fig. 2 - Planting Pot System Biowall In Family Room

Plants used include vines, shrubs, succulents, tubers, and ferns. *Epipremnum Aureum* is one of the vines, while the selected shrubs and tubers are *Iris Pseudacorus* and *Chlorophytum Comosum Variegatum,* respectively. *Sansevieria* is a succulent plant, and the fern group employed is *Nephrolepis Exaltata*. The selection of vegetation is based on various criteria. first is the plant's ability to thrive in low light conditions, with a light intensity ranging from 50 to 250 fc. The second is based on their compatibility with the interior (Satwiko et al., 2020), ease of availability, adaptability, and ability to grow in tropical climates. The size of the biowalls is determined by the average leaf area of the selected plants, which is around 10 m^2 for five plant species. Figure 3 visually represents the plant species used and the average leaf area per pot.

Epipremnum Aureum = 0.968 m^2

Iris Pseudacorus = 3.238 m^2

Chlorophytum Comosum = 2.26 m^2

Sansevieria = 1.121 m^2

Nephrolepis Exaltata = 2.819m^2

Fig. 3 - Average of Leaf Area Per Pot

It measures room thermal, visual, and respiratory variables for 30 consecutive measurements. The measurement period starts from March to April 2022. There is no record of rainfall during this period. Measurements are taken every two hours at 8:00 am, 10:00 am, 12:00 pm, 2:00 pm, and 4:00 pm, with and without biowalls. It is not feasible to simultaneously measure the study with and without biowalls because it occurred in tropical landed dwellings.

This study employed multiple devices, as shown in Figure 4, to gauge the environmental parameters. These devices encompass a thermometer-hygrometer to assess temperature and humidity, a lux meter to gauge light intensity, a sound level meter to determine noise, an air quality detector to measure CO_2, HCHO, and VOC, as well as an air pollutant meter to measure PM2.5 levels. A hot wire anemometer is used to measure wind speed. All digital instruments undergo calibration per standard operating procedures. On-site calibration is carried out by comparing the measurements with the primary calibration instruments in the laboratory. The maximum deviation is less than 5% per of the International Bureau of Weights and Measures standard.

Thermo-Hygrometer

Lux meter

Sound Level Meter

Air Quality Detector

Air Polutan Meter

Hot Wire Anemo Meter

Fig. 4 - Research Instruments

To prove that the measurable parameter differences occur due to the addition of the biowalls, the rooms were conditioned to be closed, without any changes to the space-filling elements during measurements with and without the biowalls. Furthermore, air changes and user intensity levels are also measured and analyzed using T-test statistical analysis to determine whether there is a significant effect. These measurements are taken simultaneously with the measurement of each sub-variable to ensure accurate and reliable results.

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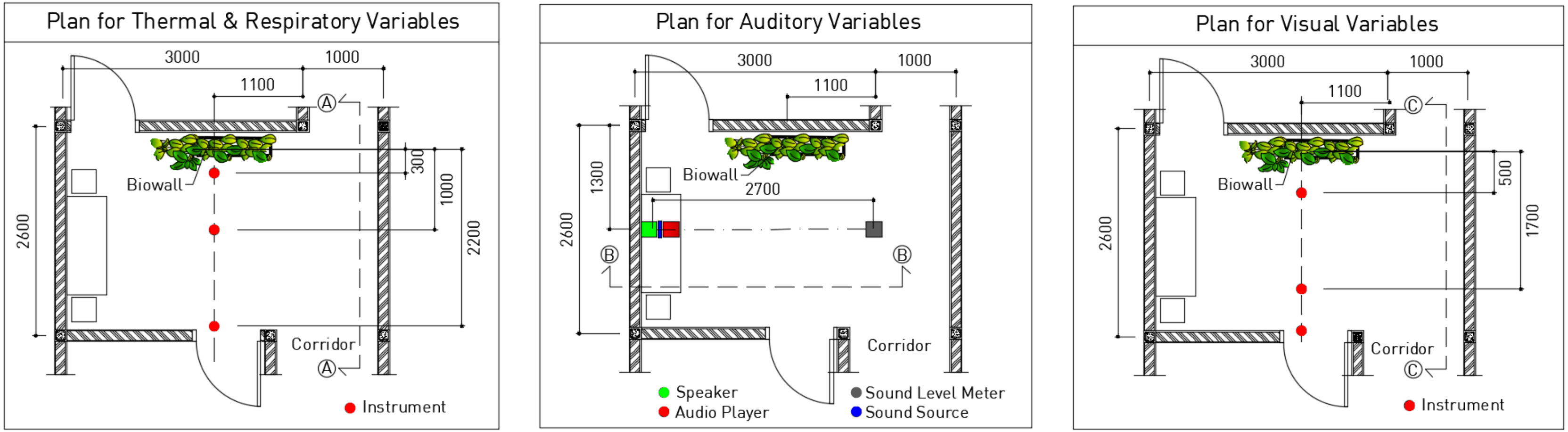

Fig. 5- Plan of Measurement Point for All Variables

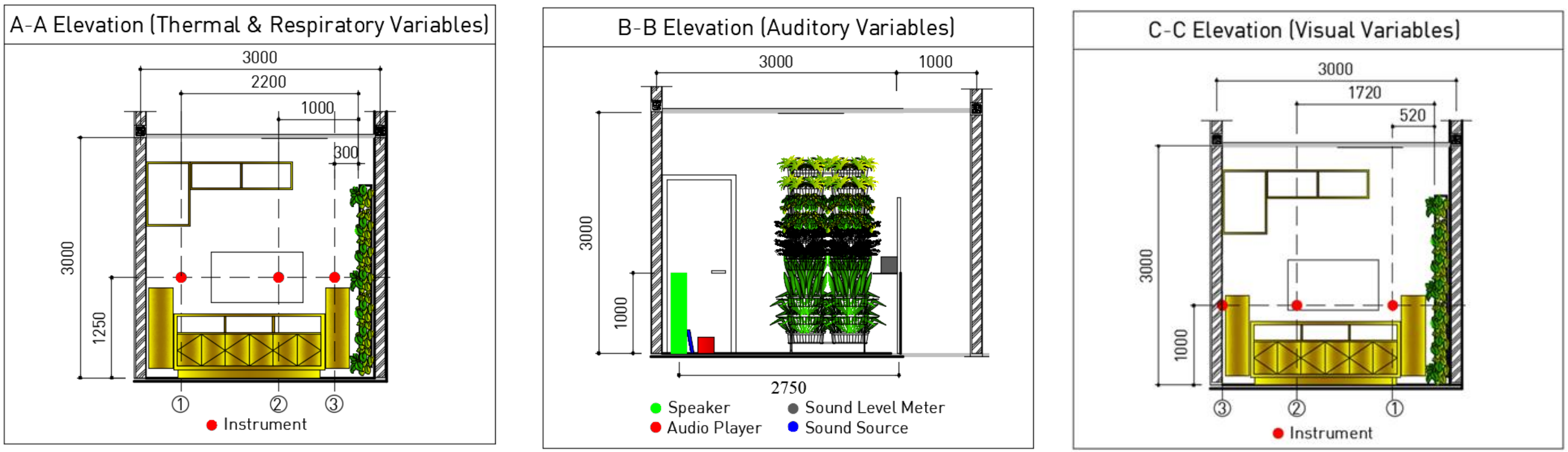

Fig. 6 - Sections of Measurement Point for All Variables

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Figures 5 and 6 show the measurement scenario for all variables. The visual variable measured is light intensity, and the results showed a difference in measurements with and without biowalls, indicating its ability to reduce light intensity. Measurements are taken during the day under clear and non-rainy conditions; hence, it is expected that the contamination of sunlight affects the measurement results is constant. For the auditory variable, measurements were taken on two conditions, namely rooms with and without biowalls in low, medium, and high frequencies. The sound source was kept constant, using a tone generator set at a loud enough volume to mask other noises that could disturb the measurements. The sound frequencies measured were divided into low (100 to 315 Hz), medium (400 to 1250 Hz), and high (1600 to 5000 Hz) frequency ranges.
Descriptive analysis was carried out based on mathematical calculations. As shown below, the formulas used are the difference, difference percentage, and average difference percentage.

Difference = $A_{wo(X)} - A_{w(X)}$..................................(1)

Difference Percentage (Dif) (%)

= $((A_{wo(X)} - A_{w(X)})/A_{wo(X)}) * 100\%$ ....(2)

Average Difference Percentage (%)

= $(Dif_1 + Dif_2 + ... + Dif_n)/n$ ....(3)

With:
$A_{wo(X)}$ = Average of Sub-variable Measurement without Biowall
$A_{w(X)}$ = Average of Sub-variable Measurement with Biowall
X = Sub-variable

FINDINGS AND DISCUSSION

Table 1 was created to illustrate how environmental conditions were regulated during measurements taken with and without the presence of biowalls. The table indicates that every sensor condition has been set up to reduce the impact of environmental factors on the measured sub-variables. Therefore, it was concluded that the changes in the measured results between the conditions with and without biowalls could be attributed solely to the presence of biowalls.

Table 1. Room Conditioning before Measuring

Conditioning	Analysis	Thermal	Visual	Respiratory	Auditory
The door closed permanently	There was no contamination from outside	V		V	V
Space-filling elements to be constant	The absorption and reflection of the space-filling elements were assumed to be constant	V	V	V	V
The significance sample-independent T-test results for air change rate = 0.184	The air change rate does not significantly affect room measurements	V		V	V
The significance sample-independent T-test results for users = 0.051	The quantity of users does not significantly affect room measurements	V	V	V	V
Measurement to be done in dry weather, not raining	Sunlight contamination was considered constant		V		
The position and intensity of the light source were constant	There was no other light source to interfere		V		
The sound source was set at a relatively high and constant volume	The volume of other sounds was lower than the measured sound source, so it didn't affect it				V

IMPACT OF BIOWALLS ON THERMAL SENSORS

Thermal sensors were utilized to measure temperature and humidity in the family room, both with and without biowalls. Without biowalls, the average daily temperature in the family room fluctuates between 27.97°C to 30.51°C, with the highest temperature occurring at 2:00 pm and the lowest at 8:00 am. In contrast, with biowalls, the average daily temperature ranges from 26.92°C to 29.19°C, with the highest temperature observed at 12:00 pm and the lowest at 8:00 am. Based on Figure 7, it appears that the biowalls have a cooling effect on the family room throughout the day, beginning at 8:00 am and continuing until 4:00 pm (100%).

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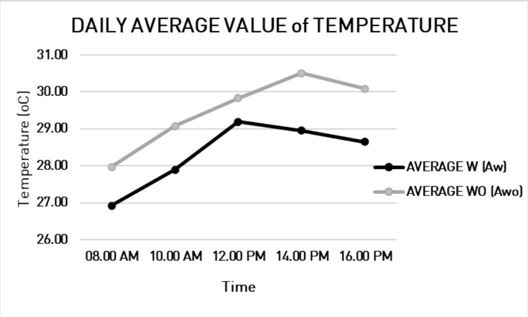

Fig. 7 – Daily Average of Temperature

The data presented in Table 2, indicated that the temperature difference in the family room ranges from 0.64 to 1.56°C. Interestingly, the trend suggests that the biowalls have a cooling effect on family rooms, as the temperature difference is lower compared to the condition without biowalls. The average temperature reduction due to the biowalls was 3.98%.

These findings are consistent with other studies that have reported a reduction in steady-state heat of 18.7% to 39.8% (Pan et al., 2020) by implementing a modular biowalls system on a campus in Hong Kong with a subtropical climate, regardless of weather conditions. Moreover, other studies found that biowalls, using vegetation such as *Epipremnum Aureum* and *Chlorophytum Comosum*, can lower the temperature between 0.8°C and 4.8°C (Pérez-Urrestarazu et al., 2016). The cooling effect of water vegetation *Azolla* can cause different interior cooling levels in four configurations (Parhizkar et al., 2020).

The family room experiences average daily humidity fluctuations between 92.56% and 99% without biowalls, with the highest humidity occurring at 8:00 and the lowest at 2:00 pm. However, with biowalls, the average daily humidity varies between 96.67% and 99%, with the highest levels recorded at almost all measurement times, except at 12:00. Figure 8 indicates that biowalls have a humidifying effect on the family room, starting from 8:00 am until 4:00 pm when it reaches 100%.

Table 2. Average Difference Percentage for Temperature

TIME	$(A_{w(T)})$ (°C)	$(A_{wo(T)})$ (°C)	Difference (1) (°C)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	26.92	27.97	1.04	3.73%	3.98%
10.00 am	27.89	29.08	1.19	4.09%	
12.00 pm	29.19	29.83	0.64	2.16%	
2.00 pm	28.96	30.51	1.56	5.10%	
4.00 pm	28.64	30.09	1.44	4.80%	

$A_{w(T)}$ = Temperature Average with Biowall $A_{wo(T)}$ = Temperature Average without Biowall

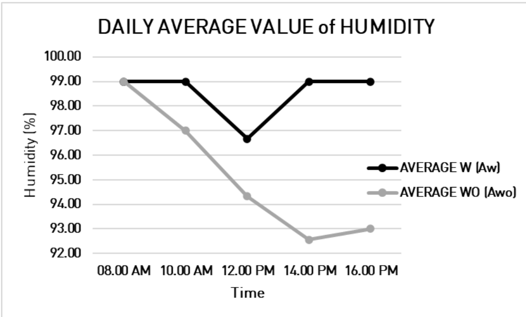

Fig. 8 – Daily Average of Humidity

Table 3 shows that the difference in humidity levels between the family room conditions with and without biowalls ranges from -6.44% to 0.00%. The trend in humidity difference reveals that biowalls' condition is higher than without biowalls, thereby indicating the addition of biowalls leads to more humid family rooms. Biowalls provide an average humidity increase by -3.59%.

Other studies showed similar results, such as offices in Nanjing city, with an average relative humidity increase of 3.1-6.4% (Shao et al., 2021), a prototype in Indonesia with a 72.5% increase (Widiastuti et al., 2020), and Chinese schools with significant humidity increases but low fluctuations (Li et al., 2019). Generally, plants affect temperature and humidity sensors through evapo-transpiration (Moya et al., 2017). Plant species, active root, and stomata influence the process. Therefore, biowalls are a viable alternative for thermal conditioning in urban dwellings that use a significant amount of glass

Table 3. Average Difference Percentage for Humidity

TIME	$(A_{w(H)})$ (%)	$(A_{wo(H)})$ (%)	Difference (1) (%)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	99.00	99.00	0.00	0.00%	-3.59%
10.00 am	99.00	97.00	-2.00	-2.06%	
12.00 pm	96.67	94.33	-2.33	-2.47%	
2.00 pm	99.00	92.56	-6.44	-6.96%	
4.00 pm	99.00	93.00	-6.00	-6.45%	

$A_{w(H)}$ = Humidity Average with Biowall $A_{wo(H)}$ = Humidity Average without Biowall

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materials thereby increasing interior temperature due to sunlight penetration (Purwanto & Tichelmann, 2018).

IMPACT OF BIOWALLS ON VISUAL SENSORS

The visual sensors measure the light intensity inside the family rooms with and without biowalls. The average light intensity in the family room without biowalls was 70.36 lux, with a high of 71.33 lux at 12:00 am and a low of 68.78 lux at 4:00 pm. The average light intensity with biowall was 68.56 lux. The difference between these values was the light reduction caused by the biowalls. Figure 9 show that the biowalls can reduce the light intensity in the family rooms at any time (100%).

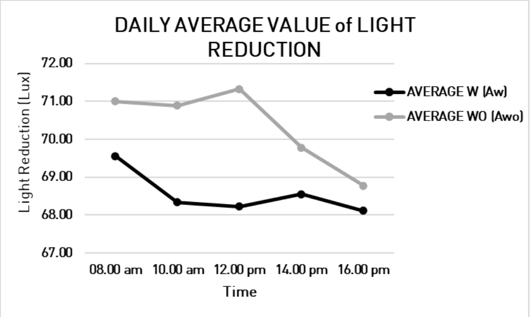

Fig. 9 – Daily Average of Light Intensity

The data in Table 4 indicated that the presence of biowalls in the family rooms caused a reduction in the intensity of light. Specifically, the light reduction in the family room ranged from 0.67 - 3.11 lux. The light reduction trend indicates that the condition with biowalls can cause the rooms' light intensity to be lower. On average, the addition of biowalls led to a decrease in light intensity of 2.54%.

These findings are consistent with previous studies, indicating that biowalls can reduce sunlight intensity by up to 26.95% (Kristanto et al., 2021) or 31.18-51.71% on the 7th floor of a building

Table 4. Average Difference Percentage for Light Reduction

TIME	($A_{w(L)}$) (lux)	($A_{wo(L)}$) (lux)	Difference (1) (lux)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	69.56	71.00	1.44	2.03%	2.54%
10.00 am	68.33	70.89	2.56	3.61%	
12.00 pm	68.22	71.33	3.11	4.36%	
2.00 pm	68.56	69.78	1.22	1.75%	
4.00 pm	68.11	68.78	0.67	0.97%	

$A_{w(L)}$ = Light Reduction Average with Biowall $A_{wo(L)}$ = Light Reduction Average without Biowall

in Indonesia (Kristanto et al., 2020). The visual impact of the plants appears to be related to their characteristics, with thick and wide leaves, as well as tall and dense plants, having the greatest effect on the rooms' visual conditions.

IMPACT OF BIOWALLS ON RESPIRATORY SENSORS

This study measured variables related to smell and respiratory sensors, specifically the concentrations of CO_2, VOC, HCHO, and PM2.5 in rooms both with and without biowalls. The average daily concentration of CO_2 without biowalls varied between 552 and 594 ppm, with the highest and lowest concentration of 2:00 and 12:00 pm, respectively. On the other hand, with biowalls, the average daily CO_2 concentration varied between 541 ppm and 587 ppm, with the highest and lowest concentration of 12:00 and 10:00. Based on Figure 10, biowalls were found to reduce CO_2 concentration in the family room by 60% of the day, specifically at 10:00, 2:00, and 4:00.

Table 5 showed the difference in CO_2 concentration between the family room, which ranges from -35.33 ppm to 36.56 ppm. This suggests that the presence of biowalls has resulted in a lower CO_2 concentration compared to without biowalls. The addition of biowalls has led to a decrease in CO_2 concentration in the rooms. The average percentage reduction in CO_2 concentration due to the expansion of biowalls was 0.58%.

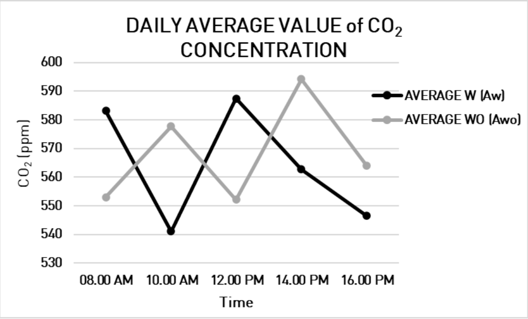

Fig. 10 – Daily Average of CO2 Level

Preliminary studies found that in the test room, biowalls with *Nephrolepis exaltata* significantly reduce CO_2 concentration (Moya et al., 2021), while *Chlorophytum comosum* and *Epipremnum aureum* effectively decreased it in low light intensity (Torpy et al., 2017). Plants significantly impact CO_2 concentration as they use photosynthesis to produce O_2 during the day. This process is influenced by various factors, such as temperature, light intensity, CO_2 concentration, water concentration, photosynthate concentration, and plant growth stage.

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The average daily concentration of VOCs in the family room without biowalls ranges from 0.155 ppm to 0.177 ppm, with the highest value observed at 10:00 and the lowest at 12:00. On the other hand, the average daily VOC concentration with biowalls ranges from 0.152 ppm to 0.278 ppm, with the highest concentration at 12:00 and the lowest at 10:00. Based on Figure 11, biowalls only demonstrate a reduction in VOC concentration at 10:00 (20%).

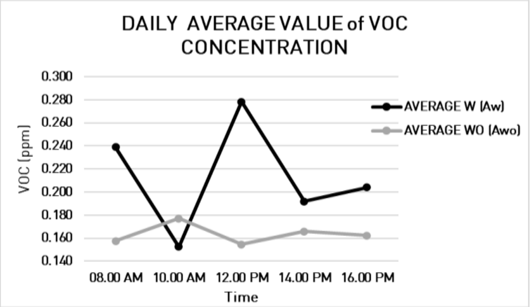

Fig. 11 – Daily Average of VOC Level

Table 6 shows that the difference in VOC concentration in the family room ranges from {(-0.12) - (0.02)} ppm. This implies that biowalls increase the VOC concentration in the family room. The percentage increase in the average VOC concentration in the rooms was -31.75%. However, Sowa's study indicated in the test room, that biowalls can reduce VOC concentration by up to 48% (Sowa et al., 2019). The difference in these results refers to Cáceres that the effectiveness of biowalls in removing VOC concentration depends on the type of contaminant used (Suárez-Cáceres & Pérez-Urrestarazu, 2021).

The average daily concentration of HCHO without biowalls fluctuates between 0.020 ppm and 0.025 ppm, with the highest levels observed from 8:00 to 10:00 and the lowest levels at 12:00. Conversely, the average daily HCHO concentration with biowalls varies from 0.021 ppm to 0.035 ppm, with highest levels at 12:00 and the lowest levels at 10:00 am. According to Figure 12, biowalls only reduce the HCHO concentration by 20% at 10:00.

Table 5. Average Difference Percentage for CO_2 Level

TIME	($A_{w(C)}$) (ppm)	($A_{wo(C)}$) (ppm)	Difference (1) (ppm)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	583.1	553.0	-30.11	-5.45%	
10.00 am	541.1	577.7	36.56	6.33%	
12.00 pm	587.4	552.1	-35.33	-6.40%	0.58%
2.00 pm	562.7	594.2	31.56	5.31%	
4.00 pm	546.6	564.0	17.44	3.09%	

$A_{w(C)}$ = CO_2 Level Average with Biowall $A_{wo(C)}$ = CO_2 Level Average without Biowall

Table 6. Average Difference Percentage for VOC Level

TIME	($A_{w(V)}$) (ppm)	($A_{wo(V)}$) (ppm)	Difference (1) (ppm)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	0.239	0.158	-0.08	-51.59%	
10.00 am	0.152	0.177	0.02	13.98%	
12.00 pm	0.278	0.155	-0.12	-80.03%	-31.75%
2.00 pm	0.192	0.166	-0.03	-15.61%	
4.00 pm	0.204	0.162	-0.04	-25.51%	

$A_{w(V)}$ = VOC Level Average with Biowall $A_{wo(V)}$ = VOC Level Average without Biowall

Table 7. Average Difference Percentage for HCHO Level

TIME	($A_{w(HC)}$) (ppm)	($A_{wo(HC)}$) (ppm)	Difference (1) (ppm)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	0.032	0.025	-0.007	-28.57%	
10.00 am	0.021	0.025	0.004	15.18%	
12.00 pm	0.035	0.020	-0.016	-79.21%	-27.97%
2.00 pm	0.027	0.023	-0.004	-16.02%	
4.00 pm	0.028	0.021	-0.007	-31.22%	

$A_{w(HC)}$ = HCHO Level Average with Biowall $A_{wo(HC)}$ = HCHO Level Average without Biowall

Table 7 indicates that the difference in HCHO concentration between the family room with and without biowalls ranges from {(-0.016) - (0.004)} ppm. These

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results suggested that the addition of biowalls leads to higher HCHO concentration levels, with the difference indicating an increase.

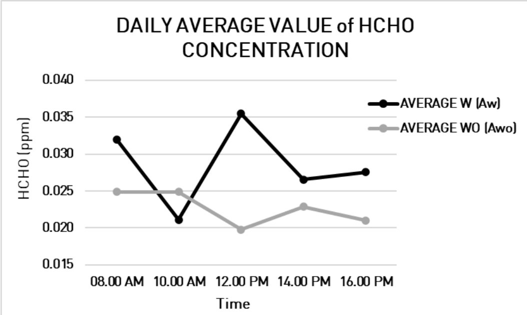

Fig. 12 – Daily Average of HCHO Level

The different types of plants show different yields related to HCHO levels, as revealed by Sowa, who stated biowalls with *Sansevieria trifasciata* reduce HCHO concentration by 35%, while *Epipremnum aureum* reduces it by up to 71% (Sowa et al., 2019).

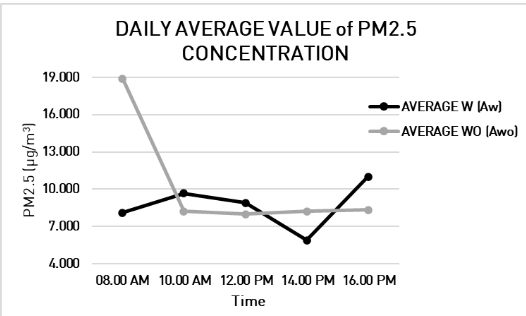

Fig. 13 – Daily Average of PM2.5 Level

Regarding the family room, the average daily PM2.5 concentration without biowalls fluctuates between 8.00 micrograms per cubic meter (μg/m^3) and 18.89 μg/m^3, with the highest levels observed

Table 8. Average Difference Percentage for PM2.5 Level

TIME	($A_{w(P)}$) (μg/m^3)	($A_{wo(P)}$) (μg/m^3)	Difference (1) (μg/m^3)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
8.00 am	8.11	18.89	10.78	57.06%	4.95%
10.00 am	9.67	8.22	-1.44	-17.57%	
12.00 pm	8.89	8.00	-0.89	-11.11%	
2.00 pm	5.89	8.22	2.33	28.38%	
4.00 pm	11.00	8.33	-2.67	-32.00%	

$A_{w(P)}$ = PM2.5 Level Average with Biowall $A_{wo(P)}$ = PM2.5 Level Average without Biowall

at 8:00 am and the lowest levels at 12:00. Conversely, the average daily PM2.5 concentration with biowalls varies from 5.89 μg/m^3 to 11.00 μg/m^3, with the highest levels at 4:00 and the lowest levels at 2:00. As shown in Figure 13, biowalls reduce PM2.5 concentration in the family room by 40% only at 8:00 and 2:00 during the day. Table 8 shows that the difference in PM2.5 concentration in the family room ranges from -2.67 μg/m^3 to 10.78 μg/m^3. The difference indicates that the presence of biowalls results in a lower PM2.5 concentration. This means biowalls decrease PM2.5 concentration in the family room. The percentage decrease in average PM2.5 concentration due to the addition of biowalls was 4.95%.

One study found that biowalls can remove 45.78% of PM0.3-0.5 (Pettit et al., 2017). Weerakkody suggested that the ability of biowalls to reduce particulate concentration depends on various leaf characteristics such as ridges, stomatal density, leaf width, hair/trichomes, vines, and grooves (Weerakkody et al., 2018). Besides photo-synthesis, the phytoremediation process in plants can also contribute to reducing respiratory conditions by absorbing soil, water, and air through stomata. Several factors can affect phytoremediation, including temperature, soil pH, number of plants, plant age, lifespan, and plant species (Moya et al., 2017).

IMPACT OF BIOWALLS ON AUDITORY SENSORS

Figure 14 illustrates the impact of biowalls on the acoustic environment by measuring the amount of noise reduction in the family across low, medium, and high frequencies. The results showed a decrease in sound intensity due to the presence of biowalls.

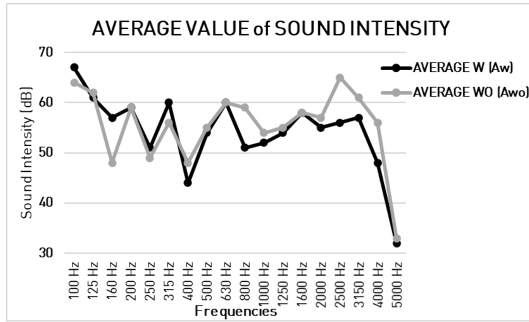

Fig. 14 – Daily Average of Sound Intensity

In the family room, the reduction in sound intensity at low, medium, and high frequencies is due to the addition of the biowalls. The reduction in sound intensity at low frequencies only occurs at 125 Hz or by 16.7%. At medium frequencies, the sound intensity decreases at 400 Hz, 500 Hz, 800 Hz, 1000 Hz, and 1250 Hz, or by 83.3%. Meanwhile, at high frequencies, the sound intensity decreases at 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz, and

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5000 Hz, or by 83.3%.
Table 9 presents the noise reduction values at low, medium, and high frequencies, which vary between (-9) - (1) dB, (0.00-8.00) dB, and (0.00-9.00) dB in the family room. The noise reduction trend suggests that biowalls work more effectively at medium and high sound frequencies, with a higher reduction in sound intensity as the frequency increases. The average percentage of noise reduction due to the biowalls were -5.51%, 4.87%, and 6.87% for low, medium, and high frequencies, respectively.

Table 9. Average Difference Percentage for Noise Reduction

FREQ (Hz)		$(A_{w(N)})$ (dB)	$(A_{wo(N)})$ (dB)	Difference (1) (dB)	Dif Percentage (2) (%)	Average Dif Percentage (3) (%)
Low frequency	100	67	64	-3.00	-4.69%	-5.51%
	125	61	62	1.00	1.61%	
	160	57	48	-9.00	-18.75%	
	200	59	59	0.00	0.00%	
	250	51	49	-2.00	-4.08%	
	315	60	56	-4.00	-7.14%	
Medium frequency	400	44	48	4.00	8.33%	4.87%
	500	54	55	1.00	1.82%	
	630	60	60	0.00	0.00%	
	800	51	59	8.00	13.56%	
	1000	52	54	2.00	3.70%	
	1250	54	55	1.00	1.82%	
High frequency	1600	58	58	0.00	0.00%	6.87%
	2000	55	57	2.00	3.51%	
	2500	56	65	9.00	13.85%	
	3150	57	61	4.00	6.56%	
	4000	48	56	8.00	14.29%	
	5000	32	33	1.00	3.03%	

$A_{w(N)}$ = Noise Reduction Average with Biowall; $A_{wo(N)}$ = Noise Reduction Average without Biowall

According to Davis, biowalls in the test room have a high sound absorption coefficient at high frequencies, reaching 1 (Davis et al., 2017). At medium frequencies, the coefficient ranges from 0.2 (green facade and continuous living wall system) to 0.9 (modular walls system) (Attal et al., 2019). Another study showed a significant increase in sound absorption coefficient across the frequency spectrum by biowalls (Thomazelli et al., 2017). The success of biowalls in influencing visual conditions depends on plant characteristics such as green color, leaf density, and coverage.

CONCLUSION

In conclusion, the presence of biowalls can impact the human multisensory conditions in tropical landed dwellings. With respect to thermal sensors, biowalls can decrease the average daily temperature and increase the average daily humidity in rooms. The measured average temperature difference decreases by 1.18 °C while the average humidity difference increases significantly by -3.36 %. This implies that a biowall module of a planting pot system of 10 m^2 leaf area can result in a 0.20% improvement in thermal conditions in the family room.
Regarding visual sensors, the presence of biowalls can reduce interior light intensity. The amount of light reduction is between 1.8 lux. Therefore, a 10 m^2 leaf area of biowalls can improve visual conditions (light intensity) by 2.54% in the family room.
It has been observed that biowalls can lower concentrations of CO_2 and PM2.5 but may have a different effect on VOC and HCHO concentrations. The increase in VOC and HCHO concentration was 0.05 and 0.0058 ppm, respectively. The decrease in CO_2 and PM2.5 concentrations were 4.02 ppm and 1.62 μg/m^3, respectively. Overall, 10 m^2 leaf area biowalls can decrease respiratory conditions (CO2, VOC, HCHO, and PM2.5) by 13.55% in the family room.
Regarding auditory conditions, biowalls can effectively reduce sound at medium frequencies by 2.67 dB, as well as high frequencies by 4.00 dB. This means that 10 m^2 biowalls in the family room can improve auditory conditions (noise reduction) for medium frequencies by 4.87%. Meanwhile, at high frequencies, it increases the conditions by 6.87%. This fact is in line with the main concept of forest therapy to build a multisensory experience in the natural environment to improve health and well-being.
This study successfully demonstrated the effect of biowalls on human multisensory conditions in tropical landed dwellings. The differences in results can be attributed to various factors, including furniture quantity, position, dimension, material, measurement time, and local climate. Future studies should focus to develop biowalls in controlled room to minimize uncertainties.

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