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Determination of the biowall effective area to induce holistic sensory comfort

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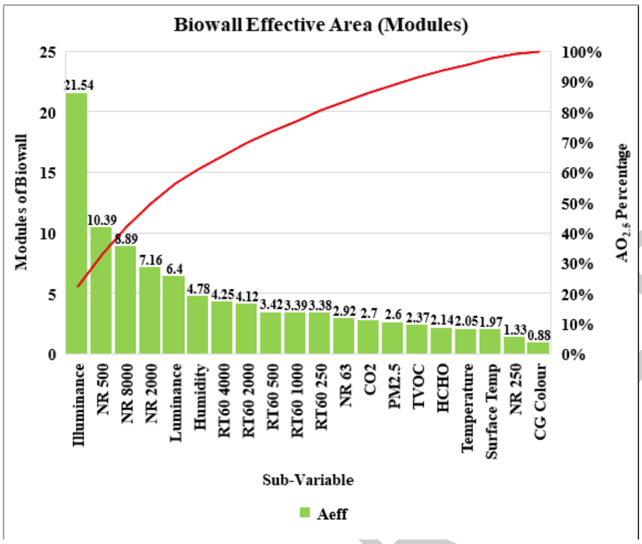
Graphical abstract



ABSTRACT

Biowalls are a new phenomenon in interior urban areas, which has proven to contribute positively to sensory comfort. But people use biowalls in different dimensions. Based on field facts, determining the biowall dimensions for human sensory comfort has not emphasized clear principles. The research aims to obtain the effective area of a biowall inducing sensory comfort comprehensively and simultaneously in tropical landed dwellings. Therefore, this study used the experimental method to extract the effective areas of the biowall to generate thermal, audial, visual, and respiratory comfort. The analysis was mathematically conducted through polynomial quadratic equations and directly or inversely proportional to the overall value regarding a generalization attempt. The variables measured included temperature, humidity, surface temperature, reverberation time, noise reduction, illuminance, luminance, and colour mapping, as well as levels of CO_2, TVOC, HCHO, and PM2.5. The result showed that biowall effective area inducing thermal, audial, visual, and respiratory comfort for a (3000 × 3000 × 2500) mm^3 room was 2.5 modules or 12.5 m^2 leaf area. This value was able to provide an increase in the sensory comfort level for the thermal, audial, visual, and respiratory variables by 59.22 %, 76.64 %, 32.35 %, and 98.88 %, respectively.

Keywords: Biowall, Biowall Area, Thermal, Audial, Visual, Respiratory, Holistic Comfort

1. Introduction

Humans are known to have an innate tendency to affiliate with the natural environment, including vegetation. This is marked by the rise of biowall as a new phenomenon in urban public spaces. The phenomenon describes any form of vegetative wall surface (Burhan and Karac 2013), including the vertical vegetation growing on or adjacent to it (Stav 2016). The biowall keeps people alert and productive, reduces stress, and promotes a sense of well-being, asides from the beauty (Culver *et al.* 2014). Biowall is also associated with sensory comfort, including thermal, audial, visual, and respiratory comfort (Song *et al.* 2019).

To describe biowall terminology, several nomenclatures are observed, such as vertical gardens (Jain 2016), as well as living wall (Mannan and Al-Ghamdi 2020; Tudiwer and Korjenic 2017; Suárez-Cáceres *et al.* 2021), and green wall (Assimakopoulos *et al.* 2020; Attal *et al.* 2021; Attal *et al.* 2019a; Thomazelli *et al.* 2017; Libessart and Kenai 2018; Musy *et al.* 2017; Feitosa and Wilkinson 2020; Kazemi *et al.* 2020; Pettit *et al.* 2018; Poorova *et al.* 2018). Biowall is synonymous with green walls, vertical vegetation, vertical gardens and living walls (Andadari 2021). In this study, it is defined as a living wall consisting of specific types of plants, in pots that are arranged on a vertical interior of the test chamber.

The underlying phenomenon in this research was the area of biowall based on previous studies. The ratio of biowall area to space was recorded using several different measurements in in-situ studies. According to Bianco *et al.*, a size comparison of the chamber and biowall was used, namely 2 × 1.8 × 1.8 m^3 and nine modules at 0.4 × 0.5 m^2 (Bianco *et al.* 2017). Meanwhile, some used a chamber of 3 × 3 ×3 m^3, and a single-sided cover for the entire wall surface (Coma *et al.* 2017). Other experts also mentioned the size of the chamber only, without stating the capacity of biowall, such as 5.1 × 3.1 × 3.1 m^3 (Manso and Gomes 2016), 0.8 × 2.45 × 2.45 m^3 (Šuklje *et al.* 2016), 2.5 × 4 × 2.9 m^3 (Serra *et al.* 2017), 3.8 × 7.8 × 3 m^3 (Shao *et al.* 2021a), and 3 × 3 × 3 m^3 (Pérez *et al.* 2016). In this case, no explanation was observed regarding the determination of the biowall area ratio, based on the method and standard implemented.

According to a broad perspective, biowalls have been reported to affect one's perception because the buildings with large and dominant biowalls were considered very beautiful and helped revitalize the atmosphere (Burhan & Karac 2013). This indicated that the perception of the phenomenon emphasized its colour, number of plants, and size (Meral *et al.* 2018). The large size of biowall also showed its effect on buildings (Radić *et al.* 2019). However, the dimensions of the phenomenon need to be considered due to the impacts of the unit value on cost efficiency (Veisten *et al.* 2012). De Vries *et al.* also mentioned that the size and number of biowall are unimportant for general health, compared to the quality of the phenomenon (De Vries *et al.* 2013).

In inducing sensory comfort, the sensational performance of biowall is partly proven to some extent. This shows that the phenomenon is associated with thermal only, visual only, audial only, or respiratory comfort only. Regarding thermal performance, the biowall is capable of cooling the interior surface temperatures up to 1.7 °C, lower than bare structures (Hoelscher *et al.* 2016). For visual performance, the western and southern tropic biowall in a 1 × 1 × 1 m^3 test chamber reduce more sunlight at 31.18–51.71 % and 28.4–54.87 %, compared to the unplanted facade, respectively (Kristanto *et al.* 2020). By simulating biowall at a 16 cm thickness system, the average acoustic absorption coefficient reaches 0.2 (300-1000 Hz), 0.2 (200-1000 Hz), and 0.9 (300-1000 Hz) with a green facade, as well as continuous and modular living walls, respectively (Attal *et al.* 2019b). Based on the respiratory comfort, *Nephrolepis Exaltata* Bostoniensis in the test chamber of 0.6 × 0.6 × 0.6 m^3 was able to remove PM0.3–0.5 and PM5-10 particulate levels by 45.78 % and 92.46 % on the green wall, respectively (Pettit *et al.* 2017).

A clear standard is not observed regarding the study perspective, which emphasized the area of biowall effectively used to cause sensory comfort. For perception and sensation, the biowall with specific areas is able to partially contribute to human sensory comfort. In inducing this comfort structure, the partial understanding of the biowall performances is not scientifically acceptable. This is because the essence of comfort is all-encompassing, regarding multisensory stimulation, the sensors prioritize sight, touch, hearing, and smell.

Biowall Effective Area (BEA) is a concept providing effective-area biowall as an alternative to induce sensory comfort, including comprehensive thermal, audial, visual, and respiratory comfort at the same time within a specific space volume. This concept is subsequently offered as an alternative to developing a more ecological and sustainable tropical residential comfort. Therefore, this study aims to extract the value of the BEA, which is effective in providing overall and simultaneous sensory comfort to tropical land dwellings with a specific volume. The experimental measurement method was used in the landed test chamber (Figure 1), with the analysis mathematically conducted through polynomial quadratic equations. This analytical performance was directly or inversely proportional to the overall constant, A_{eff}, regarding a generalization attempt. The variables measured included temperature, humidity, and surface temperature (thermal comfort), Noise Reduction (NR) and Reverberation Time (RT60) (audial comfort), illuminance, luminance and colour mapping (visual comfort), as well as levels of CO_2, TVOC, HCHO, and PM2.5 (respiratory comfort).

Figure 1. Some measurement documentation with various numbers of biowall modules

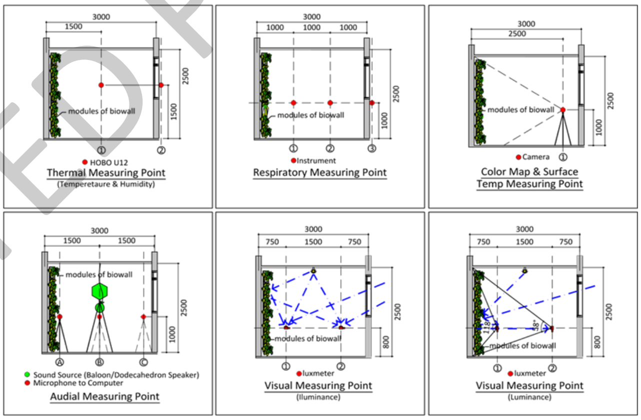


Figure 2. The plan of test chamber and measuring point

2. Methodology

This study was conducted in Semarang, Central Java, Indonesia, which is geographically located at around 7°11'01"–7°16'81" South Latitude and 110°36'04"–110°41'25" East. This location has two periods, the dry and rainy seasons, and is topographically at an altitude of 321-573 masl. The locus selection criteria are based on the conditions in the middle of the tropics within Indonesia.

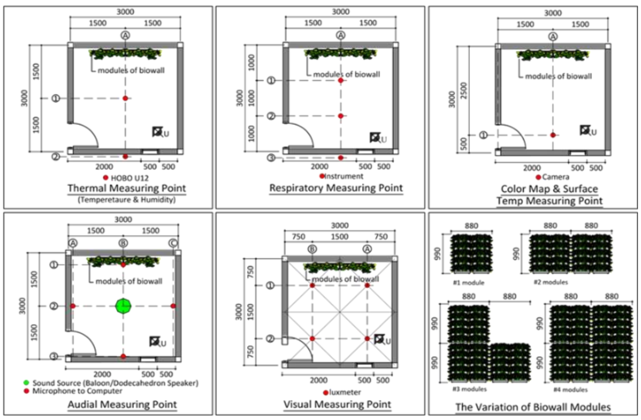


Figure 3. The plan of test chamber and measuring point

Figures 2 and 3 shows the test chamber dimension 3000 × 3000 × 2500 mm^3 and the measuring point, with the wall and ceiling comprising drywall and gypsum board, respectively. The floors, frames and doors, as well as the glass also contain ceramic, wood, and clear glass, respectively. Subsequently, ventilation is observed in the form of mosquito netting.

Biowall pot planting was used as an experimental treatment. This system emphasizes the walls with potted plants placed on special iron frames (Paull *et al.* 2020). The total implemented system was four modules, with each having an 880 × 40 × 990 mm^3 frame and containing ten pots. Five pots contained *Epipremnum Aureum* with an average leaf area of 0.24 m^2, and five others contained *Nephrolepis Exaltata* with an average leaf area of 0.71 m^2. So, the total leaf area per module is around 5 m^2. This type of substrate subsequently used a mixture of soil, fuel husks, and manure at a ratio of 1:2:0.25, with the volume of each pot being approximately 0.05 m^3.

The selection criteria of plants prioritize the aspects of the light intensity obtained by the vegetation, the ease of plant adaptation, tropical care, and interior fit level (Satwiko *et al.* 2020). Low-light plants with a light intensity of 50–250 footcandles were selected (Trinklein 2016). Another consideration is their ability to sequestrate carbon; in the long term, it positively impacts buildings' carbon footprint, especially for *Epipremnum Aureum* (Plitsiri & Taemthong 2022) and *Nephrolepis Exaltata* (Pérez-Urrestarazu *et al.* 2016).

The external and internal Hobo-Thermocouple data loggers (see Figure 4) were used to measure temperature and humidity, with the Flir Camera prioritizing the analysis of surface temperature conditions. For audials, an amplifier-mixer-stabilizer, microphone, dodecahedron speakers, laptop, and balloon/pink noise were implemented as sound sources, with the Audio Real-Time Analysis (ARTA) used as the data processing software.

Regarding visual variables, a lux metre was used to measure illuminance and luminance, with the Canon EOS M3 camera and its tripod detecting coloured mapping through colour analysis software. Other tools also included air quality detectors to measure CO_2, TVOC, and HCHO levels, with an air pollutant metre then analyzing PM2.5 particulate statuses. Although all the instruments were digital devices, they were still calibrated before measurement purposes, according to standard operating procedures. This was carried out by using on-site calibration, through the measurement comparison with primary instruments in the laboratory, at a maximum deviation of less than 5 % regarding BIPM standards (BIPM-Bureau International des Poids et Mesures, n.d.). Data collection and analysis were divided into three methods (shown in Table 1), with the information acquisition period ranging from September to December 2022.

Table 1. Measurement and analysis method

Item	#1 Method	#2 Method	#3 Method
Variable & Sub-variable	Thermal: Temperature and Humidity	Thermal: Surface Temperature	Audial: RT60 and NR
	Respiratory: CO_2, TVOC, HCHO, and $PM_{2.5}$	Visual: Iluminance and Luminance	Visual: Color Mapping
Measuring Position	Inside and Outside	Inside	Inside
Measuring Time	45 times		
Treatment	#0 = Without Biowall		
	#1 = 1 Module Biowall		
	#2 = 2 Module Biowall		
	#3 = 3 Module Biowall		
	#4 = 4 Module Biowall		
Mathematic Analysis	Formula #1		
	↓		
	Formula #2	Formula #2	
	↓	↓	
	Formula #3	Formula #3	Formula #3
	↓	↓	↓
	Polynomial Quadratic Equation	Polynomial Quadratic Equation	Polynomial Quadratic Equation
	↓	↓	↓
	Determinants	Determinants	Determinants
	↓	↓	↓
	A_{eff} per sub-variable	A_{eff} per sub-variable	A_{eff} per sub-variable
	↓	↓	
	→ A_{eff} overall for Test Chamber Volume		←

Data processing used mathematical analysis to obtain the effective value of each variable, with the procedure shown in Table 1. In this stage, the raw data were processed through three stages. Firstly, the determination of indoor and outdoor measurement differences, as well as the anticipation of condition distinctions due to inconsistent measuring periods. The difference in measurements was carried out by reducing the indoor output from the outdoor output of the test chamber. The formula used was as follows:

$$D_x = X_{in} - X_{out} \quad (1)$$

With:

D_x = The difference between internal and external measurement for X variable at a particular time with a specific treatment

X_{in} = Measurement of Each X Variable and Conditions, Inside the Test Room

X_{out} = Measurement of Each X Variable and Conditions, Outside the Test Room

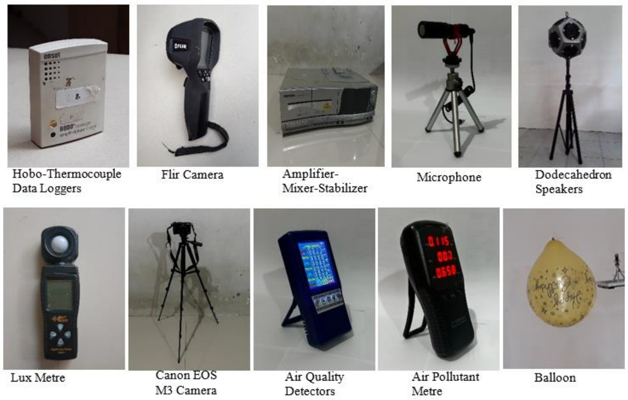


Figure 4. The main instruments for thermal, audial, visual, and respiratory measurements

Secondly, the determination of the average value of the internal and external measurement differences of the test chamber. This analysis was carried out for each treatment, which includes five conditions, namely the enclosure without a biowall, and with one, two, three, and four modules.

$$\bar{A}_x = (D_{x1} + D_{x2} + D_{x3} + \ldots + D_{x4})n^{-1} \quad (2)$$

With:

$\bar{A}_x$ = The average difference between internal and external measurement for X variable, with a specific treatment

D_{x1-n} = The difference between internal and external measurement for X variable, at a particular time with a specific treatment 1to n

n = Number of measurements

Thirdly, the actualization of measurement fluctuations, due to the addition of a biowall. This indicated that the average output of the measurement difference with each module treatment was always reduced by the result of the distinction without a biowall.

$$F_1 = \bar{A}_{x1} - \bar{A}_{x0} \quad (3)$$
$$F_2 = \bar{A}_{x2} - \bar{A}_{x0}$$
$$F_3 = \bar{A}_{x3} - \bar{A}_{x0}$$
$$F_4 = \bar{A}_{x4} - \bar{A}_{x0}$$

With:

F_{1-4} = Fluctuations of Variable Measurement due to the addition of 1-4 modules

$\bar{A}_{x1-4}$ =Average Variable Measurement with the addition of 1-4 modules

$\bar{A}_{x0}$ = Average Variable Measurement without the biowall module

Based on the outputs of F_{1-4}, mathematical analysis was then carried out by determining the polynomial quadratic equation for the fluctuations of each condition. These second-order algebraic equations contain extreme values, which are often maximum or minimum coefficients.

$$y = ax^2 + bx + c \quad (4)$$

With:

y = Polynomial Quadratic Equation

$a\ b\ c$= Known Variables

x= Unknown constant

According to the analytical objectives, the determinant value of each polynomial quadratic equation was determined. This step emphasized the acquisition of the effective value of each variable. This indicated that the calculation of the quadratic equation led to the effective value of the biowall quantity for each variable.

$$y' = 2ax + b \rightarrow Optimum\ Value = (X_{opt}, Y_{opt}) \rightarrow X_{opt} = A_{eff} \quad (5)$$

Determination of the effective value regarding all variables was carried out by observing the tendency of the frequently occurring effective value/variable. In addition, the percentage of the direct/inverse proportion treatment was added from the overall effective value, according to the nature of each variable improvement.

$$Percentage\ A_{constant} = (Y_{constant} / A_{eff}) \quad (6)$$

$$Average\ A_{constant} = (\%A_{constant(1)} + \%A_{constant(2)} + \ldots + \%A_{constant(n)})n \quad (7)$$

3. Result

Several initial procedures have been carried out to ensure that all changes in the variables measured in the test chamber were solely due to the presence of the biowall. It was the independent sample T test for measuring air velocity in the test chamber and calculating the standard deviation of the measurement results for all variables. The results of the separated sample T test for air velocity in the test chamber were 0.184 above the significance limit of 0.05, which indicated that the air velocity in the test chamber during measurement did not have a significant effect. The standard deviation for each thermal, audial, visual, and respiratory variable was always below the measurement average. This shows that the distribution of measurement data was homogeneous. By the provisions of SNI 16-7062-2004, measurements were operated by one person with no reflected cloth so that the lighting measurements were not affected. Apart from that, the condition of the test chamber door was permanently closed during the measurement to ensure there were no contaminants and disturbing sounds.

3.1. Thermal comfort–inducing biowall

For the temperature and humidity, measurements were conducted inside and outside the test chamber, to obtain a fixed value due to time and condition differences. This condition did not apply to surface temperature measurements, which were only carried out in the test chamber. The fluctuations in the thermal variables also prioritized formulas 1, 2, and 3, as shown in Figure 5. In Figure 5, three quadratic polynomial equations were obtained for each sub-variable. Each equation was determined to obtain the value of y' and the effective value.

For the temperature sub-variable, the A_{eff} biowall value was 2.05 modules. This indicated that the temperature chamber became coldest when 2.05 biowall modules were added to the test enclosure. The temperature drop due to the module addition was 0.6019 °C. The comfortable standard of room temperature for dwellings in Indonesia, based on the regulations of the Indonesian Minister of Health, is 18 to 30 °C. So, adding a biowall of 2.05 modules can provide a comfortable effect of 2 % in the room.

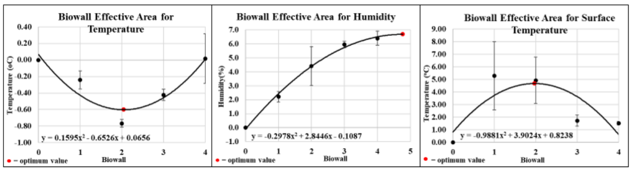


Figure 5. The fluctuation of thermal variabel with biowall treatment

Meanwhile, the addition of a biowall effectively increased the humidity of the test chamber, proving that the A_{eff} value for this sub-variable was 4.78 modules. The maximum humidity increased by 6.6839 %. Based on the regulations of the Indonesian Minister of Health, the comfortable standard of humidity for dwellings in Indonesia was 40 to 60 %. So, adding 4.78 modules of biowall can provide an 11 % comfortable effect in the room.

Regarding the surface temperature, the addition of a biowall to the chamber subsequently increased the heat level of the platform. This showed that the peak surface temperature of 4.6768 °C occurred with the provision of 1.97 modules. The graph shows that the decrease in surface temperature in the test chamber occurs when the addition of biowall starts from 4.15 modules, with each module being able to reduce 5.2876 °C. It should also be understood that no clear standards regarding surface temperature comfort limits apply indoors.

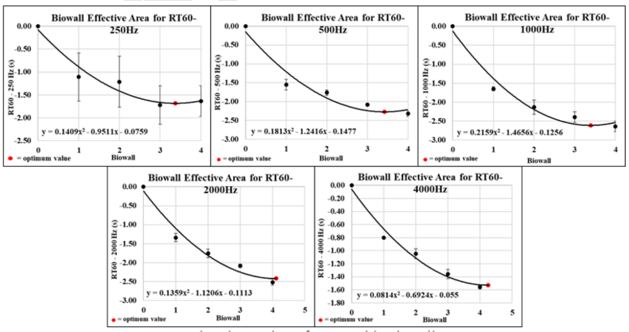


Figure 6. The fluctuation of RT60 with Biowall treatment

3.2. Audial Comfort – Inducing Biowall

The RT60 fluctuations emphasized formulas #3 and the ARTA software response impulse output, as shown in Figure 6. The sound source for the RT60 sub-variable was determined using an inflated balloon and then recorded in real-time operating ARTA software. The measurement uses the Integrated impulse response method per the ISO3382.2 standard regarding Reverberation Time in an ordinary room. These frequencies were divided into low (63 Hz, 125 Hz, and 250 Hz), medium (500 Hz and 1000 Hz), and high categories (2000 Hz, 4000 Hz, and 8000 Hz).

The quadratic equation causes the minimum and maximum A_{eff} biowall values. In Figure 6, the minimum value of the A_{eff} biowall is commonly observed when a > 0 occurs on RT60 with a sound frequency range of 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Meanwhile, A_{eff} biowall is maximum when a < 0 and occurs at low and high frequencies of 63/125 Hz and 8000 Hz, respectively. This cannot be analyzed further because the negative value requires more in-depth research. For the minimum A_{eff} biowall, the existing extreme value was the short period (s) used by the sound to decrease by 60 dB to silence. In this analysis, the minimum A_{eff} biowall at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000Hz was achieved through the addition of 3.38, 3.42, 3.39, 4.12, and 4.25 modules, with a decrease in time fluctuations of 1.6809 s, 2.2734 s, 2.6128 s, 2.4205 s, and 1.5278 s, respectively. The comfortable standard for RT was one second maximum. So, adding A_{eff} modules of biowall, especially for middle and high frequencies, can provide more than 200 % comfort regarding Reverberation Time in the room.

Based on the NR sub-variable, the sound source was determined using the pink noise from the tone generator. This noise frequency was obtained using octave band #1, at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz. The recording of the pink noise waves was also carried out in real-time using ARTA software. This measurement subsequently used the Integrated impulse response method, according to the ISO9614-1 standard concerning the Determination of the Sound Power Level from a Noise Source. The fluctuations in the NR variable focused on the ARTA software response impulse output and formula 3, as shown in Figure 7.

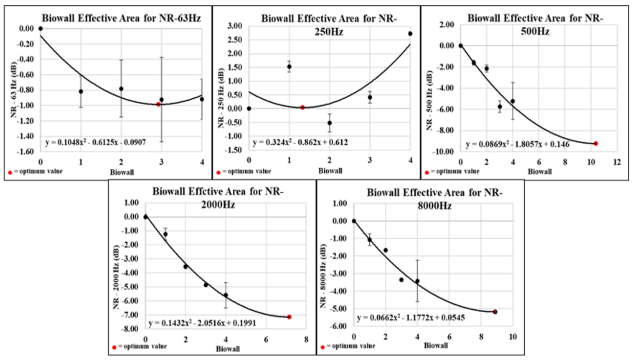


Figure 7. The fluctuation of NR with Biowall Treatment

Regarding Figure 7, the A_{eff} value is minimum when a > 0 occurs in NR at 63 Hz, 250 Hz, 500 Hz, 2000 Hz, and 8000 Hz. Meanwhile, A_{eff} is maximum when a < 0 occurs at 125 Hz, 1000 Hz, and 4000 Hz. Since the frequency of 125 Hz, 1000 Hz and 4000 Hz cause negative A_{eff} values, they are subsequently ignored due to the addition of biowall not significantly affecting the chamber. For the minimum A_{eff}

value, the existing extreme value was the largest sound power reduction level in the test chamber (dB), due to the addition of a biowall, which causes less noise. At 63 Hz, 250 Hz, 500 Hz, 2000 Hz, and 8000 Hz, the minimum A_{eff} for NR was achieved through the addition of 2.92, 1.33, 10.39, 7.16, and 8.89 modules, with the sound power reduction fluctuation of 0.9862 dB, 0.0387 dB, 9.2321 dB, 7.1498 dB, and 5.1771 dB, respectively. Based on the regulations of the Indonesian Minister of Health, the comfortable standard of NR for dwellings in Indonesia was 85 dB maximum. So, adding A_{eff} modules of biowall, especially for middle and high frequencies, can provide the comfortable regarding Noise Reduction in the room, 8 % and 6 %, respectively.

3.3. Visual Comfort – Inducing Biowall

For visual variables, the sub-variables measured included illuminance, luminance, and colour mapping. Illuminance and luminance were measured within the test chamber without biowall conditions, as well as with one, two, three, and four modules. They were also measured using a lux metre, with the measurement method using the Indonesian National Standard 16-7062-2019. Regarding the colour mapping variable, data collection was only accomplished once for each treatment. The measurement of the colouration percentage was also performed using colour analysis software. For the determination of this mapping, the percentage compared to each treatment was the most dominant colour when four modules were added, namely Camouflage Green. This aimed to understand the pattern by which the colour change affected the illuminance and luminance levels of the test chamber. The visual fluctuations emphasized formulas 2 and 3, as shown in Figure 8.

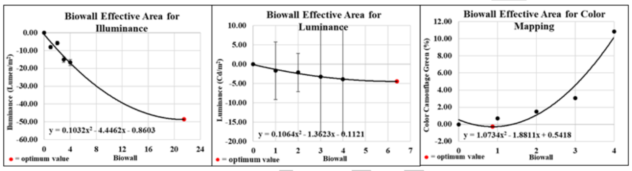


Figure 8. The Fluctuation of Visual Variabel with Biowall Treatment

In Figure 8, the quadratic equation graph showed only one form of A_{eff} biowall, with a minimum value of a > 0. This subsequently occurred in the illuminance, luminance, and camouflage-green mapping. For illuminance and luminance, the extreme value of the minimum A_{eff} was the dimmest or lowest light intensity, due to the addition of a biowall. The minimum value for these sub-variables was achieved by the addition of 21.54 and 6.40 modules, with the light reduction magnitude of 48.7453 lumen/m^2 and 4.4727 cd/m^2, respectively. The comfortable standard of illuminance for tropical dwellings in Indonesia was 150 lumen/m^2 maximum. So, adding A_{eff} modules of biowall can provide the comfortable regarding illuminance and luminance in the room, 32 % and 3 %, respectively. According to the camouflage-green mapping, the extreme value of the minimum A_{eff} was the test chamber condition with the lowest colouration percentage. The minimum value of the sub-variable was achieved by adding a 0.88 biowall with a camouflage-green percentage of 0.2832 %. There were no standards regarding colour mapping, but the camouflage-green colour was cold ones, so the more of it, the more visual comfort.

3.4. Respiratory Comfort – Inducing Biowall

The sub-variables measured for respiratory variables were the levels of CO_2, TVOC, HCHO, and PM2.5. These measurements were subsequently conducted without biowall conditions, as well as with the addition of one, two, three, and four modules. The fluctuations in the respiratory variables also prioritized formulas 1, 2, and 3, as shown in Figure 9.

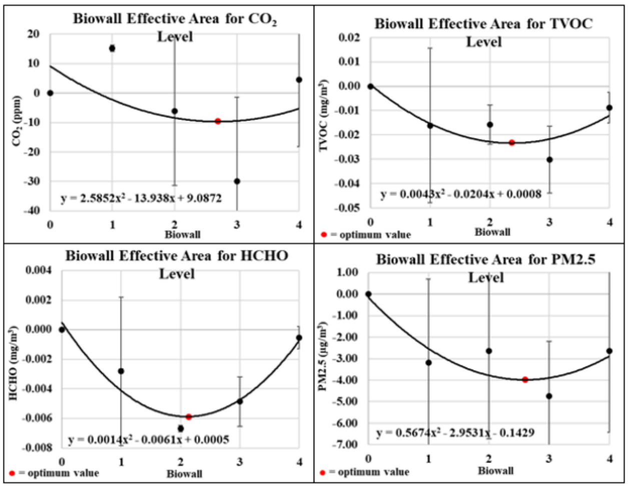


Figure 9. The Fluctuation of Respiratorial Variabel with Biowall Treatment

Figure 9 showed the performance of a mathematical analysis, to obtain a polynomial quadratic equation for each variable. From these values, the determination of y' was carried out to obtain the effective coefficient of each sub-variable. Based on Figure 9, the A_{eff} value of all sub-variables was minimum with a > 0. For the CO_2, TVOC, HCHO, and PM2.5 levels, the extreme value of the minimum A_{eff} was the least from each sub-variable content, due to the addition of a biowall. Regarding CO_2 levels, the A_{eff} value was 2.70 module with a reduced peak fluctuation of 9.6985 ppm. Meanwhile, the A_{eff} values for TVOC, HCHO, and PM2.5 were achieved with the addition of 2.37, 2.14, and 2.60 modules, with the reduced fluctuations of 0.0234 mg/m^3, 0.0059 mg/m^3, and 3.9849 µg/m^3, respectively. Based on the regulations of the Indonesian Minister of Health, the comfortable standard of CO_2, TVOC, HCHO, and PM2.5 levels for dwellings in Indonesia were 1000 ppm, 9.69 mg/m^3, 0.12 mg/m^3, and 35 µg/m^3, respectively. So, adding the A_{eff} modules of the biowall can provide an 1 %, 0.2 %, 5 %, and 11 % respiratory comfort effect (CO_2, TVOC, HCHO, and PM2.5 levels) in the room.

3.5. Holistic Sensory Comfort – Inducing Biowall

Based on the determination y' in all sub-variables, the A_{eff} was obtained, as shown in Table 2. This proved that the A_{eff} value varied for each sub-variable between 0.88-21.54 modules. The highest trend of the A_{eff} values obtained for all variables ranged from 2.05-2.92 with six sub-variables, indicating that the average coefficient was 2.5 modules. This was used as a reference number for the effective value

($A_{2.5}$) of all sub-variables. Furthermore, the A_{eff} magnitude of each sub-variable was converted to a 2.5 module, by substituting the x-value of 2.5 in each polynomial quadratic equation, to obtain the conversion rate. According to this $AO_{2.5}$ percentage, the average was then calculated for each variable, as shown in Table 2.

Table 2. Percentage of Effective Value of Biowall in Module 2.5

Variable	Sub-Variable		A_{eff}	$A_{2.5}$ Percentage (6)	$AO_{2.5}$ (7)
Thermal	Temperature		2.05	94.53 %	59.22 %
	Humidity		4.78	76.92 %	
	Surface Temperature		1.97	6.19 %	
Audial	RT60	250	3.38	93.58 %	93.58 %
		500	3.42	93.19 %	93.29 %
		1000	3.39	93.39 %	
		2000	4.12	85.23 %	84.42 %
		4000	4.25	83.61 %	
	NR	63	2.92	98.09 %	95.04 %
		250	1.33	91.98 %	
		500	10.39	41.43 %	41.43 %
		2000	7.16	56.44 %	52.16 %
		8000	8.89	47.79 %	
Visual	Illuminance		21.54	23.24 %	32.35 %
	Luminance		6.40	63.78 %	
	Camouflage Green Colour		0.88	10.02 %	
Respiratory	CO_2		2.70	98.98 %	98.88 %
	TVOC		2.37	99.70 %	
	HCHO		2.14	96.99 %	
	PM2.5		2.60	99.85 %	

4. Discussion

Regarding temperature, the A_{eff} value was achieved by adding a biowall of 2.05 modules to the test chamber, to reduce the heat level. In these conditions, the magnitude of the maximum temperature decrease subsequently reached 0.6019 °C. When the size was converted to 2.5 modules or a leaf area of 12.5 m^2, the ability of the biowall to reduce the temperature of the chamber was only observed at around 94.53 %. This sufficiently proved that the presence of a biowall provided a cooling effect in the test chamber. The ability of biowalls to reduce heat is due to the role of plants in binding carbon gas to minimize room heat. On the other hand, plants are also living things that carry out the breathing process, so when the biowall area exceeds the optimum threshold, heat will accumulate due to the large amount of CO_2 the plant releases during the breathing process. These findings show that biowalls could be passive cooling in single buildings. These results were in line with a previous analysis, where biowall reduced heat conduction by 18.7-39.8 % (Pan *et al.* 2020). In the analysis, a modular system was used on a campus with a subtropical climate in Hong Kong. In Spain, the analysis on sunny and cloudy days was able to reduce the interior temperature by 0.8 °C and 4.8 °C at different distances, using active living walls in a university hall (Pérez-Urrestarazu *et al.* 2016). Geogreens in a Mediterranean climate also decreased the average daily surface and interior thermal amplitudes by 11.3 °C and 15 °C during the summer (Manso and Gomes 2016).

Based on the test chamber humidity, the optimum value was obtained when 4.78 biowall modules were added, with a fluctuation of 6.6839 %. When only 2.5 modules were added, the improvement in increasing the chamber humidity level was only 76.92 %. This relative humidity elevation was directly proportional to the analysis of Shao *et al.* in offices of 3.1-6.4 % (Shao *et al.* 2021b). Meanwhile, biowall trials in Indonesia increased humidity by 72.5 %, using prototyping (Widiastuti *et al.* 2020). Humidity also increased significantly in Chinese schools, although had a low fluctuation in (Li *et al.* 2019). These changes in temperature and humidity were influenced by the evapotranspiration process carried out by plants in the biowall (Moya *et al.* 2017). The physical factors affecting the evapotranspiration process included temperature, atmospheric pressure, solar radiation, water vapour force, and wind speed. Meanwhile, the vegetative factors were plant and stomatal types, as well as active root depth. Air velocity must be considered in interior design so trapped air does not occur, which might cause mold and bacteria to proliferate.

On the surface temperature, the addition of 1.97 modules to the chamber was able to increase the heat of the average wall by 4.6768 °C. This value emphasized the hottest condition on the biowall surface. When converted to a 2.5 quantity, the performance in cooling the average surface temperature was only 6.19 %. According to Hoelscher *et al.*, the surface temperature of the outer biowalls was up to 15.5 °C, which was lower than bare walls. Meanwhile, the interior walls were up to 1.7 °C (Hoelscher *et al.* 2016). The similarity in the effect of biowall on surface temperature was confirmed despite the difference of the mechanism implemented. This increase in the heat was possible because the position of the biowall was attached to a wall whose outer side was exposed to direct sunlight. This heat increase depended on the thermal conductivity of wall material used. Materials with decreased water content and a high degree of saturation would cause a decrease in thermal conductivity; thermal insulation can increase significantly (Mekaideche *et al.* 2021).

For the audial comfort in the RT60 sub-variable, the optimum value (A_{eff}) of the biowall ranged from 3.38 to 4.25 modules at all frequencies, regarding the acceleration of reverberation time. This was accompanied by the magnitude of the sound decay time fluctuation, which ranged from 1.6809 to 1.5278 seconds. When converted to a biowall of 2.5 modules, this value caused a 93.58 %, 93.29 %, and 84.42 % decrease in reverberation time, for low, medium, and high frequencies, respectively. The sound absorption coefficients in the University of Ecuador's reverberation chamber were (0.59 - 0.80), 1.00, and 1.00 at low, medium, and high frequencies between (100 - 315) Hz, (400 - 1250) Hz, and (1600 - 5000) Hz, respectively, with the addition of substrates and ferns on the walls (Davis *et al.* 2017). Sound waves will experience reflection, refraction, diffraction, absorption and interference when passing through a medium. As a result, the power of the sound will weaken. This means that when a sound source passes through the biowall medium with an optimum value, the biowall's ability will remain the same at its optimum value. This is shown in Figure 6, whereby by increasing the biowall area after the optimum value, the RT60 reduction value tends to be close to the same.

In the NR sub-variable, the distribution of A_{eff} ranged from the addition of 1.33 to 10.39 modules at all frequencies. At the largest A_{eff} value (10.39 modules), the greatest reduction in sound intensity was 9.2321 dB. This was comparable to the analysis of Wong *et al.*, where increased frequency caused elevated sound absorption with greater biowall coverage (Wong *et al.* 2010). However, the A_{eff} values represented the highest sound reduction (quietest) at 63 Hz, 250 Hz, 500 Hz, 2000 Hz and 8000 Hz. In sound intensity, fluctuations also ranged from a decrease of 0.0387 dB to 9.2321 dB. At a conversion magnitude of 2.5 modules, the sound reduction increased due to the addition of 95.04 %, 41.43 %, and 52.16 % biowall for low, medium, and high frequencies, respectively. This proved that biowall was able to be an optimal sound reducer. These results were in line with Azkorra *et al.*, where the weighted sound reduction index (Rw) and absorption coefficient by green walls were 15 dB and 0.40, respectively (Azkorra *et al.* 2015). The ability of plants to affect the acoustic quality through sound sources' absorption mechanisms.

Based on the illuminance level, the A_{eff} value was achieved when the test chamber was provided with an additional biowall of 21.54 modules. The illuminance reduction decreased by 48.7453 lumen/m^2. This was the peak number causing the dimmest condition of the chamber. However, the biowall performance in illuminance reduction was only 23.24 % when 2.5 modules were solely used. Regarding the luminance level, the A_{eff} value was achieved when the test chamber was provided with an additional wall of 6.4 modules, with a luminance drop of 4.4727 cd/m^2. These results showed that biowall affected the illuminance and luminance levels in the test chamber. Another aspect proved that the phenomenon reduced light intensity by 26.95 % (Kristanto *et al.* 2021), with western tropic greenery facades decreasing sunlight by 31.18 % to 51.71 % (Kristanto *et al.* 2020). A unique property of light waves is polarization, or the reduction in light intensity, because the direction of light propagation is always perpendicular. This means that increasing the area of the biowall from its optimum value will not affect the performance of the biowall in influencing the level of illumination and room luminance, as seen in Figure 8.

For colour mapping, the highest percentage produced a camouflage-green colouration when adding four biowall modules. This colouration was used as a benchmark for determining optimal colour mapping values. The polynomial quadratic equation also showed a graph of the A_{eff} minimum value ($a > 0$) in this sub-variable. This value produced the lowest camouflage-green percentage, regarding the addition of 0.88 biowall at 0.2823 %. When converted into 2.5 modules, the colour percentage increased by 10.02 %. The green colour level affected illuminance and luminance, due to its inclusion in the dark colouration category, with a reflectance level or light absorption of around 0.1 or 80 %, respectively. This result supported the illuminance and luminance levels of the test chamber, which realistically became dimmer by adding a specific biowall area. The ability of plants to influence the visual environment depends on the density, leaf colour and dimensions.

According to the levels of CO_2, TVOC, HCHO and PM2.5, the optimum value occurred with the addition of 2.70, 2.37, 2.14 and 2.60 modules. The A_{eff} reduction values in the levels of CO_2, TVOC, HCHO and PM2.5 were 9.6985 ppm, 0.0234 mg/m^3, 0.0059 mg/m^3, and 3.9849 µg/m^3, respectively. Based on the respiratory variables, the biowall performance in reducing each sub-variable level was 98.88 % when the magnitude conversion was performed at 2.5 modules.

These positive results were in-line with previous literature, specifically when associated with specific plant species. Green wall with *Nephrolepis exaltata* Bostoniensis was capable of removing PM 0.3 to 0.5 levels by 45.78 % and 92.46 % (Pettit *et al.* 2017). *Nephrolepis exaltata* was also able to reduce CO_2 levels significantly (Moya *et al.* 2021). In reducing TVOC concentrations within Spanish indoor spaces, *Chlorophytum comosum* was found to be the most efficient species (Suárez-Cáceres and Pérez-Urrestarazu 2021). The addition of interior potted plants reduced TVOC and formaldehyde levels by 48 % and 145 %, respectively (Sowa *et al.* 2019).

In this respiratory topic, the most important condition prioritized the use of plant species with high phytoremediation capabilities, which affected both air quality and human comfort (Moya *et al.* 2017). Stomata also performed the air absorption system in plants during ordinary gas exchange (Moya *et al.* 2017). Moreover, phytoremediation increased due to the number, efficiency, and age of plants at high temperatures, with soil pH ranging from 5.5 to 7.0. That means the choice of plant species significantly affects the respiratory performance of the biowall.

5. Conclusion

Based on these results, all the sub-variables for thermal, audial, visual, and respiratory comfort were tested and observed to be capable of inducing sensory comfort. Meanwhile, biowall effective area (A_{eff}) had negative values in RT60 and NR, at frequencies of 63/125/8000 Hz and 125/1000/4000 Hz, respectively. The sub-variables were not analyzed due to being insignificantly effective. This indicates the need for adequate future analysis for this item. The main results show that the biowall areas required to induce holistic sensory comfort were not directly proportional to the volume of the space. A certain limit was the effective value of the required biowall area.

From these results, the biowall effective area in inducing thermal, audial, visual, and respiratory comfort varied with an approximate value of 2.5 modules or 12.5 m^2 leaf area. This value applies to a test chamber with size (w x d x h) (3000 x 3000 x 2500) mm^3, with the room material, locus, type of biowall, type of plant, and substrate explicitly used according to the description. In inducing thermal, audial, visual, and respiratory comfort with a magnitude of 2.5 modules, the percentages of biowall performance were 59.22 %, 76.64 %, 32.35 %, and 98.88 %, respectively. Generally related to the comfort standards in Indonesia, adding the biowall with an effective area can provide a comfortable effect on each sub-variable with a different percentage except for the surface heat and colour mapping sub-variables because there were no applicable standards.

These results are significant as a reference for using a biowall at-home scale in inducing human sensory comfort. Therefore, future analyses need to test the use of different species as enrichment for these outputs. Further research is needed regarding the formula to determine the BEA as a generalization attempt, and it is necessary to link these results digitally based on artificial intelligence, IoT, or application which can significantly assist users, architects, and stakeholders in determining the effective biowall area in the dwelling.

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