ADOPTING CONCEPT OF BIOPHILIC DESIGN TO ENHANCE HEALTHY INDOOR: AN EXPERIMENT ON MOSS-BASE FOR TROPICAL BUILDING

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Abstract. The modern world is increasingly focused on sustainability, promoting the concept of a greener Earth. This forms the foundation for Industry 6.0, which aims to harness emerging technologies in harmony with nature, supporting sustainability principles where technology complements rather than dominates the environment. Within this framework, there is growing interest in exploring Nature-Based Solutions (NbS) for buildings, aiming to enhance indoor performance. The concept of integrating nature with the built environment is referred to as Biophilic Design (BD). It encompasses a variety of strategies, among which the incorporation of plants is prominent as a widely adopted practice in industry. Numerous indoor plants, such as Spider Plant, Peace Lily, Areca Palm, Rubber Plant, Aloe Vera, Pothos (commonly known as Money Plant), and non-vascular plants, such as bryophyte species, are widely used in BD. This study specifically investigates the efficacy of integrating moss plants (a type of bryophyte species), which are abundant in tropical countries like Sri Lanka, due to their ability to improve indoor air quality (IAQ). An experimental research method was employed to assess the effectiveness of moss plants in enhancing the IAQ. The experiment conducted under a controlled environment proved that Moss plants effectively reduced particulate matter (PM_{10}) and removed formaldehyde. These findings establish a foundation for future research to develop this concept into a commercially practical product, using moss as a readily available resource in Sri Lanka.

Keywords. Moss (Bryophyte), IAQ, Biophilic Design, Indoor Air Quality, Healthy Indoor, Tropical Environment

1. Introduction

Rapid urbanization and climate challenges underline the importance of sustainable architectural practices that enhance human well-being and environmental health. Nature-Based Solutions (NbS) provide a framework to address issues like climate change and urban heat through ecosystem integration (Cohen-Shacham et al., 2016). Biophilic design (BD), which aligns with key NbS strategies, incorporates natural elements into built environments to improve aesthetics, mental health, and IAQ, particularly in tropical environment (Kellert, 2008; Zhong et al., 2022). Moss, a non-vascular plant abundant in tropical regions like Sri Lanka, offers a low-maintenance, cost-effective BD solution due to its ability to reduce particulate matter (PM) and volatile organic compounds (VOCs) while regulating humidity (Gong et al., 2019; Perini et al., 2020). This study evaluates the efficacy of moss as a BD element in enhancing IAQ in a controlled tropical indoor setting, Sri Lanka, measuring PM2.5, PM_{10}, formaldehyde, CO_2, temperature, and humidity. By comparing moss-integrated and control setups, the research aims to confirm moss as a sustainable BD element, contributing to healthier indoor spaces and aligning with Industry 5.0’s vision of technology-nature harmony (Sadick & Kamardeen, 2024).

https://doi.org/10.31705/ICFMF2025.9

2. Literature Review

The escalating challenges of urbanisation and climate change have underscored the need for sustainable architectural practices that enhance human well-being while mitigating environmental impact (Haider & Kapur, 2024). Addressing this, Nature - based Solutions (NbS) have been identified as a potential solution (Kabisch et al., 2017) since it is a collection of environmentally friendly techniques and actions that aim to protect, sustainably manage, or restore ecosystem to address the urbanisation challenges, such as climate change, biodiversity loss, and urban heat, while promoting human well-being and environmental benefits (Cohen-Shacham et al., 2016). Under this circumstances, Biophilic Design (BD) has emerged as a pivotal approach aligning with NbS techniques, rooted in the innate human connection to nature, aiming to integrate natural elements into built environments to create harmony, aesthetics, and functionality (Beatley, 2011; Saha et al., 2024; Seddon et al., 2020). According to Kellert (2008) and Zhong et al. (2022), BD emphasizes the integration of natural light, vegetation, natural elements and shapes, and organic materials to foster a connection between humanity and the natural world, reflecting an intrinsic human desire for such engagement. Among the various BD applications in a building, incorporating plants or vegetation is one of the most common and widely embraced practice in the built environment worldwide (Beatley, 2016). Incorporating plants and vegetation yields multiple benefits, such as enhanced mental well-being, increased productivity, and improved thermal comfort (Klaniecki et al., 2018; Lan & Liu, 2023). Moreover Kellert (2008) and Zhong et al. (2022) emphasized, the plant application stands out as a cornerstone for establishing a naturalistic indoor environment that also enhances indoor air quality (IAQ).

Numerous indoor plants have been scientifically approved to improve air quality and promote healthier living environments. These plants offer multiple benefits, including the removal of pollutants, increased humidity, and enhanced aesthetic appeal (Dela Cruz et al., 2014). Among them, non-vascular plants, such as moss, liverworts, and hornworts, are more flexible in designing a naturalistic indoors while improving the IAQ (Paoli et al., 2023). Even though mosses, liverworts, and hornworts are all non-vascular plants belonging to the Bryophyte division, liverworts and hornworts need more dampness or waterlogged habitats, and specific wet environmental requirements, making them less practical and highly sensible to the indoor environment (Capozzi et al., 2023; Kumar & Kumar, 2023). In contrast, mosses exhibit remarkable adaptability to low light and high humidity levels which has led to commonly found indoors (Capozzi et al., 2023). Therefore, mosses can be derived from other Bryophyte species as an ideal plant for indoor tropical environments due to their unique adaptability and environmental benefits (Raymond et al., 2017). Mosses are non-woody plants, that typically grow only a few centimetres in height and primarily rely on their leaves to absorb water and nutrients (Chaffey, 2014). Like other plants, mosses perform photosynthesis, converting carbon dioxide and sunlight into energy to produce their own nutrients (Wang et al.,2018; Zhang et al.,2021). Their densely packed root system and leaves support to absorb water and more nutrients from the atmosphere (Gutiérrez et al., 2023). Therefore, moss has gained attention, particularly in tropical contexts, due to its unique ecological and practical advantages (Kato-Noguchi et al., 2010;

Negi & Chaturvedi, 2016; Vieira et al., 2014).Moss can thrive on various substrates with minimal maintenance, and fewer resource requirements, making it a cost-effective alternative to traditional greenery that often incurs high installation and upkeep costs (Perini et al., 2020; Sadick & Kamardeen, 2024). Furthermore, moss's ability to grow epiphytically on building surfaces offers creative design flexibility, such as moss walls (Heffernan, 2019; Wang & Cheng, 2020).

In Sri Lanka, moss can be commonly seen in indoors, covering pots and bonsai plants, as an aesthetic and rustic design element. Examples of these practical applications are presented in Figure 1.

Figure 1: Indoor Covering Pots

Those indoor moss applications are currently prevalent among interior designers to enhance a naturalistic, rustic aesthetic look in places such as in commercial spaces residential interiors etc. (Cruz et al., 2023; Quiet Earth Moss, 2021). Inspired by these practices, it is suggested that, instead of implementing traditional green walls, moss-based panels or designs, such as MosSkin system evaluated in Italy (Perini et al., 2020), may be a more possible integration for BD. This approach offers advantages not only in terms of initial implementation costs but also from a maintenance perspective.

To grow mosses indoors under tropical conditions, regulation of temperature, humidity, lighting, and irrigation is essential, as supported by multiple studies. Mosses can grow at temperatures of 15-30 °C (Varela et al., 2021; Yin et al., 2023; Zechmeister et al., 2023). Zechmeister et al. (2023), stated that for the better growth of moss, humidity should be optimally and daily ranges between 50% and 90%, ensuring hydration while preventing fungal growth. Lighting is another crucial parameter for the growth of moss. Zechmeister et al. (2023) recommended light intensities between 2000 and 6000 lux, aligning with Wang et al. (2018), who achieve growth at 3175 lux, using artificial white light. Irrigation methods for the moss vary across the studies, but all emphasize the importance of maintaining consistent moisture levels without waterlogging. Udawatta et al. (2018) conducted a study on outdoor moss cultivation in Moratuwa, Sri Lanka (a tropical country), successfully growing moss under an average temperature of 27 °C, 75 % of humidity with 12 hours of photoperiod (the period in a day an organism is exposed to light) at 1100 lux under a twice a day water supply. Therefore, the above literature supports that careful regulation of temperature from 15°C to30°C, humidity from 60% to 90%, lighting 2000 – 6000 lux, and irrigation requirement is essential to achieve an optimal growth.

In addition to its aesthetic appearance mosses are identified as a significant contributor for enhancing health indoors in many research studies. For instance, studies by Gong et al. (2019) and Gutiérrez et al. (2023) demonstrate the ability of moss to purify indoor air by filtering particulate matter (PM) and volatile organic compounds (VOCs). Experimental results indicate a reduction in PM levels from 1,000 μg/m³ to below 200 μg/m³ within hours while regulating the humidity, mitigating noise through its porous structure, and providing thermal insulation, thereby enhancing occupant comfort and safety (Lee & Kim, 2021; Van Renterghem, 2018; Bakatovich & Gaspar, 2019).

When testing particulate matter, the Environmental Protection Agency (2023) in the USA has identified the particle diameter of 2.5 and 10 micrometers (i.e., $PM_{2.5}$ and PM_{10}) are critical metrics for assessing indoor air quality (IAQ) due to their significant health impacts and prevalence in indoor environments. $PM_{2.5}$, capable of penetrating deep into the lungs and bloodstream, is linked to respiratory and cardiovascular diseases, while PM_{10} irritates the upper respiratory tract, worsening conditions like asthma (WHO, 2021).

VOC is a border category of chemicals that evaporate easily and contained carbon (Gao et al., 2024). Formaldehyde is a specific organic compound which falls under the umbrella of VOCs. (Skipper et al., 2024). In this study formaldehyde levels are measured as they may cause eye, nose, throat irritation, respiratory issues, and potential cancer risk (Salthammer et al., 2010). CO_2 is monitored as its high levels result in drowsiness and reduced cognitive function particularly when high level of CO_2 prevails in a less ventilated indoor space (Satish et al., 2012). Additionally, humidity and temperature levels are assessed to check their reaction with the moss plant, enabling the reduction of heat in indoor spaces, especially in tropical contexts where high humidity and warmth prevail.

This study explores the integration of moss as a BD element in tropical indoor environments, aiming to evaluate its applicability and effectiveness, as a sustainable solution for improving health, by impacting indoor quality in tropical buildings.

2. Methodology

3.1 EXPERIMENTAL DESIGN

To reach the aim of the study, the experiment was designed to evaluate the impact of moss integration on IAQ under controlled tropical environmental conditions.
Therefore, the experiment was conducted in a controlled indoor environment in a 50 cm × 50 cm × 50 cm sealed glass chamber kept at the University of Moratuwa, Sri Lanka, replicating a tropical indoor environment with a temperature of 27 ± 2°C and relative humidity of 75 ± 5%. Two setups were investigated:
(1) **Experimental condition** featuring a moss to assess IAQ

(2) **Control condition** without moss to serve as a baseline for comparison.

IAQ was assessed using particulate matter (PM2.5 and PM_{10}), formaldehyde (HCHO), carbon dioxide (CO_2), temperature (°C), and relative humidity (%). Figure 2 and Figure 3 illustrate configurations of these setups, along with the pollutant generators for carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PM). The moss species selected for this experiment was cushion moss, a type commonly found in Sri Lanka.

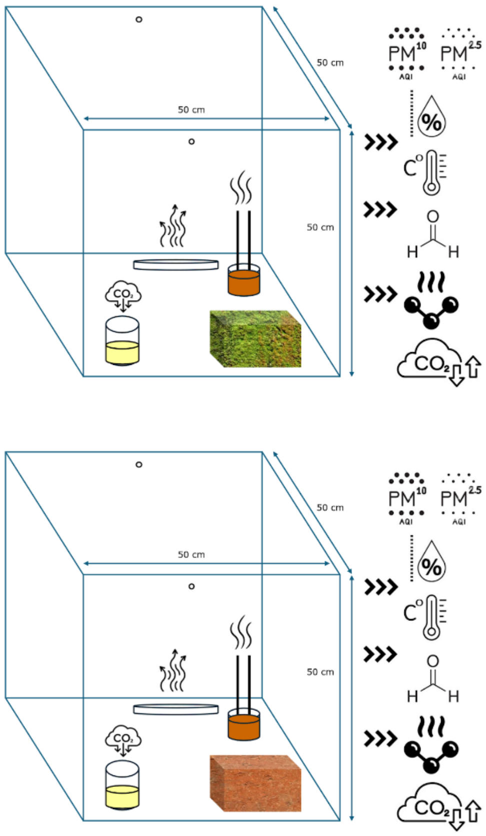
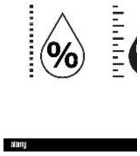
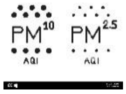
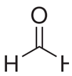


Figure 2: Experimental Condition

As shown in Figure 2, a porous brick block of 10 cm × 20 cm × 5 cm (width × height × depth) was used as the substrate, which was covered with the cushion moss species developed from a pulp prepared using local materials, such as washed moss, aloe vera gel, and compost tea, in the ratio of 2:1:1 (tablespoons), and blended to a 5 seconds consistency using a blender. The Control condition consisted of an identical brick substrate without moss coverage as shown in Figure 2 Air quality was evaluated using three indoor air quality instruments: a CO_2 meter, a particulate matter (PM) meter, and a formaldehyde meter.
The illustrations provided above are labeled for ease of identification, as outlined in Table 1.

Table 1: Explanation of Symbols

	Brick with moss		Temperature		Humidity		acetic acid and sodium bicarbonate
	Brick without moss	 	VOC		PM $_{2.5}$ & PM $_{10}$		Incense Sticks (2)
	Formaldehyde		C0$_2$		Thinner		Measure

3.2 EXPERIMENTAL PROCEDURE

To create the polluted environment inside the sealed glass chamber, two incense sticks were ignited to simulate combustion-related emissions, while carbon dioxide (CO_2) was produced via a controlled chemical reaction between acetic acid (CH_3COOH) and sodium bicarbonate ($NaHCO_3$) following the method used by Tharak et al. (2022). The combustion of the incense stick, coupled with the introduction of acetone, resulted in elevated concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), and formaldehyde within the chamber. Air quality measurements were conducted at the beginning of the experiment (0 minutes) and after 30 minutes. Subsequently, continuous monitoring was performed over 8 hours, as informed by methodologies outlined in Gong et al. (2019) and Stojanovska et al. (2022). Following this, the chamber was left undisturbed overnight. On the subsequent day, air quality readings were recorded at 2-hour intervals. The experiment procedure is illustrated in Figure 3.

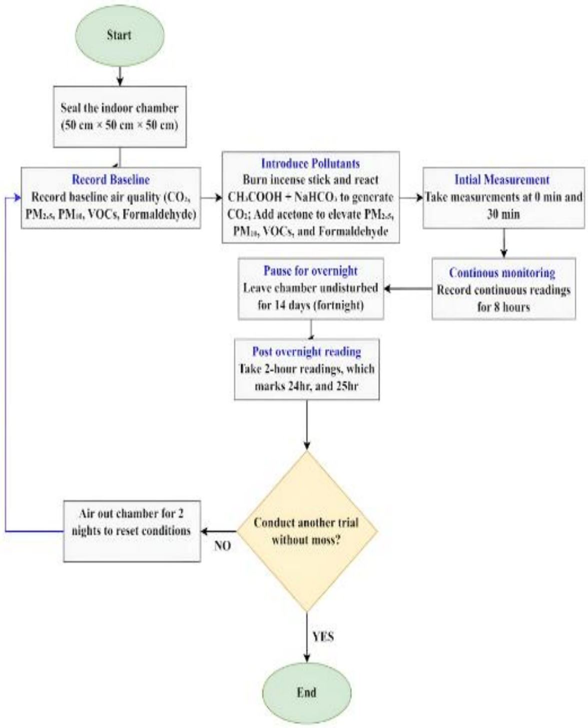
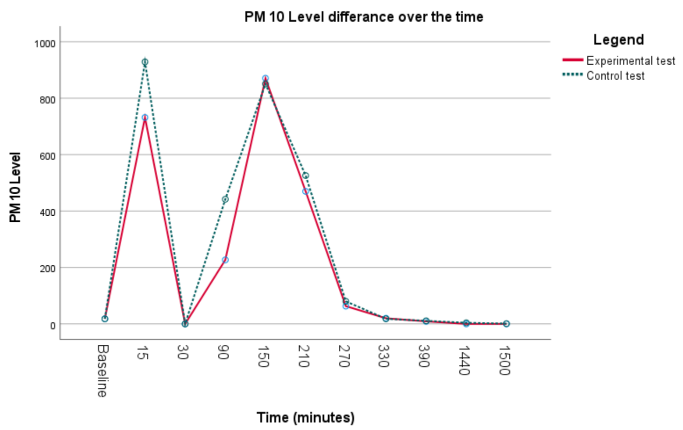


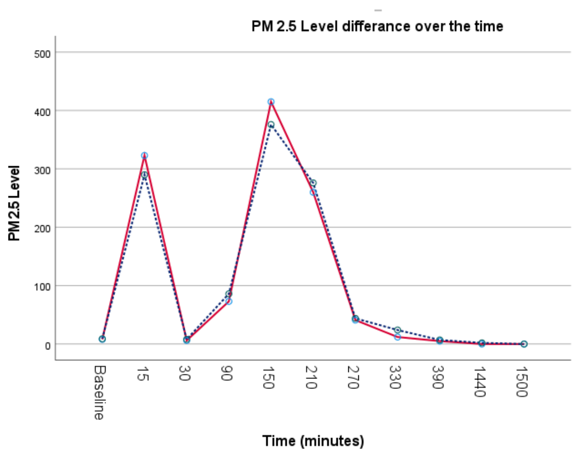
Figure 3: Experiment Procedure

4. Results and Discussion

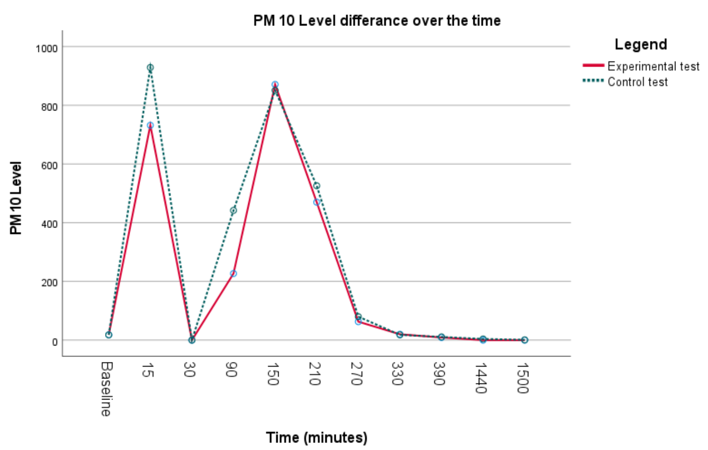
The effects of the moss plant on pollutant levels are presented in Figures 5 to 10. The readings for each point are detailed in Table 2. For data analysis, a General Linear Model was employed using IBM SPSS -27 software, and the rate of impact for each pollutant was calculated. The results for each pollutant are discussed below.

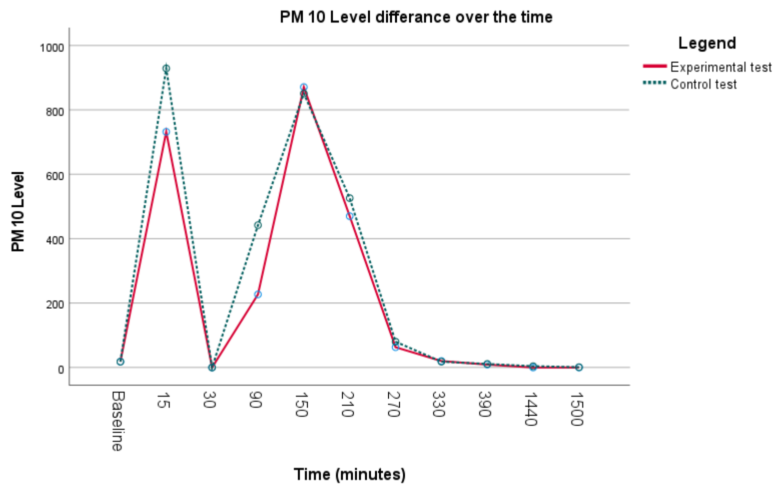
4.1 GRAPHICAL REPRESENTATION





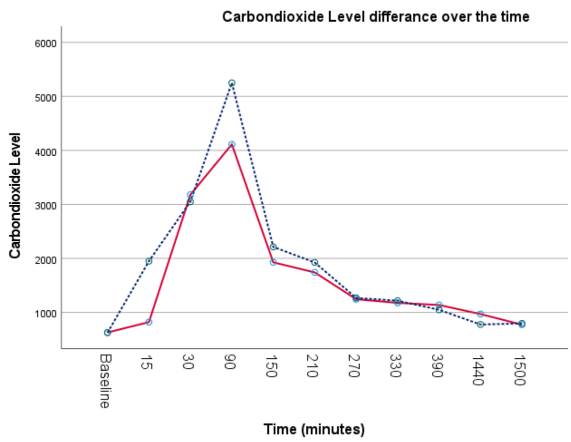
4.1.1 PM 2.5 AND PM 10





Figures 5 and 6, illustrate $PM_{2.5}$ and PM_{10} levels over 1500 minutes in a controlled chamber experiment, comparing Experimental and Control conditions. Initially, both $PM_{2.5}$ and PM_{10} levels spike sharply in both conditions, peaking around 90 minutes ($PM_{2.5}$: ~450 µg/m³ for Experimental, ~400 µg/m³ for Control; PM_{10}: ~900 µg/m³ for Experimental, ~700 µg/m³ for Control). The Experimental condition exhibits a steeper decline post-peak, dropping to ~50 µg/m³ for $PM_{2.5}$ and ~100 µg/m³ for PM_{10} by 300 minutes, indicating a faster normalization rate. In contrast, the Control condition decreases more gradually, stabilizing at ~150 µg/m³ for $PM_{2.5}$ and ~200 µg/m³ for PM_{10} after 300 minutes. By 1500 minutes, Experimental levels remain lower ($PM_{2.5}$: ~25 µg/m³; PM_{10}: ~50 µg/m³) compared to Control ($PM_{2.5}$: ~100 µg/m³; PM_{10}: ~150 µg/m³). This suggests Experimental condition has effectively reduced pollutants faster than Control Condition, supporting its potential for air quality improvement.

4.1.2 *Carbon dioxide Level*



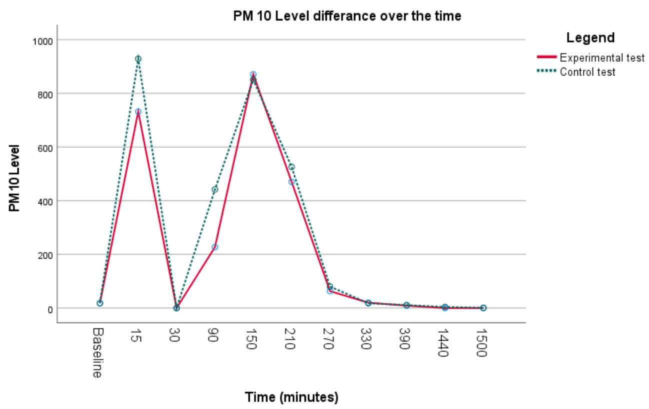
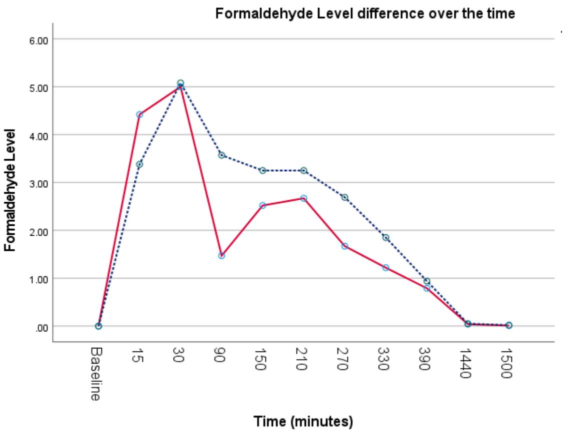


Figure 7, illustrates carbon dioxide (CO_2) levels over 1500 minutes, comparing Experimental and Control conditions. Both show a sharp CO_2 rise, peaking at 90 minutes (Experimental: ~5500 ppm, Control: ~5000 ppm). Post-peak, Experimental condition exhibits a steeper decline, reaching ~1500 ppm by 300 minutes, while Control decreases more slowly to ~2000 ppm. By 1500 minutes, Experimental condition stabilizes at ~500 ppm, lower than Control at ~1000 ppm. A minor CO_2 increase in the Experimental condition around 1200 minutes, post-overnight, may result from limited ventilation in the sealed environment, reducing CO_2 dispersal (Smith et al., 2021). Additionally, night-time respiration by plants, which release CO_2, could contribute, as a plant, moss likely continues this process overnight (Johnson & Lee, 2022). This aligns with findings that sealed buildings trap pollutants and plant respiration affects indoor CO_2 (Jones & Brown, 2020). The steeper Moss slope overall highlights its efficacy in air purification.

4.1.3 Formaldehyde Level



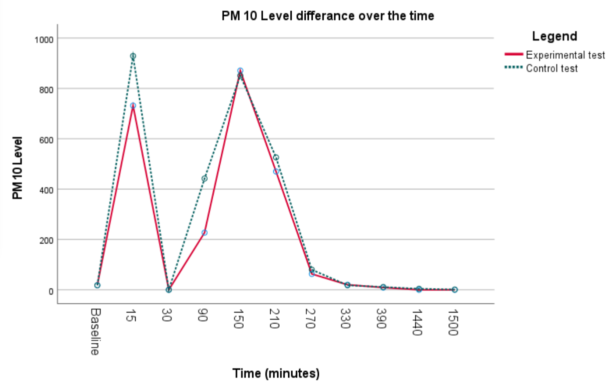
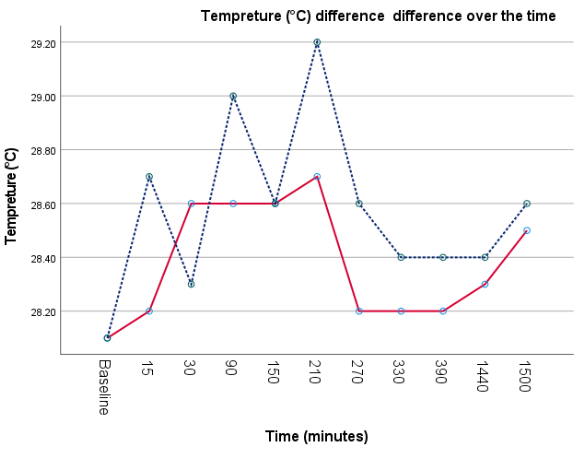


Figure 8 displays formaldehyde levels over 1500 minutes, comparing Experimental and Control conditions. Both conditions show a rapid increase, peaking at 90 minutes (Experimental: ~5.0 ppm, Control: ~4.5 ppm). Experimental condition has exhibited a steeper decline post-peak, dropping to ~2.0 ppm by 300 minutes, while Control condition decreases more gradually to ~2.5 ppm. By 1500 minutes, Experimental condition has stabilized at ~0.5 ppm, lower than Control at ~1.0 ppm. The steeper slope of Experimental condition indicates a faster formaldehyde reduction rate, suggesting its superior efficacy in mitigating this pollutant. This highlights Moss's potential for improving air quality in controlled environments.

4.1.4 Temperature level variations



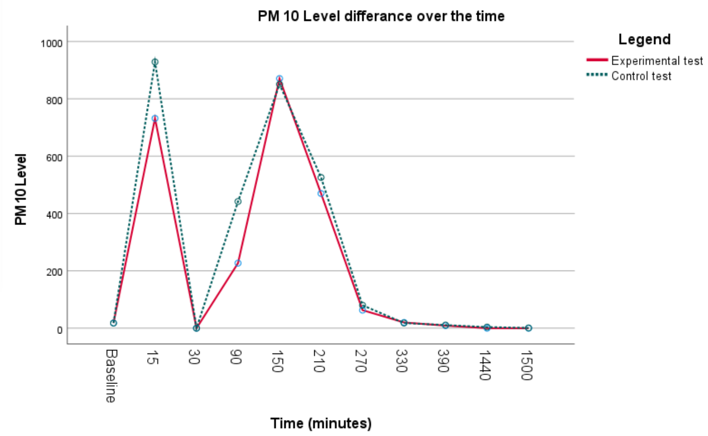
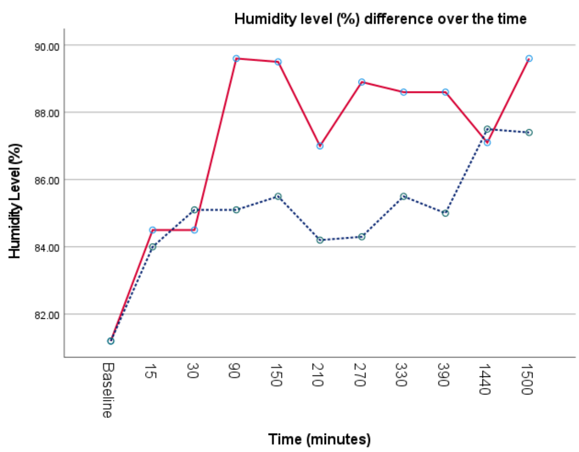


Figure 9, the temperature and CO_2 (Figure 7), are observed an interconnected dynamics between Experimental and Control conditions over 1500. Temperature in the Experimental condition peaks higher (~29.9°C at 90 minutes) than Control (~29.7°C), coinciding with the CO_2 peak (Experimental: ~5500 ppm, Control: ~5000 ppm). This suggests that moss plant's metabolic activity, such as respiration, may contribute to both CO_2 release and heat generation during this period (Johnson & Lee, 2022). Post-peak, Experimental condition has shown a steeper CO_2 decline (~500 ppm by 1500 minutes) and temperature stabilization (~29.5°C), while Control condition has stabilized at ~1000 ppm CO_2 and ~29.6°C. The minor CO_2 increase in Experimental condition around 1200 minutes, post-overnight, aligns with a slight temperature rise, likely due to night-time respiration and limited ventilation, as found by (Smith et al., 2021). These patterns indicate moss plant's active role in modulating both CO_2 and temperature more effectively than the Control condition.

4.1.5 Humidity variation



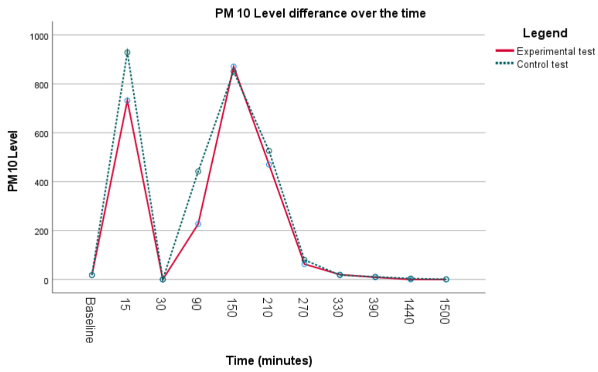


Figure 10 depicts humidity levels over 1500 minutes, comparing Experimental and Control conditions. In Experimental condition, the humidity rises sharply to ~89% by 90 minutes, peaking at ~90% around 300 minutes, while in Control condition, it increases steadily to ~87%. Both stabilized by 1500 minutes (Experimental: ~89%, Control: ~86%). This elevation in Experimental condition may result from its transpiration, releasing water vapour and enhancing humidity as similar to the study by Davis and Patel (2023). CO_2 levels peak concurrently (Experimental: ~5500 ppm, Control: ~5000 ppm at 90 minutes), declining to ~500 ppm and ~1000 ppm, respectively, by 1500 minutes. Temperature peaks align (Experimental: ~29.9°C, Control: ~29.7°C at 90 minutes), stabilizing at ~29.5°C and ~29.6°C. The humidity, CO_2 and temperature correlation suggests moss plant's metabolic activity drives moisture and CO_2 release, moderated by transpiration (Smith et al., 2021). Limited ventilation may have amplified these effects (Jones & Brown, 2020). Moreover, further studies should explore ventilation impacts to optimize Moss's air-purifying potential.

High humidity indicates more water vapour in the atmosphere, which can influence temperature. Water vapour has a high specific heat capacity, meaning it absorbs and retains heat effectively, slowing temperature changes. Thus, high humidity typically reduces temperature fluctuations, preventing rapid cooling or heating. However, it can make the air feel warmer due to reduced evaporation of sweat, impacting perceived temperature rather than actual temperature (Wexler, 2021). In the experiment, Experimental condition humidity peaked at ~90%, while temperature stabilized at ~29.5°C, suggesting humidity can moderate temperature variances.

Moss as a plant primarily emits water vapour through transpiration, a process where water absorbed by its tissues is released into the atmosphere, increasing humidity (Davis & Patel, 2023). Unlike vascular plants, moss as a non-vascular plant or Bryophyte lacks true roots but absorbs water through its surface by capillary action as they lack true stomata found in vascular plants. In the sealed chamber, moss plants' transpiration likely contributed to the observed humidity rise (from ~82% to ~90%), as it easily emitted water vapour from its surface during metabolic processes. This aligns with its CO_2 reduction role, where moisture release is a byproduct of respiration (Johnson & Lee, 2022).

The analysis of (Figures 5-10) proves that moss plant (Experimental condition) has consistently and effectively performed in removing PM_{10} and formaldehyde, showing steeper declines, while its impact on $PM_{2.5}$ stays considerably lower but has a positive impact. Additionally, the dynamic regulatory patterns of CO_2, humidity, and temperature can be further explored.

Table 2: Experiment data collection on both experimental condition and control condition.

Time slots in minutes	**$PM_{2.5}$ (μg/m³)**		**PM_{10} (μg/m³)**		**CO_2 (ppm)**		**Formaldehyde (ppm)**		**Temperature (°C)**		**Humidity (%)**	
	Moss	No	Moss	No	Moss	No	Moss	No	Moss	No	Moss	No
0m	8	9	18	18	629	625	0	0	28.1	28.1	81.2	81.2
15m	323	290	732	929	821	1950	4.42	3.38	28.2	28.7	84.5	84
30m	6	8	0	0	3180	3051	5	5.08	28.6	28.3	84.5	85.1
90m	73	86	227	442	4113	5251	1.47	3.57	28.6	29	89.6	85.1
150m	415	376	871	851	1928	2213	2.52	3.25	28.6	28.6	89.5	85.5
210m	260	276	470	526	1741	1926	2.67	3.25	28.7	29.2	87	84.2
270m	41	44	63	80	1245	1269	1.67	2.69	28.2	28.6	88.9	84.3
330m	12	24	20	18	1177	1217	1.22	1.85	28.2	28.4	88.6	85.5
390m	5	7	9	11	1138	1049	0.79	0.94	28.2	28.4	88.6	85
1440m	0	2	0	4	970	777	0.04	0.05	28.3	28.4	87.1	87.5
1500m	0	0	0	1	773	797	0.01	0.02	28.5	28.6	89.6	87.4

4.2 GENERAL RATE OF CHANGE ANALYSIS

The general rate of change of a pollutant refers to the variation in pollutant concentration over time. This measure evaluates the speed at which pollutants are reduced, with a steeper negative slope, indicating a more rapid normalization of pollutant levels (Seinfeld & Pandis, 2016). As suggested in Li et al. (2022), Equation 1 is used to assess the rate of change of pollutants for this experiment.
Pt=The rate of change of pollutants over the time

Table 3 presents the rates of change in percentages for each pollutant and the varying patterns of indoor conditions over time under Experimental conditions with moss plant and Control conditions without moss plant.

Table 3: The Rate of change calculation results.

Pollutant	% Change Experimental C.	% Change Control C.	Difference (Experimental - Control)
$PM_{2.5}$	-100.00%	-100.00%	0.00%
PM_{10}	-100.00%	-94.44%	-5.56% (Moss better)
CO_2	22.89%	27.52%	-4.63% (Moss better)

Formaldehyde	16.16%	12,12%	-4.049% (Moss better)
Temperature	1.42%	1.78%	-0.36% (Moss less increase)
Humidity	10.34%	7.14%	3.20% (Moss more increase)

These results in Table 3, reveal distinct patterns when comparing Experimental and Control conditions on $PM_{2.5}$, PM_{10}, VOC, CO_2, formaldehyde, temperature, and humidity. Comparing the Experimental and Control conditions, PM_{10} reduction is more effective with moss, showing a faster rate of change (-2.1176 vs. -2.0000) and achieving 100% reduction in Experimental condition, compared to 94.44% in Control condition, indicating moss's superior efficacy for larger particulates. The positive results in Experimental condition for formaldehyde levels, show a slower rate of increase compared to Control condition, emphasizing its potential to reduce formaldehyde level. Temperature has increased in both conditions, but the results from the Experimental condition show a lower rate of increase, indicating the moss plant's ability to exert a cooling influence. However, humidity has increased more significantly in Experimental condition with moss plant, consistent with its moisture-retaining transpiration process.

6. Conclusion

This study conducted experiments using a Moss plant (a Bryophyte) to evaluate its effect on removing Particulate Matter (PM) and formaldehyde levels, VOCs, as well as variations in the composition of air within a controlled indoor space. The results revealed that moss reduces $PM_{2.5}$ levels but faces challenges in mitigating rising CO_2 levels due to external factors, such as ventilation. Conversely, it excels in reducing PM_{10} and formaldehyde, while also moderating temperature and enhancing humidity if the ventilation is poor, especially during nighttime. Further studies could refine these insights by isolating these factors to optimize moss's application in indoor air quality management and as an ideal element for developing the Biophilic Design concept in tropical indoor environments under tropical conditions.

7. References

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