DEVELOP A BIOPHILIC DESIGN FILTER FOR ENHANCING INDOOR AIR QUALITY IN TROPICAL BUILDINGS

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Abstract. Rapid densification in built environments has intensified IAQ challenges, underscoring the need for adaptive and sustainable filtration strategies. This study develops a biophilic design filter system for tropical indoor spaces, integrating moss (bryophyte species), coconut coir, and steam-activated coconut shell biochar as a modular green wall system. Material selection prioritized locally available, cost-effective materials with good air permeability for filtration. The proposed filter system was tested in a controlled environment using a comparative approach between experimental (with filter) and control (without filter) setups. 0.5 m x 0.3 m x 0.3m box with two ducting fans was used to make the testing chamber, that utilized as the controlled environment. The key IAQ parameters, including $PM_{2.5}$, PM_{10}, TVOC, CO_2, temperature, and humidity, were continuously monitored over 20 minutes period following pollutant generation. Specific pollutant decay function and linear regression analysis were applied to analyse the effectiveness of the filter system using removal rates and the Clean Air Delivery Rate (CADR). Results demonstrated that particulate removal, with decay constants increasing from 0.03 to 0.26 min^{-1} for $PM_{2.5}$ and from 0.00357 to 0.26 min^{-1} for PM_{10}. TVOC removal showed enhancement of 0.10 to 0.14 min^{-1}, while CO_2 reduction improved slightly (0.03 to 0.06 min^{-1}). This moss biochar integrated filter can be a low cost, waste derived, and scalable nature-based solution for enhancing IAQ in tropical indoor environments.

Keywords. *Biophilic Design, Indoor Air Quality, Coconut Shell Biochar, VOC, PM*

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1. Introduction

The increased number of dense indoor spaces due to rapid urbanization has led to poor indoor air quality (IAQ) due to the accumulation of ample air pollutants within the enclosed spaces. Among these VOCs are a broad class of carbon-based chemicals, which easily evaporate under low room temperature and persistent in the air for long periods and difficult to degrade, making them a critical pollutant to measure in the study (Han et al., 2010; Li et al., 2024). Meantime PM_{10} leads to significant respiratory disorders such as asthma, and $PM_{2.5}$ is also highly critical because it can easily penetrate the deeper parts of the lungs (Nandan et al., 2021). Further, variations in CO_2 also lead to headache, fatigue, sick building syndrome, sleepiness and reduced cognitive function in less ventilated indoor environments (Cao et al., 2022).

This situation has escalated the demand for sustainable architectural approaches that enhance indoor environmental quality and occupant well-being (Goel et al., 2022). Biophilic Design (BD), an extension of biophilia, represents a nature-based strategy that integrates living systems (plants, trees, and green walls) into buildings to improve human health, comfort, and IAQ (Dalay & Aytaç, 2021; Jung et al., 2023).Green walls (GW) as BD elements improving IAQ, visual aesthetics, and psychological well-being through nature-based exposure (Hong et al., 2017). Moss emerged as a low maintenance, cost effective, and locally

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abundant BD solution for the tropical setting of Sri Lanka due to its ability to eliminate air borne pollutants (Fernando & De Silva, 2025; Singh & Choudhary, 2025). However, its standalone performance is limited for air filtration (Ajien et al., 2023). As a result, researchers have proposed various developments. For instance, the coconut shell biochar has been used to remove gaseous pollutants (Ajien et al., 2023; Gong et al., 2019; Wang & Wang, 2019). Additionally, optimized substrate configurations have been developed to improve VOC biodegradation and overall pollutant removal as well (Nissar et al., 2025; Pettit et al., 2018a). This study experimentally evaluates the BD integrated modular approach air filter as a GW enhancement system for tropical dense indoor environments, demonstrating its effectiveness as a future-adaptive facility solution that supports sustainable IAQ management through renewable waste-derived materials integrating with flexible biophilic design.

2. Literature view

2.1 USE BD FOR IAQ ENHANCEMENT

Rapid urban densification behaviour and climate changes raise concerns in indoor environmental quality intensely in tropical indoor settings, where high humidity, limited natural ventilation, and elevated pollutant levels can compromise occupant health and comfort (Juangjandee et al., 2022). In response, BD solutions emerged as the best strategy for indoors, which extends beyond the aesthetic appearance to reconnect indoors with nature elements that support occupant wellbeing and improve indoor air quality (Zhong et al., 2022). Recent studies recognized that BD interventions are enhancing thermal comfort while regulating microclimate effects, and enhancing human wellbeing through vegetation, natural materials, and biologically active substrates (Matheson et al., 2023; Moya et al., 2019). Indoor environments are mainly polluted from air pollutants like VOC, PMs, ozone, oxides of carbon and Sulphur, heavy metals, and biological contaminants (Morgan et al., 2022; Nandan et al., 2021). Exposure to these pollutants can trigger various toxicity mechanisms indoors and lead to health problems, impaired cognitive abilities, and reduced productivity (Kumar et al., 2023). Therefore, it is obvious that IAQ is a fundamental factor affecting people's well-being.

2.2 PLANT-BASED BDS

Plants are increasingly identified as a biological element that engages with indoor air by physically capturing contaminants, absorbing them physiologically, and transforming them through microbial processes (Matheson et al., 2023). Therefore, plant-based solutions have gained a growing emphasis as an effective BD strategy to address these IAQ issues (Fernando and De Silva, 2025; Kumar et al., 2023).

Green wall systems are recognized as an attractive BD design that can effectively be used as botanical air purifiers when properly designed (Goel et al., 2022). When considering BD aspects to plants in IAQ, vascular plant species as well as bryophytes, liverworts and mosses can be used to form the modular biophilic installations as they effectively enhance the air quality and foster healthier living spaces by contributing to eliminating pollutants, increasing humidity, and boosting visual appeal (Dela Cruz et al., 2014; Irga et al., 2018). Therefore, more recently, non-vascular plants like mosses have emerged as a promising alternative for IAQ.

For vascular plants (VP), the air pollutants elimination highly depends on the leaf traits, whereas the uniform spreading and entire thallus surface of the moss allows for pollutant uptake from the whole area (Sæbø et al., 2012). Many VPs show selectivity in VOC absorption, while the moss absorbs both lipophilic VOCS (benzene) and hydrophilic VOCs (formaldehyde) without any selectivity (Fernando & De Silva, 2025; Gong et al., 2019). Meantime, due to the sensitivity of moss, they act as bio-indicators to determine the polluted environments. Simultaneously, moss shows notable morphological and physiological adaptability in response to environmental stressors, with a potential for heavy metal uptake as well (Singh & Choudhary, 2025). Further, moss is a non-soil-based plant, unlike the VP, which heavily relies on the water and nutrients from the soil for its root growth (Kumar et al., 2023). When developing modular air filters, the load optimization needs to be considered. Perini et al. (2020) demonstrate moss is a low cost, low maintenance option which suitable for large scale GW applications, due to its low requirements for water and nutrients, and high desiccation tolerance. Therefore, this study is focused on the moss plant as a BD element in the filter development.

GW studies emphasized that substrate properties such as air filled porosity, moisture retention and water holding capacity, permeability, nutrient retention and structural stability influence the pollutant removal process and pressure drop characteristics (Pettit et al., 2017, 2018). Many substrates can be used for plants, such as peat moss, coconut coir, perlite, rockwool, compost, kenaf fibre, mineral wool, epiweb, xiam, and geotextile (Armijos-Moya et al., 2022; Fernández-Cañero et al., 2012; Ibrahim et al., 2018; Pettit et al., 2018a). Among these, coconut coir (CC) was identified as a natural fibrous medium in many studies, highlighting it as a promising material for tropical regions due to its abundance, low cost, biodegradability and potential mechanical durability (Ru et al., 2023). Furthermore, its high total porosity and favourable air and water balance in the root zone promote healthy root growth for plants, unlike the soil-based substrates (Okul & Campagnaro, 2023; Pettit et al., 2018b). Moreover, CC can be identified as a natural fibrous medium, making it suitable as a filter panel medium to regulate pressure drop across the panels (Ru et al., 2023). These factors support CC as an effective fibrous medium while providing a suitable plant-growing substrate.

2.3 USE BIOFILTERS FOR IAQ ENHANCEMENT

Biofilters also known as botanical air purifiers, primarily utilize nature-based materials such as diverse living plants and any sustainable alternatives for air purification (Chong et al., 2021; Montaluisa-Mantilla et al., 2023; Pettit et al., 2018a; Ravindra & Mor, 2022), along with various microbial communities, engineered substrates, or growth media such as activated carbon, biochar, perlite, coconut fibre, or compost, which provide both adsorption capacity and microbial establishment surfaces (Armijos-Moya et al., 2021; Pettit et al., 2018a) to eliminate pollutants from indoor air. Modular active biofiltration systems made of vegetation have a sharp focus on substrate development, as it is the main biofiltration matrix, which enables microbial degradation, polluted mass transfer between panels and adsorption (Moya et al., 2019).

Biochar is a carbon rich and low-cost renewable biomaterial derived from biomass and has been used for several environmental applications, such as wastewater treatment, soil remediation (Wang et al., 2017), adsorbent for contaminant removal in aqueous systems (Alkurdi et al., 2019), biofuel production, energy storage, carbon sequestration, and pollutant remediation (Ahmed et al., 2024; Gwenzi et al., 2021). However, it is a relatively underdeveloped application for indoor air purification filters, despite growing demand for low cost and sustainable alternative materials (Yang et al., 2018). Among various biochar production feedstocks, coconut shell (CS) could be an economical and sustainable solution for Sri Lanka, as it generates approximately 2.5 million tons of coconut biomass for the year 2019 (Ajien et al., 2023). Converting this biomass into biochar offers a sustainable solution to waste management while providing a high-performance filtration material.

Though various biomass sources, such as woody biomass, agricultural residues, manures, and food waste can be used for biochar production, the selection of feedstock highly influences the physicochemical properties and adsorption performance of the final product(Alkurdi et al., 2019; H. Wang et al., 2017; J. Wang & Wang, 2019). Associated with these alternatives, nut and fruit shell-based biochars, specifically CS, exhibit fixed carbon content and higher lignin, well-developed microporosity, higher surface area, and superior mechanical strength, making them more suitable for air filtration applications (Ajien et al., 2023; J. Wang & Wang, 2019).

In air purification, Coconut shell Biochar (CSB) utilizes the adsorption mechanism that purifies the indoor air even under low concentrations of pollution levels (Du et al., 2020; Zouari et al., 2024). Since the raw biochar does not provide sufficient adsorption capacity, CSB is often activated physically or chemically to improve its pollutant removal properties (Wang & Wang, 2019). Mechanistically, microporosity, pore structure and specific surface area are the main factors affecting the CO_2 capture (Bamdad et al., 2018), while VOC removal is subjected to physical adsorption, partitioning, and weak molecular attractions between aromatic carbon structures (π - π interactions) for aromatic VOCs (Zhang et al., 2020; Zhao et al., 2022). Although CSB currently exhibits limited $PM_{2.5}$ and PM_{10} trapping efficiency, the proven particulate capture performance of other biochar variants justifies the need for its experimental assessment as well.

2.4 AIR POLLUTANTS IN INDOOR SPACES

The Environmental Protection Agency, (2026) has identified that the particle diameter of 2.5 and 10 micrometres (i.e., PM2.5 and PM10) are critical metrics for assessing indoor air quality (IAQ) while World Health Organization WHO, (2021) recommended the 24-hour safe limits as ≤ 15 µg/m³ for $PM_{2.5}$ and ≤ 45 µg/m³ for PM_{10} due to their significant health impacts in enclosed spaces. Similarly, exposure to the TVOCs also leads to long term health effects, and the WELL standard recommends that TVOCs should remain below 500 $\mu g/m^3$ for healthier indoor spaces. Carbon Dioxide (CO2) is a gaseous pollutant, although not directly toxic in normal environmental conditions, and it is considered an indicator of ventilation requirements (Persily, 2021). Further, ASHRAE (2025) suggests that CO_2 levels should be maintained below 800 ppm to ensure adequate ventilation. Additionally, temperature and humidity were considered as supporting environmental parameters, as they affect the pollutant behaviour, emission rates, and occupant comfort (Kumar et al., 2023).

Indoor environments in both households and offices are exposed to a range of common air pollutants as discussed above, which mainly originate from sources such as cigarette smoke, mosquito coils, incense burning, fuel combustion, building materials, furnishings, office equipment, cleaning products, and high occupancy density (Fohimi et al., 2022; Morgan et al., 2022; Nandan et al., 2021).

3. Methodology

3.1 EXPERIMENTAL DESIGN

To reach the aim of this study, the moss, coconut coir and coconut shell biochar integrated air filter was designed and tested for the IAQ in a controlled tropical environment by assessing PM2.5, PM10, TVOC, CO2, temperature, and humidity. The experiment was conducted at the University of Moratuwa, Sri Lanka, replicating a tropical indoor environment with a temperature of 27 ± 3°C and relative humidity of 75 ± 10%. Two setups were investigated

1. **Experimental condition** performed with a filter unit to assess the IAQ
2. **Control Condition** performed without the filter unit as a baseline for comparison

Figure 1 illustrates the developed setup for the experiment.

3.1.1 Actual Setup

Figure 1, Actual Experiment setup (1) control (2) Experimental

A tightly sealed acrylic flow through chamber (FTC) (0.5 m x 0.3 m x 0.3m) made of polypropylene (Figure 1) was used in this experiment to be compatible with the filter design (0.3m x 0.1m x 0.3 m) to assess the pollutant removal. The top of the FTC was designed to place the filter unit inside the chamber, and ducting was attached to one side of the FTC, connected to the other end to the combustion chamber, which was attached upstream, where pollutants were generated, as illustrated in Figure 1, for both control and experimental conditions. There were two 12 V DC 4020 fans (40 × 40 × 20 mm) connected to the combustion chamber and FTC to improve the suction of the air pollutants. Once the air stream passed through the filter module, it flowed to a secondary exhaust chamber through the flexible duct containing instruments to collect air samples and measure the concentration of pollutants. An additional 12 V DC 4020 fan was installed at the exhaust outlet to maintain continuous airflow and support vacuum-driven pollutant movement through the system (Figure 1). This follows the methodology used by Pettit et al. (2017).

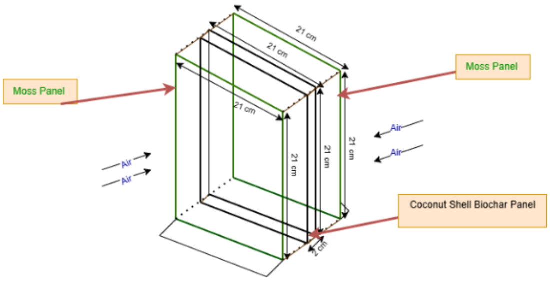

Figure 2, Filter Configuration- Panel positions moss and coconut shell biochar

Moss panels were developed with the coconut coir as the base layer due to its excellent air permeability. A thin red brick clay layer was applied to the top of the coconut coir layer to improve nutrient availability and provide adequate anchorage for moss growth, while carefully maintaining the airflow properties of the panel system. Moss panels were covered with cushion moss species grown from a pulp prepared using local materials, such as washed moss, aloe vera gel, lime and compost tea, in the ratio of 2:1:1:1 (tablespoons). Steam activated coconut shell biochar was packed as 2cm thick layer between two moss panels while carefully maintaining the air flow properties of the air filter panels. Figure 3 illustrates the image of these panels. Air quality measurements were carried out by using a CO_2 meter, PM meter and VOC meter in this experiment.

Figure 3, Actual setups (1) - Filter configuration including panels, (2) the front panel installed with moss (3) filter installation in the experiment chamber

3.2 EXPERIMENTAL PROCEDURE

To create the polluted environment inside the FTC, multiple pollutant sources were introduced into the combustion chamber to replicate the most common air pollutants in dense built environments. These include two incense sticks and cigarette smoke ignition, evaporation of commercial paint thinner and burning of mosquito repellent, following pollutant generation approaches reported in previous studies (Chong et al., 2021; Gong et al., 2019; Morgan et al., 2022). Air pollutant parameters were measured immediately after pollutant generation once the peak concentration (C_0) was achieved at t=0 min, followed by continuous monitoring over a 20-minute sampling period for each parameter tested. A reduction to 5% of the initial mass concentration within the 20-minute duration was considered the lowest acceptable pass value, following the methodology outlined by (Chong et al., 2021).

3.3 EQUATIONS FOR THE DATA ANALYSIS

Numerous chamber studies and air filter studies commonly model the removal of air pollutants as first-order exponential decay process, which signifies the removal rate at any time is proportional to the concentration present. This assumption is validated in all cases, such as natural deposition, leakage, and air filter action, which exist and are given by equation 1 (Küpper et al., 2019; Schmohl et al., 2022).

$$C(t)=C_0^{e-kt} \qquad (1)$$

For a strong quantitative analysis, this exponential form (function 1) is transferred to natural logarithm to eliminate the significant variance in observed data and fit with the standard decay analysis protocols in ASHRAE and IAQ studies, where the total rate decay constant was analysed using equation 2 (Chong et al., 2021; Stephens et al., 2022).

$$K = - [\ln (C / C_o)]/t \qquad (2)$$

where: C =Concentration at time t, C_o=Peak concentration, t =Time (min), K= Total decay rate constant (min^{-1})

Next, this logarithm equation was used to derive the linear equation in the form of;

$$Y=m\ X \qquad (3)$$

Where Y= $\ln (C / C_o)$, X= t, slop m= -k,

The concentration ratios, $\ln(C/C_o)$, were plotted against time (t) to determine the decay constant (k) for both control and experimental conditions.

3.3.1 Clean Air Delivery Rate (CADR)

Clean Air Delivery Rate (CADR) is measured to evaluate how effectively an air filter removes pollutants under the test conditions. Simply, this signifies the volume of clean air produced per unit time by the system (Chong et al., 2021; Lo et al., 2024; Schmohl et al., 2022; Shaughnessy & Sextro, 2006).

CADR was calculated using Equation 4;

$$CADR= V (K - K_n) \qquad (4)$$

Where: V = Volume of test compartment (m^3), K = Decay constant with filter, K_n = decay constant without filter

3.3.2 Efficiency of pollutant removal

The efficiency of the pollutant removal was calculated to measure the pollutant variation over time. As suggested in Jagnade & Panwar (2024), Equation 5 was used to measure the pollutant removal efficiency.

$$\eta = 100\ (1 - C / C0\ ) \tag{5}$$

where, η - is the removal efficiency, C_0 - is the maximum initial concentration, C- Concentration after 20 minutes

4. Results and Discussion

Total decay rate constant (equation 2) of the developed filter was calculated using IBMS SPSS 31 to minimize errors in observed data and to get a statistically fit estimation for the total decay rate constant (K).

4.1 PM2.5 LEVEL

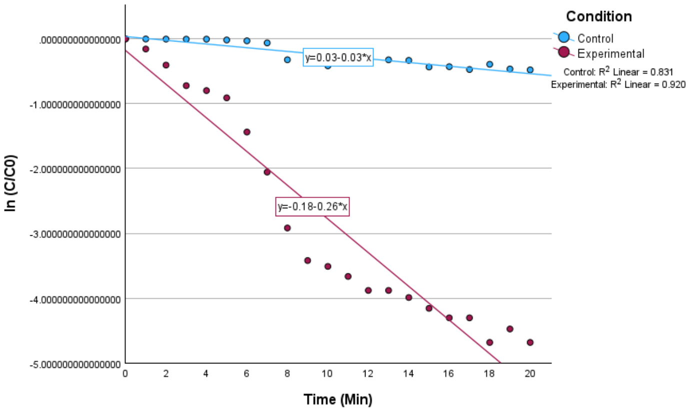

Figure 4, PM2.5 Level

Figure 4 illustrates the decay of the $PM_{2.5}$ concentration trend over 20 minutes. The regression equation obtained from SPSS analysis for the control condition was y=-0.03x + 0.03, indicating a small negative slope. The decay constant for this experiment was the absolute value of the slope, $K_{control} = 0.03\ min^{-1}$. This relatively low decay rate in the control condition shows natural removal mechanisms within the chamber, such as surface deposition on chamber walls, minor air leakage and gravitational settling of particles. The experimental condition demonstrated a relatively higher negative slope (i.e. linear decrease of y=-0.26x - 0.18) compared to the control condition. The decay constant obtained from equation 2 was $K_{exp} = 0.26\ min^{-1}$, which is substantially higher than the control value, implicating moss and CSB effectively adsorbing the particles. This enhanced decay rate validates the effectiveness of the developed moss–biochar filter in accelerating $PM_{2.5}$ removal within the chamber.

4.2 PM10 LEVEL

Figure 5 illustrates that the ln(C/C₀) values of PM₁₀ in the control environment exhibited a gradual and relatively weak linear decrease over time. The decay constant was $K_{control}$ =0.00357min^{-1}, reflecting a very slow natural removal rate within the control chamber.

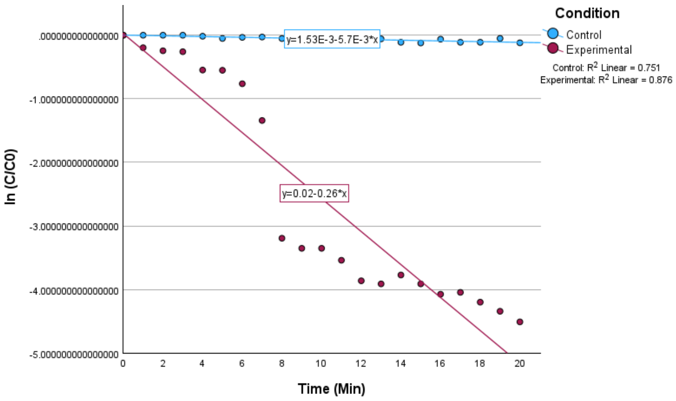

Figure 5, PM 10 Level

This limited reduction can be attributed to passive mechanisms. Simultaneously, under experimental conditions, a steeper linear decline in ln(C/C₀) with time was observed (Figure 5). The regression equation obtained was y=-0.26x+0.02, with a higher R^2 = 0.876 value, which validated the applicability of the first-order decay model for the filter operation. The decay constant was K_{exp} =0.26 min^{-1}, which is substantially greater than under control conditions. This difference between the control and experimental decay constants confirms that pollutant reduction is largely driven by the filtration system rather than natural decay processes.

4.3 TVOC LEVEL

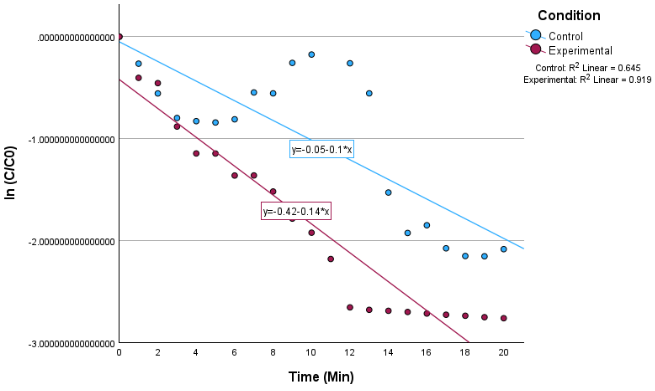

Figure 6, TVOC Level

Under control conditions (Figure 6), the ln(C/C₀) values show a normal decreasing trend over time, while the data exhibit noticeable variability around the regression line. This reduction can be attributed to passive removal mechanisms such as gravitational settling and surface deposition. In contrast, the experimental condition illustrated in Figure 6 demonstrates a more consistent linear decline in

$\ln(C/C_0)$ with time. The regression equation was determined as y=-0.14x-0.14, with a higher $R^2 = 0.919$, indicating a strong linear relationship and confirming that the decay closely follows first order decay model during filter operation. The decay constant derived was $K_{exp} = 0.14$ min^{-1}, which is higher than that observed under control conditions. This shows a potential impact for the TVOC pollutant removal.

4.4 CARBON DIOXIDE LEVEL

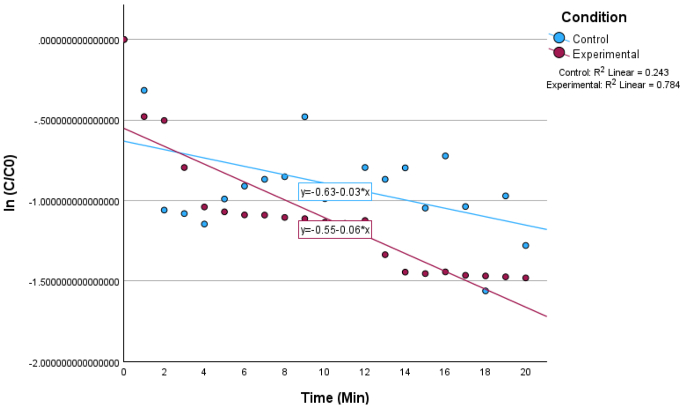

Figure 7, CO2 Level

The CO2 concentration trend for both control and experimental followed first order kinetic trend as illustrated by the linear relationship between $\ln(C/C_0)$ and time (Figure 7). In the control condition, the decay constant obtained was $K_{control} = 0.03$ min^{-1}. Further, the relatively low coefficient determination ($R^2 = 0.243$) determines a weak conformity to the first-order decay model, suggesting limited natural CO_2 removal within the chamber. In contrast, in the experimental condition y=-0.55-0.06X and decay constant as $K_{exp} = 0.06$ min^{-1}. This was approximately two times greater than that of the control, indicating an enhanced CO_2 removal rate due to the filter system. Table 1 shows the data collection on both experimental and control conditions.

Table 1, IAQ parameters on Control (C) and Experimental (E) conditions

Time (Min)	**PM 2.5 (µg/m³)**		**PM 10 (µg/m³)**		**TVOC (ppm)**		**CO2 (ppm)**		**Temperature (C°)**		**Humidity (%)**	
	C	E	C	E	C	E	C	E	C	E	C	E
0	1904	1406	2000	2000	7763	7763	3231	3231	30.3	31.4	75.8	75.8
1	1900	1202	2000	1643	5956	5182	2356	2002	30.4	30.6	73.5	72.3
2	1897	938	2000	1566	4447	4920	1120	1954	30.3	31.3	73.5	73.3
3	1894	683	2000	1543	3495	3213	1096	1459	30.6	31.8	73.4	73
4	1895	633	1968	1156	3388	2468	1027	1142	30.8	31.8	72	73
5	1871	566	1900	1152	3344	2466	1200	1108	31.4	31.8	71	74.2
6	1847	334	1934	932	3450	1987	1300	1087	31.4	31.7	70	72.6
7	1789	180	1944	523	4490	1989	1356	1086	31.6	31.8	70.2	72.1
8	1379	76	1898	82	4451	1699	1378	1070	31.8	31.7	69.6	71.9
9	1324	46	1898	70	6001	1302	2000	1062	31.8	31.8	68.9	71.7

10	1256	42	1878	70	6513	1134	1202	1039	31.8	31.9	68.6	72.7
11	1322	36	1889	58	2615	876	1234	1031	31.9	31.8	72.1	72.9
12	1345	29	1878	42	5978	545	1459	1050	31.9	31.8	69.9	72.7
13	1378	29	1888	40	4451	532	1356	849	31.7	31.8	68.9	71.9
14	1366	26	1789	46	1682	527	1456	762	31.67	31.8	73.4	71
15	1234	22	1770	40	1131	521	1134	755	32	31.9	73.4	72.1
16	1239	19	1878	34	1220	513	1568	763	31.68	30.8	72	71.9
17	1187	19	1789	35	973	507	1145	747	32.67	32	69.1	71.7
18	1286	13	1789	30	902	502	678	744	32.67	32	69.5	71.6
19	1196	16	1901	26	900	495	1223	740	32.59	29.9	68.8	71.6
20	1180	13	1774	22	965	490	899	735	32.89	30	68.6	71.6

4.5 CLEAN AIR DELIVERY RATE (CADR)

Performance of CADR is shown in Table 2. Results show that the proposed filter is more effective for removing PM 10, PM2.5 and TVOC and gives the least performance for CO_2.

Table 2, CADR and efficiency of pollutant removal (EPR) in control and experimental setups

Pollutant	K control (min^{-1})	K exp (min^{-1})	K filter (min^{-1})	CADR (m^3/min)	CADR (m^3/h)	EPR (%) Exp setup	EPR (%) Control setup
$PM_{2.5}$	0.030	0.260	0.230	0.010	0.621	99.08 %	38.02%
PM_{10}	0.00357	0.260	0.25643	0.012	0.692	98.9 %	11.3%
TVOC	0.10	0.140	0.040	0.002	0.108	93.79%	87.57%
CO_2	0.03	0.06	0.03	0.00135	0.081	77.25%	72.17%
Humidity	–					−5.5%	−9.50%
Temperature	–					4.45%	+ 8.55 %

5. Discussion

The proposed filter demonstrated high removal efficiencies of 99.08% for $PM_{2.5}$, 98.9% for PM_{10}, and 93.79% for TVOC, confirming the strong combined effect of adsorption, biological processes and mechanical effect. When compared with moss-only green walls (Fernando & De Silva,2025), which reported 16.16% formaldehyde removal and 22.89% CO_2 reduction. The present integrated system significantly increased the TVOC removal to 93.79% and the CO_2 reduction to 77.25%.This noted improvement addressed the high microporous structure and specific surface area of steam activated coconut shell biochar, which enhances VOC adsorption through van der Waals forces and pore filling, as mainly identified for the activated carbon materials (Gwenzi et al., 2021; Nuryana et al., 2020; Zakaria et al., 2023). Similar studies also proved that integrating activated carbon with botanical biofilters substantially improves VOC removal performance compared to plant-based systems alone (Pettit et al., 2018b). In contrast, when compared with coconut shell biochar only air purifiers (Zakaria et al., 2023)) the improvements were relatively marginal ($PM_{2.5}$ improved by ~1% and PM_{10} by ~2%), suggesting that the moss coir combination additionally provides particle capture. However, there was a 4% improvement in TVOC removal, which indicates that the combined biological and adsorption mechanisms performed well. Further, the observed CO_2 reduction in this experiment confirmed that the photosynthetic activity of the moss utilized CO2 as a carbon source under sunlight exposure, consistent with previous researchers' findings (Fernando & De Silva, 2025; Sevik et al., 2017).

Notwithstanding the intense filtration performance, several practical considerations should be addressed in real-world applications. It needs a periodic moisture maintenance to sustain moss growth (Perini et al., 2020) while the adsorption capacity of CSB depends on the pollutant exposure amount; Therefore, as mentioned in previous research studies (Gwenzi et al., 2021; Wang & Wang, 2019), saturation levels must be monitored, with timely replacement or regeneration required to maintain efficiency. Moreover, long-term durability of the substrate and potential pressure drop across the filter media require further investigation (Pettit et al., 2018a). This system is most applicable for dense indoor spaces such as high-rise residential units, office partitioned work areas and smoking areas, particularly in tropical buildings with limited ventilation. Over the long term, occupants may benefit from exposure reduction to PMs and VOCs, improved respiratory health, enhanced cognitive performance, and overall well-being due to improved IAQ and biophilic integration, as highlighted by other researchers (Cao et al., 2022; Gomes et al., 2025).

6. Conclusion

This study experimentally evaluated a biophilic green wall filter integrating moss, coconut coir, and coconut shell biochar for its effectiveness in removing particulate matter ($PM_{2.5}$, PM_{10}), TVOC, and CO_2 while influencing indoor microclimatic conditions within a controlled chamber environment. The findings revealed there was a significant enhancement for $PM_{2.5}$ and PM_{10}. There was a moderate impact on TVOC reduction, indicating that contact time-dependent pollutant reduction by the biochar. In contrast, CO_2 reduction showed only marginal improvement, suggesting that biological assimilation by moss and physical adsorption by biochar and coconut coir provide limited removal under short time durations.

However, this study was limited to a small-scale experiment and short-term experimental duration, which could not fully represent real indoor environmental conditions. Factors such as long-term performance, biochar saturation, maintenance requirements, and varying airflow conditions were not broadly investigated. Therefore, future studies should focus on full scale real world uses, optimization of airflow and contact time, and replacement strategies for biochar to ensure long-term performance. Overall, this study provides a quantitative foundation for developing biochar integrated BD systems for densely occupied indoor spaces by further adapting them as partition walls or green curtains in spaces such as offices and smoking areas.

7. References

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