

Vertical Green Walls for PM Reduction

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Abstract

Indoor particulate matter (PM), especially PM_{2.5} and PM₁₀, significantly impacts indoor air quality and is linked to detrimental respiratory and cardiovascular health outcomes in office settings. This research assessed the efficacy of an indoor vertical green wall system in diminishing particulate matter levels within a populated office setting. A triadic experimental investigation was performed in March across three successive years under similar seasonal circumstances within a dynamic office environment. The study included an initial phase devoid of flora, succeeded by the implementation of vertical green wall systems cultivated with *Epipremnum aureum* and *Philodendron scandens*. The daily mean concentrations of PM_{2.5} and PM₁₀ were assessed under each experimental condition and analyzed using paired t-tests after verifying the normality of the paired differences. The findings indicated substantial enhancements in indoor air quality after the implementation of the green wall systems. Average PM_{2.5} levels diminished from 34 µg/m³ in baseline conditions to 26 µg/m³ with *Epipremnum aureum* and 28 µg/m³ with *Philodendron scandens*, reflecting decreases of 22.4% and 15.7%, respectively. In a similar manner, average PM₁₀ levels diminished from 55 µg/m³ to 36 µg/m³ and 42 µg/m³, indicating declines of 35.9% and 24.8%, respectively. Statistical evaluation validated that the decreases in PM_{2.5} and PM₁₀ levels were statistically significant ($p < 0.05$). Among the assessed species, *Epipremnum aureum* demonstrated a markedly superior efficiency in particulate matter removal compared to *Philodendron scandens*. These results indicate that indoor vertical green wall systems serve as a sustainable approach to reducing particulate matter and improving indoor environmental quality.

Keywords: Biofiltration, Indoor Air Quality, PM_{2.5}, PM₁₀, Particulate Matter Removal, Vertical Green Wall.

Introduction

Indoor air quality has emerged as a significant issue in contemporary urban settings, where individuals allocate a considerable amount of time to enclosed environments. As urbanization progresses worldwide, individuals predominantly occupy offices, educational facilities, commercial structures and homes, rendering the exposure to indoor pollutants increasingly significant. Subpar indoor air quality has been linked to diminished comfort, decreased productivity and an increased likelihood of both acute and chronic health issues. Particulate matter (PM_{2.5} and PM₁₀) is acknowledged as a significant environmental health hazard among indoor pollutants, owing to its capacity to infiltrate the respiratory system and exacerbate respiratory, cardiovascular and pulmonary conditions (1, 2). Indoor particulate matter emanates from multiple sources, such as occupant activities, office machinery, cleaning processes, construction materials and the intrusion of external pollutants. Thus, minimizing indoor particulate levels has become a crucial goal in

creating healthy and sustainable structures. PM_{2.5} comprises particles that possess an aerodynamic diameter of 2.5 µm or smaller, allowing them to infiltrate the lungs extensively and, in certain instances, access the bloodstream. PM₁₀ particles, despite their larger size, can still provoke irritation in the upper respiratory system and lead to inflammation.

The levels of particulate matter within structures are affected by the interplay of indoor production, outdoor entry, ventilation effectiveness and occupant actions. In workplace settings, habitual tasks like ambulating, printing, duplicating documents and rearranging furniture can disturb settled dust, leading to persistent variations in airborne particulate levels. In a comparable manner, outdoor particulates can infiltrate indoor environments via ventilation systems, windows, doors and architectural apertures, especially in urban and industrial locales where ambient pollution is significantly heightened (2). These active interactions generate indoor pollutant

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scenarios that significantly diverge from those seen in regulated laboratory settings, underscoring the necessity for pragmatic mitigation approaches that function efficiently in actual operational contexts. Traditional methods for controlling particulate matter predominantly depend on mechanical ventilation and filtration systems. Despite their efficacy, these systems frequently necessitate ongoing energy consumption, regular maintenance and operational expenses (3). In many existing buildings, inadequate maintenance or declining filter performance may reduce their long-term effectiveness. In light of increasing sustainability concerns, nature-based solutions have surfaced as viable alternatives for enhancing indoor environmental quality. Vertical green wall systems incorporate vegetation within building interiors, providing numerous advantages such as air purification, thermal regulation, aesthetic improvement and occupant wellness (3, 4).

In addition to their aesthetic charm, indoor green walls are linked to wider environmental and human-focused advantages. Prior research indicates that indoor plants can elevate perceived environmental quality, boost occupant wellness and foster healthier indoor environments while augmenting traditional building systems. Vertical green walls operate as passive systems, thereby providing an opportunity to diminish dependence on energy-consuming technologies while concurrently promoting sustainable architectural design. As a result, there has been a growing interest in integrating live plants into commercial and office spaces as companies pursue eco-friendly methods to enhance indoor environments.

The efficacy of vegetation in mitigating particulate matter is primarily due to the interception, deposition and retention of airborne particles on foliar surfaces. Plant attributes, including leaf area index, surface roughness, canopy density, trichome density and morphological traits, affect the ability of vegetation to capture airborne particles (5, 6). As airborne particulates traverse vegetation, they attach to leaf surfaces via physical and electrostatic forces before being retained on the foliage. Organisms with enhanced surface intricacy and thicker vegetation frequently exhibit superior particle retention due to their provision of expanded contact surfaces for pollutant accumulation. Prior studies have indicated that

vegetation can significantly diminish airborne particulate levels by functioning as a biological filter and facilitating particle deposition on leaf surfaces (7, 8). Nonetheless, a significant portion of the existing evidence has been obtained from controlled laboratory studies that may not accurately reflect pollutant dynamics in inhabited indoor settings (9).

While green infrastructure has shown encouraging outcomes for enhancing air quality in outdoor settings, applying these results to indoor contexts necessitates thorough assessment. Indoor settings display unique ventilation traits, occupancy behaviours and pollutant production processes that could affect plant efficacy in contrast to outdoor environments. Thus, empirical studies performed in authentic operational environments are crucial for ascertaining if the advantages noted in controlled trials can be reliably realised in inhabited structures (8, 9).

Moreover, few comparative studies have assessed the impact of plant species on particulate matter removal efficacy in indoor green wall systems. Most prior studies were performed in controlled laboratory settings, while the current research assesses green wall efficacy in a dynamic office environment marked by constant occupancy and regular operational activities. Variations in leaf morphology and surface traits may substantially influence pollutant capture efficiency; however, prolonged field studies provide limited evidence (10). The hypothesis posited that the implementation of a vertical green wall would markedly decrease indoor $PM_{2.5}$ and PM_{10} levels, with pollutant removal efficacy differing by plant species. This study examines how effective vertical green wall systems are at reducing particulate matter concentrations in an operational office setting by comparing baseline conditions with installations featuring *Epipremnum aureum* and *Philodendron scandens* under similar seasonal circumstances.

Materials and Method

Study Area

The research was conducted in Rabale, an industrial suburb of Airoli in Navi Mumbai, Maharashtra, India. The area comprises a mixture of industrial facilities and residential developments. The experimental site was located within the office premises of Winners Screen Pvt. Ltd., a

company engaged in the manufacturing of paint-processing equipment (approximate GPS coordinates 19.145406° N, 73.014338° E).

The selected environment demonstrated a dynamic indoor atmosphere where routine office and manufacturing operations resulted in continuous variations in indoor pollutant concentrations. Consequently, it is considered suitable for evaluating strategies to mitigate indoor particulate matter, as manufacturing and office activities may contribute to the generation and resuspension of airborne particulates indoors. The office was fitted with an air-conditioning system and all windows were kept closed during the monitoring period to reduce the impact of external climatic conditions and pollutant infiltration. The controlled conditions ensured that fluctuations in indoor pollutant levels could be predominantly ascribed to the experimental treatments.

The office encompassed a floor space of roughly 580 ft² (53.9 m²) and featured a ceiling height of 4.2 m, yielding an estimated room volume of 226.4 m³. Throughout the observation period, the office hosted an average of 16 individuals involved in standard administrative and production related

tasks. The HVAC system functioned according to its standard timetable from 09:00 to 19:00 hours on weekday and 9:00 to 15:00 hours weekends. The office predominantly utilized mechanical ventilation from the HVAC system, with all windows sealed throughout the monitoring period to reduce the impact of external particulate matter and to ensure uniform indoor environmental conditions during all experimental stages.

Plant Selection

Plant species were chosen following an extensive literature review, considering their adaptability to indoor environments, maintenance needs, market availability and established air-purification capabilities (11).

Epipremnum aureum

Epipremnum aureum, commonly known as Green Pothos, is a perennial evergreen climbing plant in the Araceae family, as shown in Figure 1. This species is extensively utilized in indoor settings due to its adaptability to low-light conditions, swift growth and low maintenance needs. The expansive leaf surface enhances the capture and accumulation of airborne particulates, while the microbial community associated with the root's aids in the overall air purification process (11).



Figure 1: *Epipremnum aureum*

Philodendron scandens

Philodendron scandens, as shown in Figure 2, was chosen due to its dense foliage, elevated leaf area index and appropriateness for indoor use. The expansive leaf morphology improves the acquisition and retention of suspended particles, while its adaptability to moderate light conditions

and indoor temperature fluctuations renders it appropriate for prolonged use in vertical greening systems. The species is readily accessible, economical and necessitates minimal upkeep, rendering it appropriate for practical application (11).



Figure 2: *Philodendron scandens*

Green Wall System Design

The vertical green wall structure was fabricated from lightweight aluminium and measured approximately 7 feet by 3 feet. The structure comprised six horizontal and three vertical frame members, creating several planting compartments. The framework was reinforced by a stainless-steel collection tray featuring a drainage outlet and control valve for the expulsion of surplus water. Plastic modular bio wall panels, measuring 150 mm × 450 mm, were affixed to the framework via an interlocking mechanism. One hundred fifty-six planting modules were installed in the front and rear sections of the structure. Each module included a separate planting pot equipped with drainage features.

A grid-based pipeline system was incorporated into the framework for an automated drip irrigation network. Each planting module was equipped with individual control valves to guarantee consistent water distribution. Surplus irrigation water was collected in the stainless-steel tray and channelled through the drainage system for possible reuse. An automatic timer was used to regulate irrigation scheduling, ensuring uniform moisture levels throughout the experimental duration.

The substrate comprised a blend of cocopeat and vermicompost. After planting, the vegetation was allowed to acclimatize to the indoor environment before monitoring began.

Monitoring Instrumentation

Concentrations of indoor particulate matter were assessed utilising a calibrated AWAIR Active Space air quality monitoring device. The device consistently monitored PM_{2.5} and PM₁₀ concentrations during the experimental duration. The monitoring device was placed at a typical occupant's breathing level within the office and maintained its position throughout all experimental phases to ensure measurement consistency.

Experimental Procedure

The research was executed utilising a three-phase experimental design in March over three successive years to ensure consistent seasonal conditions. In the initial phase (March 2024), indoor PM_{2.5} and PM₁₀ concentrations were continuously monitored for 30 days under baseline conditions, prior to the installation of a green wall system, thereby establishing reference pollutant levels for the study environment.

During the second phase (March 2025), a vertical green wall featuring *Epipremnum aureum*, as shown in Figure 3, was implemented within the office environment. Particulate matter concentrations were monitored for 30 consecutive days, using identical instrumentation and operational conditions, to assess the pollutant removal efficacy of the green wall system.



Figure 3: Green Wall - *Epipremnum aureum*

The vertical green wall of *Epipremnum aureum* situated in the functional office space is illustrated in Figure 3. The apparatus was strategically located at the centre of the workspace to optimise exposure to indoor air flow while ensuring standard office functions continued throughout the monitoring phase. The installation exemplifies the effective incorporation of a vertical green wall within an active work environment without interfering with regular operations. This configuration facilitated the assessment of particulate matter elimination in authentic indoor environments.

In the third phase (March 2026), the flora within the green wall was substituted with *Philodendron scandens*, as shown in Figure 4 and the monitoring protocol was reiterated over a comparable 30-day duration. Consistent monitoring protocols and

environmental conditions throughout all phases facilitated a direct comparison of species-specific efficacy in reducing indoor particulate matter concentrations and mitigating the effects of seasonal variability.

The vertical green wall of *Philodendron scandens* situated in the functional office space is depicted in Figure 4. The apparatus was strategically located at the centre of the workspace to facilitate access to indoor air flow while preserving standard office functions during the observation phase. The installation showcases the practical application of a vertical green wall featuring *Philodendron scandens* in an occupied office environment. This setup facilitated the evaluation of particulate matter elimination efficacy in authentic indoor environments.



Figure 4: Green Wall - *Philodendron scandens*

Environmental Monitoring

Indoor environmental conditions were consistently observed during the three experimental stages utilising the AWAIR Active Space air quality monitoring apparatus. The monitoring apparatus was positioned at the occupants' respiratory level and maintained in the same spot for the duration of the study to guarantee measurement uniformity. Daily mean values of temperature, relative humidity (RH) and carbon dioxide (CO₂) were

derived from ongoing measurements and utilized for further analysis. Table 1 illustrates the environmental parameters upheld throughout the three monitoring phases, indicating that temperature, relative humidity, air velocity and air changes per hour exhibited considerable stability during the study duration. These analogous conditions facilitated the reduction of environmental variability's impact on particulate matter assessments, with only slight discrepancies noted in CO₂ levels across the monitoring intervals.

Table 1: Environment Conditions

Parameter	Without Green Wall (2024)	<i>Epipremnum aureum</i> (2025)	<i>Philodendron scandens</i> (2026)
Temperature (°C)	23	25	25
Relative Humidity (%)	55	55	56
CO ₂ (ppm)	930	816	833
Air Velocity (m/s)	0.2	0.2	0.2
Air Changes per Hour (ACH)	6	6	6

Note: CO₂ = Carbon dioxide, m/s = metres per second, ACH = Air Changes per Hour, °C = degrees Celsius.

Temperature

The indoor air temperature was consistently observed during each monitoring phase to maintain uniform thermal conditions throughout the experiments. The mean indoor temperature recorded, as depicted in Table 1, was 23°C in the baseline phase without a green wall (March 2024), 25°C after the implementation of the *Epipremnum aureum* green wall (March 2025) and 25°C during the *Philodendron scandens* phase (March 2026). The minor fluctuation in temperature suggests that thermal conditions were consistent during the study, thus reducing the impact of temperature on particulate matter levels.

Relative Humidity

Relative humidity was consistently observed, as it affects the suspension, deposition and resuspension of airborne particulate matter. The mean indoor relative humidity remained at 55% throughout both the baseline and *Epipremnum aureum* observation intervals, whereas a marginally elevated average of 56% was recorded during the *Philodendron scandens* phase, as shown in Table 1. The slight fluctuation in relative humidity indicates that moisture levels were consistent during the experimental duration.

Carbon Dioxide (CO₂)

Indoor carbon dioxide levels were observed as a measure of occupancy and ventilation status. The mean CO₂ concentration during the baseline period was 930 ppm, whereas the average levels

recorded during the *Epipremnum aureum* and *Philodendron scandens* phases were 816 ppm and 833 ppm, respectively, as shown in Table 1. These metrics suggest that the indoor environmental conditions stayed within a similar range during the study, exhibiting typical variations linked to occupant presence and office activities.

Occupancy and Occupant Activities

The office housed an average of 16 individuals during standard working hours. Regular office functions encompassed administrative duties, personnel transitions, meetings, digital tasks and manufacturing-associated office activities. Occupancy trends and daily routines were largely stable across all three monitoring phases to reduce fluctuations in indoor particulate matter due to occupant actions.

Ventilation and HVAC Operation

The office utilized a centrally managed HVAC system that operated from 09:00 hrs to 19:00 hrs on weekdays and 09:00 hrs to 15:00 hrs on weekends, as shown in Table 1. All windows were kept shut during the entire monitoring duration to reduce the impact of external factors.

Statistical Analysis

Statistical evaluation was performed to ascertain if the detected fluctuations in PM_{2.5} and PM₁₀ levels across the experimental conditions were statistically significant. Given that the daily average pollutant levels were aligned with the respective calendar days throughout the three

experimental phases, paired t-tests were conducted to evaluate pollutant concentrations among the baseline condition (absent a green wall), the *Epipremnum aureum* green wall and the *Philodendron scandens* green wall. Before conducting hypothesis testing, the normality of the paired differences was assessed using the Anderson–Darling normality test. The findings validated that the paired differences adhered to a

normal distribution ($p > 0.05$), fulfilling the prerequisites for the paired t-test. Statistical evaluations were conducted using Minitab Statistical Software version 22.3 (Minitab LLC, State College, PA, USA). Statistical significance was evaluated at a 95% confidence threshold ($\alpha = 0.05$). Mean disparities, 95% confidence intervals (95% CI), t-values and p-values were documented for every paired comparison.

The paired t-test statistic was calculated using the following Equation [1]:

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} \quad [1]$$

Where, t = paired t-test statistic, $\bar{d}$ = mean of the paired differences, s_d = standard deviation of the paired differences, n = the number of paired observations.

Results

The monthly average concentrations of $PM_{2.5}$ and PM_{10} were assessed to evaluate the efficacy of the vertical green wall system under three experimental conditions:

- (a) baseline without a green wall,
- (b) a green wall featuring *Epipremnum aureum*, and
- (c) a green wall featuring *Philodendron scandens*.

Table 2 displays the daily $PM_{2.5}$ levels recorded under the three experimental conditions

throughout the monitoring duration. The data indicate persistently reduced particulate levels after the implementation of both vertical green wall systems in comparison to the baseline condition. *Epipremnum aureum* typically demonstrated the minimal daily $PM_{2.5}$ levels, whereas *Philodendron scandens* similarly diminished concentrations in comparison to the baseline. These findings suggest that vertical green walls may enhance indoor air quality in functioning office environments.

Table 2: $PM_{2.5}$ Concentrations ($\mu\text{g}/\text{m}^3$)

Date	Without Green Wall ($\mu\text{g}/\text{m}^3$)	Green Pothos ($\mu\text{g}/\text{m}^3$)	Green Philodendron ($\mu\text{g}/\text{m}^3$)
Mar 01	31	22	26
Mar 02	22	36	38
Mar 03	23	33	37
Mar 04	29	30	29
Mar 05	23	24	26
Mar 06	18	14	19
Mar 07	22	22	24
Mar 08	29	24	26
Mar 09	43	24	27
Mar 10	46	32	36
Mar 11	24	33	34
Mar 12	33	29	30
Mar 13	40	33	31
Mar 14	35	29	34
Mar 15	41	29	33
Mar 16	37	27	25
Mar 17	32	30	32
Mar 18	39	32	33
Mar 19	34	17	18
Mar 20	42	25	28
Mar 21	36	26	29
Mar 22	38	26	30
Mar 23	31	26	31
Mar 24	42	22	24
Mar 25	38	30	29

Mar 26	39	18	19
Mar 27	33	17	20
Mar 28	41	28	29
Mar 29	28	31	34
Mar 30	31	18	23
Mar 31	39	19	22

Note: PM_{2.5} = Particulate Matter with an Aerodynamic Diameter of $\leq 2.5 \mu\text{m}$, $\mu\text{g}/\text{m}^3$ = micrograms per cubic metre.

Figure 5 depicts the allocation of daily indoor PM_{2.5} levels under the three experimental scenarios. The violin plots indicate that both green wall installations altered the concentration distribution, resulting in lower values relative to the baseline condition. *Epipremnum aureum*

displayed the least average concentration and a more restricted distribution, while *Philodendron scandens* likewise showed a decrease compared to the baseline. The distribution patterns suggest enhanced removal of particulate matter in occupied office environments.

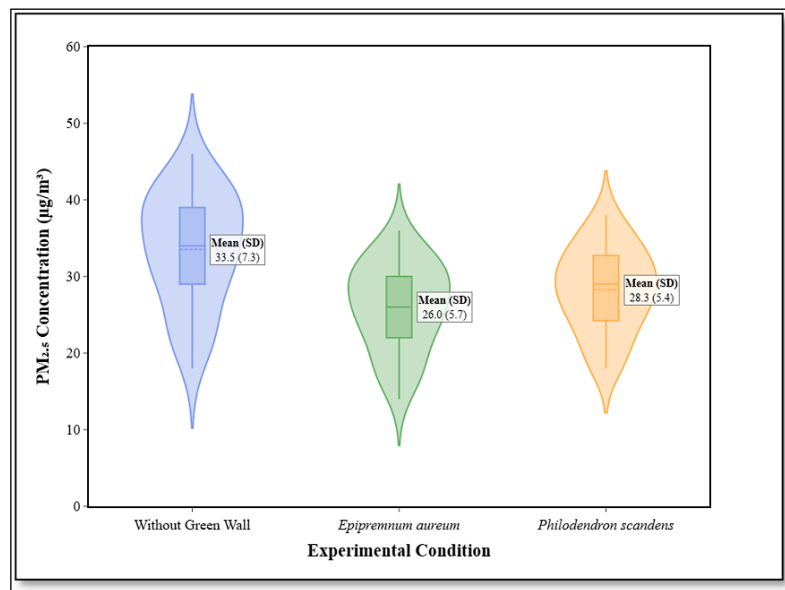


Figure 5: Distribution of Daily Indoor PM_{2.5} Concentrations

Table 3 presents the daily PM₁₀ concentrations recorded under the baseline condition and the two vertical green wall installations during the monitoring period. The results show a consistent reduction in PM₁₀ concentrations following the installation of both green wall systems compared with the baseline condition. *Epipremnum aureum*

generally exhibited the lowest PM₁₀ values, while *Philodendron scandens* also demonstrated lower concentrations than the baseline. These findings indicate that both plant species contributed to reducing coarse particulate matter under operational office conditions.

Table 3: PM₁₀ Concentrations ($\mu\text{g}/\text{m}^3$)

Date	Without Green Wall ($\mu\text{g}/\text{m}^3$)	Green Pothos ($\mu\text{g}/\text{m}^3$)	Green <i>Philodendron</i> ($\mu\text{g}/\text{m}^3$)
Mar 01	46	30	34
Mar 02	61	40	48
Mar 03	48	31	36
Mar 04	56	36	41
Mar 05	45	29	31
Mar 06	55	35	42
Mar 07	72	46	56
Mar 08	47	30	35
Mar 09	63	40	47
Mar 10	58	37	43
Mar 11	59	37	44
Mar 12	42	27	31

Mar 13	53	34	40
Mar 14	65	42	49
Mar 15	56	36	42
Mar 16	66	42	49
Mar 17	38	24	27
Mar 18	65	42	49
Mar 19	43	27	32
Mar 20	60	38	44
Mar 21	67	43	53
Mar 22	46	30	35
Mar 23	55	35	40
Mar 24	62	39	47
Mar 25	52	33	39
Mar 26	47	30	35
Mar 27	54	34	42
Mar 28	61	39	48
Mar 29	56	36	42
Mar 30	57	36	43
Mar 31	62	43	47

Note: PM₁₀ = Particulate Matter with an aerodynamic diameter of $\leq 10 \mu\text{m}$, $\mu\text{g}/\text{m}^3$ = micrograms per cubic metre.

Figure 6 illustrates the distribution of daily indoor PM₁₀ concentrations across the three experimental conditions. The violin plots demonstrate that both vertical green wall installations shifted the PM₁₀ distribution towards lower concentrations compared with the baseline condition. *Epipremnum aureum* exhibited the

lowest mean concentration and a more compact distribution, while *Philodendron scandens* also showed a noticeable reduction relative to the baseline. The distribution patterns further support the effectiveness of vertical green walls in reducing coarse particulate matter under occupied office conditions.

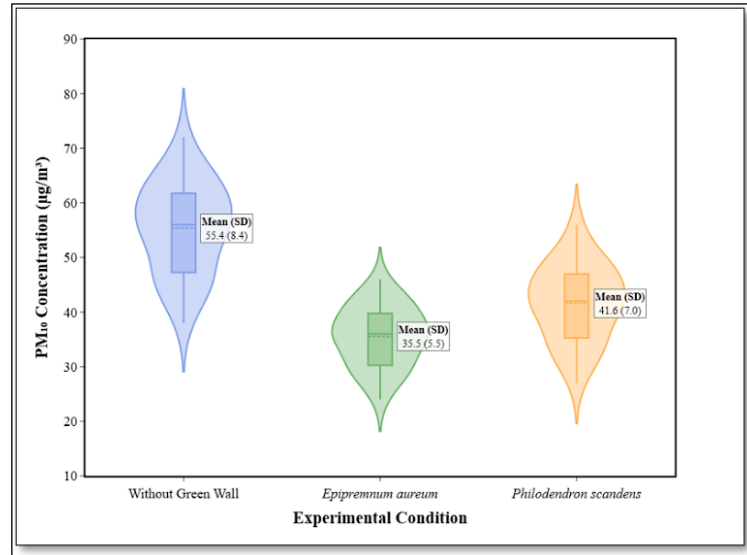


Figure 6: Distribution of Daily Indoor PM₁₀ Concentrations

Statistical Analysis of Particulate Matter Reduction

The Anderson–Darling test for normality was performed to ascertain if the paired differences met the prerequisites for parametric analysis. Table 4 displays the outcomes of the normality test for the PM_{2.5} paired comparisons among the three

experimental conditions. All comparisons yielded p-values exceeding 0.05, suggesting that the paired differences adhered to a normal distribution. These results validated that the normality assumption was met, thereby endorsing the application of the paired t-test for further statistical evaluations.

Table 1: Anderson–Darling Normality Test for Paired Differences (PM_{2.5})

Comparison	AD Statistic	p-value	Interpretation
No Green Wall – <i>Epipremnum aureum</i>	0.305	0.547	Normal
No Green Wall – <i>Philodendron scandens</i>	0.312	0.533	Normal
<i>Epipremnum aureum</i> – <i>Philodendron scandens</i>	0.701	0.061	Normal

Note: AD = Anderson–Darling, PM_{2.5} = Particulate Matter with an Aerodynamic Diameter of $\leq 2.5 \mu\text{m}$, p-value = Probability Value.

Table 5 presents the paired t-test results for PM_{2.5} across the three experimental comparisons. The analysis demonstrated that both vertical green wall systems significantly reduced PM_{2.5} concentrations compared with the baseline condition. *Epipremnum aureum* exhibited a greater average reduction of $7.52 \mu\text{g}/\text{m}^3$ (95% CI: 4.19–

$10.84 \mu\text{g}/\text{m}^3$, $p < 0.001$), whereas *Philodendron scandens* reduced PM_{2.5} by $5.26 \mu\text{g}/\text{m}^3$ (95% CI: 1.91 – $8.61 \mu\text{g}/\text{m}^3$, $p = 0.003$). Furthermore, *Epipremnum aureum* demonstrated significantly higher PM_{2.5} removal efficiency than *Philodendron scandens* (mean difference = $2.26 \mu\text{g}/\text{m}^3$, 95% CI: 1.54 – $2.98 \mu\text{g}/\text{m}^3$, $p < 0.001$).

Table 2: Paired t-test Results for PM_{2.5}

Comparison	Mean Difference ($\mu\text{g}/\text{m}^3$)	95% Confidence Interval	t-value	p-value	Interpretation
No Green Wall vs. <i>Epipremnum aureum</i>	7.52	4.19 to 10.84	4.62	<0.001	Significant
No Green Wall vs. <i>Philodendron scandens</i>	5.26	1.91 to 8.61	3.20	0.003	Significant
<i>Epipremnum aureum</i> vs. <i>Philodendron scandens</i>	-2.26	-2.98 to -1.54	-6.40	<0.001	Significant

Note: PM_{2.5} = Particulate Matter with an aerodynamic diameter of $\leq 2.5 \mu\text{m}$, CI = Confidence Interval, $\mu\text{g}/\text{m}^3$ = micrograms per cubic metre, p-value = Probability Value.

Prior to executing the paired t-test, the normal distribution of the paired differences was evaluated utilising the Anderson–Darling normality test. Table 6 displays the outcomes of the normality test for the PM₁₀ paired comparisons under the three experimental conditions. All

comparisons yielded p-values exceeding 0.05, suggesting that the paired differences conformed to an approximately normal distribution. These results validated that the normality assumption was met, thereby endorsing the use of the paired t-test for all PM₁₀ comparisons.

Table 3: Anderson–Darling Normality Test for Paired Differences (PM₁₀)

Comparison	Mean Difference ($\mu\text{g}/\text{m}^3$)	AD Statistic	p-value	Interpretation
No Green Wall – <i>Epipremnum aureum</i>	19.87	0.471	0.229	Normal
No Green Wall – <i>Philodendron scandens</i>	13.74	0.693	0.064	Normal
<i>Epipremnum aureum</i> – <i>Philodendron scandens</i>	-6.13	0.487	0.209	Normal

Note: PM₁₀ = Particulate Matter with an Aerodynamic Diameter of $\leq 10 \mu\text{m}$, AD = Anderson–Darling, $\mu\text{g}/\text{m}^3$ = micrograms per cubic metre, p-value = Probability Value.

Following the confirmation of normality, paired t-tests were conducted to assess PM₁₀ levels among the three experimental conditions. Table 7 displays the outcomes of the paired t-test, encompassing the mean differences, 95% confidence intervals, t-values and p-values for every comparison. Both vertical green wall

systems demonstrated statistically significant decreases in PM₁₀ levels relative to the baseline condition. Moreover, *Epipremnum aureum* exhibited superior PM₁₀ elimination compared to *Philodendron scandens*, suggesting that the species of plants affected the extent of coarse particulate matter mitigation.

Table 4: Paired t-test results for PM₁₀ concentrations

Comparison	Mean Difference ($\mu\text{g}/\text{m}^3$)	95% Confidence Interval ($\mu\text{g}/\text{m}^3$)	t-value	p-value	Interpretation
No Green Wall vs. <i>Epipremnum aureum</i>	19.87	18.76 to 20.98	36.64	<0.001	Significant
No Green Wall vs. <i>Philodendron scandens</i>	13.74	13.09 to 14.39	43.24	<0.001	Significant
<i>Epipremnum aureum</i> vs. <i>Philodendron scandens</i>	-6.13	-6.81 to -5.45	-18.37	<0.001	Significant

Note: PM₁₀ = Particulate Matter with an aerodynamic diameter of $\leq 10 \mu\text{m}$, CI = Confidence Interval, $\mu\text{g}/\text{m}^3$ = micrograms per cubic metre, p-value = Probability Value.

Discussion

The current research revealed that the installation of vertical green wall systems markedly decreased indoor PM_{2.5} and PM₁₀ levels in dynamic office environments. In contrast to regulated laboratory experiments, the observation took place in an active office setting characterised by ongoing human engagement and standard operations, thus demonstrating the practical relevance of green wall systems in real-world scenarios. Baseline observations documented the peak average levels of both PM_{2.5} and PM₁₀, while the incorporation of flora led to statistically significant decreases in particulate matter levels. The paired t-test demonstrated that both *Epipremnum aureum* and *Philodendron scandens* markedly diminished PM_{2.5} and PM₁₀ levels in comparison to the baseline condition ($p < 0.05$).

Among the species examined, *Epipremnum aureum* was the most effective at removing particulate matter, achieving reductions of about 22.4% for PM_{2.5} and 35.9% for PM₁₀ compared to the baseline, while *Philodendron scandens* reduced PM_{2.5} and PM₁₀ levels by about 15.7% and 24.8%, respectively. Moreover, the paired t-test analysis showed that *Epipremnum aureum* was significantly more effective than *Philodendron scandens* at reducing both particulate fractions, highlighting the importance of selecting the right plant species for the effectiveness of indoor vertical green wall systems (12).

The exceptional efficacy of *Epipremnum aureum* can be ascribed to its advantageous leaf micromorphological traits. Prior research has shown that leaf texture, epicuticular wax, surface indentations, trichomes and intricate leaf structure improve the retention of particulate matter by augmenting deposition sites and diminishing particle resuspension (13, 14). Coarse and textured leaf surfaces enhance the likelihood of mechanical trapping and adherence of airborne

particles compared to smoother leaf surfaces, thus augmenting overall particulate capture efficacy (15–17).

Epicuticular wax significantly contributes to the retention of particulates. Minute particles become integrated into the wax layer, diminishing the probability of particle resuspension and enhancing prolonged adherence to the leaf surface. In a comparable manner, wide leaves featuring distinct grooves, ridges and expanded effective surface areas enhance the likelihood of particle capture. Prior studies have indicated that *Epipremnum aureum* exhibits advantageous surface traits that enhance its ability to capture particulate matter in comparison to species with smoother leaves (16–18).

The elimination of particulate matter by vertical green walls predominantly transpires via dry deposition processes. Aerosol particles adhere to leaf surfaces via gravitational settling, inertial impaction, interception, Brownian diffusion and electrostatic attraction. The compact arrangement of the vertical green wall's foliage amplifies the effective deposition surface area and fosters continuous interaction between airborne particles and leaf surfaces, thus improving pollutant elimination. Electrostatic forces between charged airborne particles and leaf surfaces could enhance particle adherence and diminish later resuspension (19, 20).

The characteristics of airflow also affect deposition efficiency. In the current investigation, the recorded indoor air velocity of around 0.2 m s^{-1} created advantageous conditions for particle deposition by enhancing the interaction duration between airborne particles and vegetation while minimizing excessive turbulence that could lead to particle resuspension. The stratified configuration of the green wall probably diminished the local air velocity near the leaf surfaces, thereby prolonging

particle residence time and improving deposition efficacy (19, 21).

While stomata have been proposed as potential ingress routes for ultrafine particles, earlier research suggests that surface deposition continues to be the primary mechanism for the elimination of PM_{2.5} and PM₁₀. Stomatal absorption is typically limited to minuscule particles, while the majority of airborne particulates adhere to the outer leaf surface via physical deposition and adsorption mechanisms. Consequently, the significant decrease in particulates noted in this study is probably due to effective surface deposition instead of internal absorption via stomata (22).

A significant advantage of this study is that observations were carried out within the same month over three successive years, thus reducing seasonal fluctuations and enhancing the consistency of the experimental parameters. This methodology enhances assurance that the noted enhancements in indoor air quality predominantly stemmed from the implementation of vertical green wall systems instead of seasonal fluctuations in ambient particulate matter levels.

The current results indicate that indoor vertical green walls serve as an efficient passive method for reducing indoor particulate pollution in occupied office settings (23). The consistently superior removal efficiency demonstrated by *Epipremnum aureum* indicates that advantageous leaf micromorphological traits—such as leaf texture, epicuticular wax and leaf structure—significantly improve the interception and retention of particulate matter. These results align with earlier research indicating enhanced particulate retention by plant species with textured, waxy and intricately structured leaf surfaces (15, 17, 24, 25).

Conclusion

This research assessed the efficacy of indoor vertical green wall systems in diminishing particulate matter levels in a dynamic office setting. The findings indicated that both *Epipremnum aureum* and *Philodendron scandens* markedly diminished indoor PM_{2.5} and PM₁₀ levels in contrast to the baseline scenario devoid of a green wall. Among the species examined, *Epipremnum aureum* demonstrated exceptional efficacy, attaining reductions of roughly 22.4% for PM_{2.5} and 35.9% for PM₁₀, whereas *Philodendron*

scandens diminished PM_{2.5} and PM₁₀ levels by about 15.7% and 24.8%, respectively. The paired t-test analysis verified that these decreases were statistically significant at the 95% confidence threshold ($p < 0.05$).

The results indicate that vertical green wall systems serve as an efficient passive approach to enhancing indoor air quality in occupied office settings. The exceptional efficacy of *Epipremnum aureum* in pollutant removal underscores the significance of selecting appropriate plant species when designing green wall systems for the reduction of particulate matter. Moreover, the effective functioning of the system in dynamic indoor conditions illustrates its practical utility as a sustainable, nature-inspired approach to diminish occupant exposure to airborne particulates and foster healthier work environments.

Subsequent studies ought to explore the enduring efficacy of various plant species, seasonal fluctuations, maintenance methodologies and the impact of ventilation techniques and airflow dynamics on the efficiency of particulate matter removal to enhance the design and utilisation of indoor vertical green wall systems.

Abbreviations

ACH: Air Changes per Hour, CO₂: Carbon Dioxide, HVAC: Heating, Ventilation and Air Conditioning, IAQ: Indoor Air Quality, ISHRAE: Indian Society of Heating, Refrigerating and Air Conditioning Engineers, PM: Particulate Matter, PM_{2.5}: Particulate Matter with an aerodynamic diameter ≤ 2.5 μm , PM₁₀: Particulate Matter with an aerodynamic diameter ≤ 10 μm , RH: Relative Humidity, VGS: Vertical Green Wall System.

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Author Contributions

All authors contributed to the study design, data collection, analysis, manuscript preparation and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

The authors acknowledge the use of generative AI (QuillBot) to assist in the paraphrasing of certain parts of the manuscript. All content generated through AI was critically reviewed, edited and verified by the authors to ensure accuracy, originality and compliance with academic standards. The authors take full responsibility for the integrity and validity of the manuscript. No figures in this manuscript were generated using artificial intelligence or generative AI tools. Figures 1–4 are original photographs captured during the study and Figures 5–6 were generated using Python-based statistical visualization tools from the experimental dataset.

Ethics Approval

Not Applicable.

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