Assessment of Indoor Plants for Improving Indoor Environment Quality

THESIS

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by

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“Dedicated to my beloved family”

Birla Institute of Technology & Science, Pilani
Pilani Campus

CERTIFICATE

This is to certify that the thesis entitled **"Assessment of Indoor Plants for Improving Indoor Environment Quality"** submitted by **Mukesh Budaniya** ID No **2019PHXF0436P** for the award of Ph.D. of the Institute embodies original work done by him under my supervision.

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Mukesh Budaniya

Poor indoor environment quality (IEQ) is a major problem affecting occupants' health, well-being, and performance. Among the many factors, indoor air quality (IAQ), thermal comfort, visual comfort, and acoustic comfort are primarily responsible for affecting the IEQ. The IAQ is directly associated with the concentration of indoor pollutants like volatile organic compounds (VOCs) and particulate matter (PM). Specifically, PM is a critical health concern responsible for about one in nine premature deaths worldwide.

Indoor plants are introduced in buildings to improve IEQ by reducing PM and improving occupants' health and well-being; however, their effectiveness has not been well characterized. We quantified the ability of indoor plants through controlled environment chamber experiments, mathematical modeling, and experiments in simulated open-plan seating space. We investigated the relationships between the plants, PM, occupants' well-being (perceived IAQ, comfort, and emotional state), and performance.

To investigate the interactions between the plants and PM, we experimented with eleven different plant species to remove airborne PM through experiments conducted in an environmental chamber. By introducing PM into the chamber and measuring its removal rate with plants (WP) and without plants (WoP), we estimated plants' deposition velocities and clean air delivery rates (CADRs). The average deposition velocities were 93±9 cm/h for the moss plant, between 29±3 cm/h to 37±4 cm/h for the needle-leaved plants, and between 1±2 cm/h to 13±2 cm/h for the broad-leaved plants. Their CADRs were between 0.002±0.004 m^3/h to 0.084±0.009 m^3/h, which were significantly lower than those of filter-based air purifiers (CADRs = 170–800 m^3/h).

Based on environmental chamber results, we developed a mathematical model to estimate the required number of plants to reduce specific percentage of PM level indoors. Our

mathematical model revealed that large quantities of plants would be required to achieve even modest reductions in indoor PM concentrations under real-world conditions, thus highlighting their limited role in controlling indoor PM levels.

We conducted a between-subjects study in a simulated open-plan seating space to investigate the interactions between the plants and occupants' well-being. Subjective questionnaires queried the occupants regarding their perception of indoor climate, sick building syndrome (SBS) symptoms, emotional state, self-assessed performance, and overall satisfaction with the space with and without indoor plants. The participants also undertook a cognitive task targeting working memory (operation span). Participants in the group with plants (WP) rated their room to be better decorated (r, effect size = −0.42, $p < 0.0001$), had better overall visual comfort ($r = -0.22$, $p = 0.01$), felt slightly cooler ($r = 0.18$, $p = 0.02$), and perceived less air dryness ($r = 0.18$, $p = 0.03$) than the group without-plant (WoP). The WP group also had enhanced positive emotions ($|r| = 0.21$ to 0.45, $p < 0.0001$ to 0.02) and reduced negative emotions ($r = 0.18$, $p = 0.02$). Differences noted between the two groups' perception of air quality, SBS symptoms, and their subjectively or objectively assessed task performance were not significant. Overall, our findings indicated that potted indoor plants cannot compete with conventional air purifiers in terms of mechanical air cleaning efficiency, but they positively impacted room decoration, perceived thermal comfort, overall mood and occupants' psychological well-being. These natural systems are able to provide added value that mechanical systems lack, making them a unique and holistic solution for improving occupant well-being.

Symbol	Description	Units
A	Area	[m^2]
C	Particle concentration	[particles/cm^3]
E	Particle generation rate	[particles/h]
h	Ceiling height	[m]
N	Number of plants	[-]
t	Time	[h]
v	Particle deposition velocity, cm/h	[m]
$\bar{v}$	Size-averaged particle deposition velocity	[cm/h]
V	Indoor air volume	[cm^3]
r	Mann-Whitney effect size	[-]
d	Cohen's effect size	[-]

Greek symbols

β	Particle deposition loss coefficient	[h^{-1}]
ε	Reduction in particle concentration	[%]
λ	Air exchange rate	[h^{-1}]
ρ_A	Plant area density	[m^2/m^2]
ρ_N	Plant number density	[plants/m^2]

Subscripts

c	Chamber
f	Floor
i	Particle size class

out	Outdoor
p	Plant
p, one	Single plant
R	Room
c	Chamber
WP	With plant
WoP	Without plant

Abbreviations	Description
PM	Particulate matter
HEPA	High-efficiency particulate air
CADR	Clean air delivery rate
TSPM	Total suspended particulate matter
WP	With plant
WoP	Without plant
IEQ	Indoor environment quality
IAQ	Indoor air quality
VOC	Volatile organic compound
SBS	Sick building syndrome
MAPEs	Mean absolute percentage errors
TSeV	Thermal sensation vote
TSaV	Thermal satisfaction vote
HSeV	Humidity sensation vote
GSQS	Groningen sleep quality scale
OSPAN	Operation span
PEBL	Psychology experiment building language
TPV	Thermal preference vote
HAP	High arousal positive
P	Positive
LAP	Low arousal positive
LA	Low arousal
LAN	Low arousal negative
N	Negative

HAN	High arousal negative
HA	High arousal
WMT	Working memory task
DT	Distractor task
BMI	Body mass index
PMV	Predicted mean vote
IMAC	Indian model of adaptive comfort
ACDD	Adaptive cooling degree day

Chapter 1:

Introduction

1.1.Background and motivation

The indoor environment quality (IEQ) is an major concern for the scientific community because people spend over 80–90% of their life indoors [1,2]. Numerous factors contribute to shaping the indoor environment within a building, such as indoor air quality (IAQ), thermal comfort, lighting, noise levels, etc. as shown in Figure 1.1.

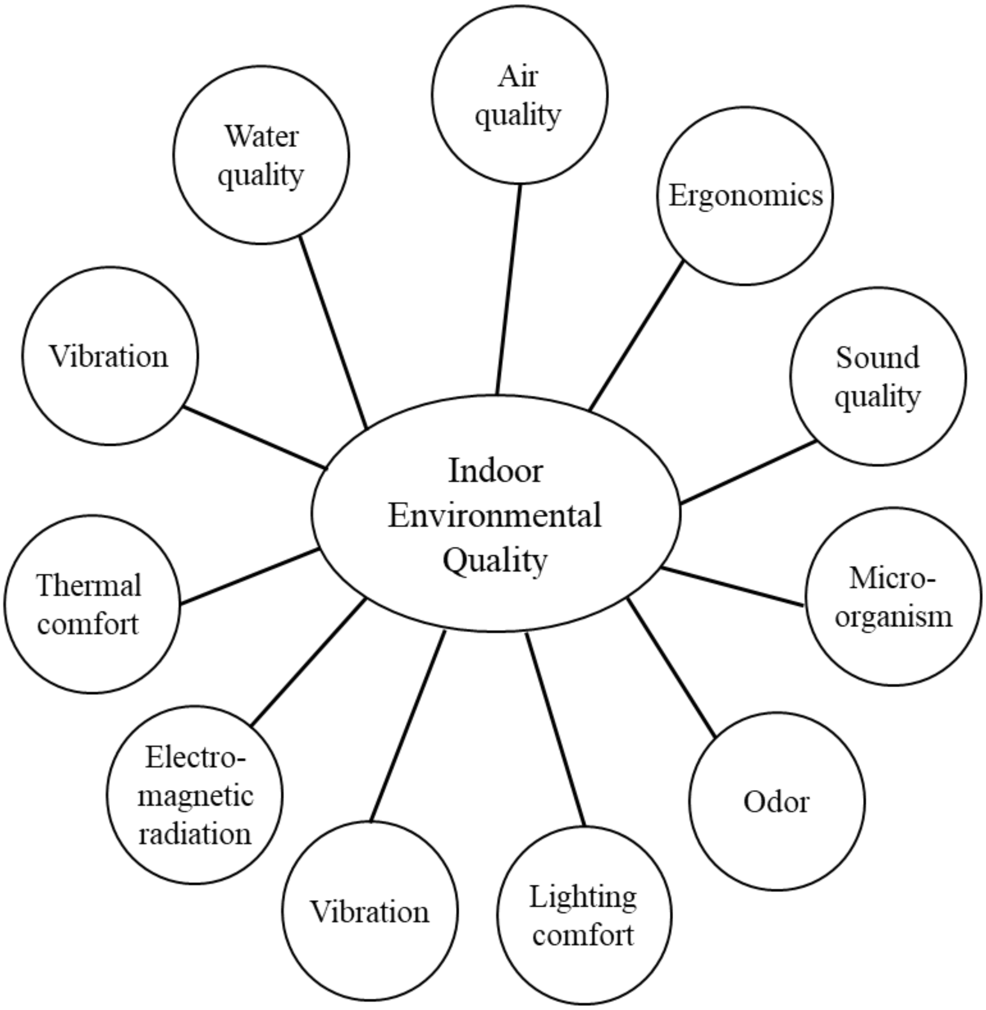


Figure 1.1. IEQ elements [3].

All these factors play crucial roles in ensuring the well-being and productivity of occupants. Among these factors, IAQ stands out as the pivotal concern, sensitive to influences from volatile organic compounds (VOCs), particulate matter (PM), and inadequate ventilation.

Within this context, the issue of PM air pollution emerges as a paramount global challenge, signifying a notable public health issue on a worldwide scale. Inhaling polluted air containing PM, estimated to have caused about 6.5 million premature deaths (about one in nine deaths) globally in 2019 [4]. Overall, exposure to $PM_{2.5}$ (particles smaller than 2.5 µm in diameter) is India's second leading cause of premature deaths, as shown in Figure 1.2.

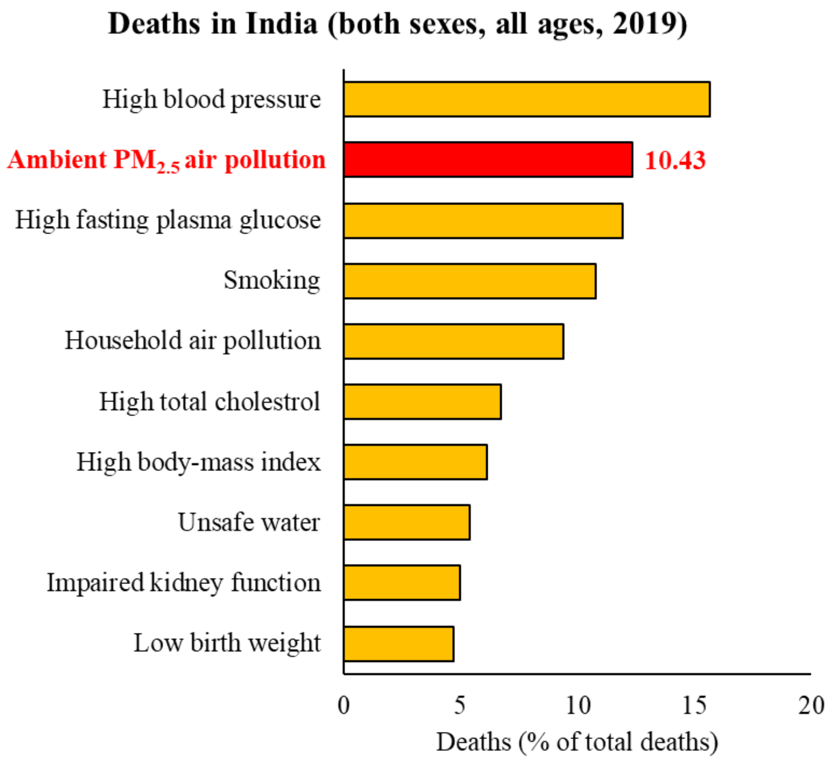


Figure 1.2. The major causes of premature deaths in India [4].

The IAQ is significantly impacted by outdoor PM, as many of the adverse effects associated with outdoor PM are linked to the inhalation of these particles indoors. This is because outdoor particles find their way indoors through ventilation and infiltration [5,6]. Ji and Zhao [7] estimated that indoor PM of outdoor origin accounts for 81–89 % of the total increase in mortality associated with exposure to outdoor PM in the United States, Europe, and China. Thus, PM significantly affects indoor air quality, leading to poor IEQ.

Poor IEQ impacts occupant comfort, well-being (health and happiness), and work performance. Poor IEQ will not just be uncomfortable for occupants; it also likely make occupant less productive [8–10]. This underperformance can have a tangible economic impact. In the USA, an assessment suggested that enhancing IEQ could result in annual savings of $37–208 billion due to improved health and increased productivity [11].

To improve IEQ, researchers are exploring sustainable building designs that can cost-effectively enhance IEQ, particularly factors like perceived thermal comfort and air quality. One intriguing avenue is integrating indoor plants as a potential PM filter and improving perceived IEQ, thereby improving occupants' emotional-state, well-being, performance, and perceived comfort. However, the quantification of these benefits remains an area requiring further investigation. These issues form the background and need for this research.

1.2. Organization of the thesis

Chapter 1	This chapter is the foundation of this thesis and presents the background, motivation, and thesis organisation.
Chapter 2	This chapter summarized the current research about the indoor plants and their benefits regarding PM removal and their co-benefits regarding occupants' well-being and performance. In addition, it also highlights knowledge gaps and methodologies for addressing research questions.
Chapter 3	This chapter presents and discusses the results of environmental chamber experiments to identify the impact of plants on PM reduction in controlled environments.
Chapter 4	This chapter presents and discusses the results of the mathematical model developed to estimate the required number of plants for specific PM reduction.

Chapter 5 This chapter presents and discusses the results of a study conducted to determine the effects of indoor plants on occupants' emotional-state, performance, and perceived comfort in an open-plan seating space.

Chapter 6 This chapter consolidates the research findings into a comprehensive discussion and draws concluding insights.

Chapter 2:

Literature review

This chapter sets the agenda for understanding the importance of indoor plants and their possible impact on indoor environment quality (IEQ). The first part of this chapter reviews the possible benefits of indoor plants for particulate matter (PM) removal. The second part of this chapter reviews the co-benefits of plants in terms of perceived indoor air quality (IAQ), occupants' emotional-state, performance, and comfort. This literature review helps us to identify the knowledge gaps that helps us to formulate.

2.1. Works on assessment of direct benefits of indoor plants in terms of PM removal

Indoor plants have been suggested as a potential solution for removing PM as well as other pollutants from indoor air [12–14]. The uptake of PM by plants may happen due to particle *deposition* on leaves, branches, and trunk surfaces [15–17] and *absorption* by the plants' stomata [18]. Additional Enhanced PM filtration can be accomplished by utilizing a mechanical blower to direct polluted air through the plant's root zone and the growth medium [19].

Two types of phytoremediation (plant-based pollutant removal) systems have been proposed for indoor use: (i) passive system and (ii) active system. A passive phytoremediation system consists of placing plants indoors and relies only on deposition and/or absorption mechanisms of plant for PM uptake. On the other hand, all three mechanisms (deposition, absorption, and filtration) contribute to PM removal in an active system. Thus, active phytoremediation systems claim to have much higher PM removal rates than passive systems; however, they also require active air transfer through the plant's root zone [20,21].

Since deposition and absorption are the primary mechanisms of PM uptake by plants in both active and passive phytoremediation systems, several studies have characterized those through experiments conducted in environmental chambers. Such studies estimate plants' PM uptake potential by comparing particle removal rates inside environmental chambers, with and without the plant specimens kept inside. Most studies reported that PM concentrations decayed much faster when the plants were present inside the chamber than when they were absent [22–28]. However, since those studies used sealed chambers, the particle removal due to air exchange did not occur, accentuating the plants' PM uptake. Based on the PM decay rates, some studies have reported PM removal efficiencies (percentage reduction in PM concentration after a few hours) for $PM_{2.5}$ (particles smaller than 2.5 μm in diameter) and PM_{10} (particles smaller than 10 μm in diameter). The 3-hour removal efficiencies were between 42–90 % for $PM_{2.5}$ and from 90–98 % for PM_{10} [23,24]. However, "PM removal efficiency" is not a very useful metric for quantifying plants' PM uptake potential because it inherently includes PM removal by deposition on chamber surfaces and air leakages; thus, overestimating plants' role in PM removal [29]. Furthermore, removal efficiency (during a decay test) depends on the volume of the experimental chamber and the time duration. Thus, the metric does not provide useful information on its own for assessing plants' performance under realistic indoor conditions.

An appropriate metric to quantify plants' PM uptake is deposition velocity (in m/s), which is defined as the PM flux on the plant surface (in $\mu g/s\text{-}m^2$) divided by its bulk air concentration (in $\mu g/m^3$), and is analogous to the film coefficient used in heat transfer calculations [30]. Since the deposition velocity quantifies the deposition per unit area of the plant, it is unaffected by the plant size and its foliage density. A large number of studies have reported deposition velocities for outdoor vegetation [31–33], with median values ranging between 108–7,596 cm/h at wind speeds between 1–10 m/s [34]. However, we could only find one investigation that reported deposition velocities for indoor plants, which were between 0.3–13 cm/h for live plants and 9–11 cm/h for artificial plants at chamber airspeeds between 0.2–0.3 m/s [28]. Note that the indoor plants' deposition velocities are orders of magnitude smaller than those reported for outdoor vegetation because particle deposition is strongly influenced by airflow conditions and surface characteristics [35,36].

The PM uptake capacity of plants can be significantly enhanced by passing polluted air through the plant's substrate, termed active phytoremediation. Torpy and Zavattaro [20] have reported that the PM uptake potential of an active phytoremediation system was two to four times that of a passive system. Further experimental investigations have reported that the plant's presence in the active phytoremediation system generally increased the system's single-pass removal efficiency [37–39]. The single-pass removal efficiencies were strongly affected by the plant's root structure; thus, it was recommended to select the plant species carefully in active phytoremediation systems [29].

In addition to the controlled laboratory studies mentioned above, some researchers have investigated plants' effectiveness in removing PM in actual indoor conditions [23,40–45]. For example, Pegas et al. [40] reported that by keeping six potted plants inside a classroom, the indoor PM_{10} concentration was reduced by 30 %, even though the outdoor concentration increased by 35 % during the same period. However, since the study did not account for the impact of ventilation and indoor sources on the classroom's PM_{10} concentration, those factors could have confounded the results. Ghazalli et al. [41] compared the PM levels in building corridors with and without a passive green wall and found that $PM_{2.5}$, PM_{10}, and $PM_{>10}$ were lowered by 48.5 %, 82.6 %, and 5.5 %, respectively, in the corridor with the green wall. Another study reported that an active bio-filter could reduce the PM concentration by 42.6 % in a classroom in 20 minutes [42]. In contrast, Hong et al. [45] reported an *increase* in the PM concentration after introducing potted plants in two day-care facilities and attributed it to changes in outdoor PM levels during the monitoring period.

2.1.1. Summary and gap areas concerning PM removal by indoor plants

The significant PM exposure to occupants may happen indoors there is need to protect people from the adverse health effects of air pollution by purifying the indoor air. The above discussion shows that indoor plants could be effective in removing PM in indoor environments [40–42]; however, the following knowledge gaps remain:

- There is limited research that assesses the potential of plants for indoor PM removal. We found only one investigation that reported PM deposition velocities for indoor plants. Furthermore, plants' clean air delivery rates (CADRs) are unknown, which is essential to quantify their air filtration capacity.
- Previous investigations have not discussed the implications of keeping live plants in realistic indoor conditions. The chamber investigations generally do not evaluate the effectiveness of indoor plants in real-world situations. In contrast, the real-world studies report the efficacy of plants without accounting for confounding factors such as ventilation, indoor sources, etc., which can bias their results.

Those research gaps motivated our investigation, which quantified the size-resolved PM deposition velocities and CADRs for several indoor plant species. The study also evaluated plants' potential to reduce indoor PM levels using a simple mass balance model without the results being affected by any confounding factors.

2.2. Works on assessment of co-benefits of indoor plants

Targeting sustainability and low-energy building designs, researchers worldwide are exploring methods to improve perceived thermal comfort and air quality in an energy-efficient manner. One direction of such explorations is including biophilic features in buildings [46], particularly indoor plants [47–50], that connect occupants to nature. To investigate the effect of biophilia in the form of plants, researchers have incorporated plants into indoor spaces in manners such as creating green walls [51] or keeping potted plants (hanging, tabletop, kept on the floor, etc.) [52–55]. Previous research has shown the possible contribution of indoor plants to reducing stress and improving mental health of occupants [56,57]. Laboratory-based and field based studies have been reported that analyzes participants' perceived improvement in IAQ [58,59] and thermal comfort [47,48,60] in the presence of plants, even when the indoor environment was the same. The presence of indoor plants has also been related to stress reduction [53,57], lowering sick building syndrome (SBS) symptoms, and improving occupants' mood [52,61] and well-being [62]. These effects could stem from the biophilic effect plants have on occupants [63], or it could also be due to the actual improvement in overall aesthetics that results from placing indoor plants [64]. Further, some studies have also reported that plants enhance objectively measured task performance [53,55,59].

Maintaining indoor conditioning is energy intensive [65], and indoor plants could present a sustainable and green alternative to improving occupant satisfaction with the indoor climate. However, placing plants indoors requires space and upfront investment as well as their care, along with issues like increased humidity [66], allergens [67], and volatile organic compounds (VOCs) emitted by the plants, soil, and pot [68].

2.2.1. Summary and gap areas concerning co-benefits of indoor plants

To the best of our knowledge, no previous work has explored the multifaceted impact of plants on indoor climate and occupants in India [69–71], and only one study has been conducted in South Asia [72].

Researchers have investigated the effect of biophilia in the form of plants using green walls [51] and indoor potted plants (hanging, tabletop, or kept on the floor) [52–55]. The evidence favoring plants improving indoor environment and occupant perception remains equivocal. Some prior works have shown their benefits, e.g., reducing stress and improving the mental health of occupants [56,57], improvement in perceived indoor air quality (IAQ) [58,59] and thermal comfort [47,60], and improvement in objectively measured task performance [53,55,59]. There also have been studies that failed to find a significant impact of plants on enhancing mood [73–75], improving perceived IAQ [48,72], or improving perceived thermal comfort and task performance [72,75].

In a recent study, we analyzed the impact of plants on IAQ, specifically for particulate matter removal. The results revealed very low clean air delivery rates (CADRs; 0.002–0.08 m^3/h) for plants, with respect to removing particulate matter [76]. Similarly, Cummings et al. [29] also reported low CADRs when using plants to remove VOCs from a room. The impact of plants on occupants thus may not be due to their impacting the indoor climate but instead could stem from biophilia [63] and due to the improvement in overall aesthetics [64]. To exploit this possible impact, placing plants indoors requires space and upfront investment as well as their care. There are also issues like increased humidity [66], allergens [67], and volatile organic compounds (VOCs) emitted by the plants [68]. For the new buildings being designed for the composite climate of India, a design intervention like having indoor plants can be relatively straightforward. It could also contribute to multiple targets under the United Nations' Sustainable Development Goal 11 "Sustainable Cities and Communities", viz., Target 11.3, "By 2030, enhance inclusive and sustainable urbanization…" and Target 11.6 "By 2030, reduce the adverse per capita environmental impact of cities…". However, such a widespread implementation requires carefully weighing the evidence of how plants impact the indoor environment and occupants.

Perusing reviews of studies [69–71,77] related to how indoor plants impact occupant perception, we identified the following limitations in the study designs:

- No study met the requirement of intention-to-treat analysis (no participant is excluded from the analysis and analysis is based on the initial group assigned).
- Limited number of studies examined the multiple dimensions that indoor plants are likely to affect, viz., emotion, cognition, thermal comfort, and satisfaction, together.
- Studies often did not use groups with similar social demographics to compare the impact of plants vs the absence of plants and participants were not blinded to the plants (as the intervention) in multiple studies.
- Several studies did not use an a priori power calculation as part of the experiment design.

Studies do not report indoor conditions of the spaces as a matter of course. The current study was designed to examine multiple dimensions: task performance, thermal comfort, air quality perception, affect (emotional state at the current moment), and perception of the indoor space. Examining multiple dimensions together, under consistent indoor conditions, lowers the inter experimental variations, improves reproducibility and aids inter-study comparisons. Our study was conducted in a classroom modified to simulate a portion of an open-plan seating space (with and without plants), while keeping consistent thermal environmental parameters (air temperature, air speed, ventilation) and participant clothing resistance were also collected to analyze participant responses with context and minimize bias. A between-subjects design ensured that the participants were blinded to the intervention. A priori power calculation was used to decide on a suitable number of participants for each arm of the study. Our study focused on answering the following questions:

- Does the presence of indoor plants influence occupants' subjective perception of their indoor environment?
- Does the presence of indoor plants impact occupants' affect, i.e., current emotional state?

- Does the presence of indoor plants have a measurable impact on occupants' cognitive performance (working memory)?

2.3. Objectives of the thesis

A detailed literature review provides a better understanding of existing research gaps in the quantification of the effectiveness of plants for PM removal and their other co-benefits. Therefore, the present study concentrates on the quantification of the effectiveness of plants, and subsequent objectives are framed as follows:

Objective 1: To quantify the PM removal potential of different indoor plant species through experiments conducted in an environmental chamber under controlled conditions like temperature, lighting, and ventilation rate.

Objective 2: To formulate the mathematical model for estimating the number of plants required for obtaining a desired amount of PM reduction for different ventilation rates in realistic indoor spaces.

Objective 3: To systematically investigate the effects of indoor plants on occupants' working environment, thermal comfort, air quality perception, sick building syndrome, emotional state, and cognitive performance through controlled experiments in a simulated open-plan seating space.

Chapter 3:

The impact of indoor plants on particulate matter reduction within the experimental chamber

This chapter presents thorough exploration of the effectiveness of indoor plants as potential solutions for mitigating particulate matter (PM) air pollution. To investigate the authenticity of this emerging approach, we conducted a comprehensive assessment with eleven different plant species' for their effectiveness' in removing PM. This investigation took place within an environment-controlled chamber, allowing us to quantify and estimate the plants' performance. Through a well-designed experiment that introduced controlled quantity of PM into the chamber, we measured its removal rate in presence and absence of plants, ultimately enabling us to derive key parameters such as deposition velocities and clean air delivery rates (CADRs). These observations reveal a diverse view of effectiveness of plants, with notable results.

3.1. Methodology

We tested the effectiveness of one moss variety (Figure 3.1a), three needle-leaved plants (Figure 3.1 b–d), and seven broad-leaved plants (Figure 3.1 e–k) for their effectiveness in removing airborne particles. The plant selection was based on local availability and included common indoor and outdoor plants of diverse leaf shapes, which was an important factor impacting PM removal. Of the selected plants, Snake plant (*Sansevieria trifasciata*) and Money plant (*Epipremnum aureum*) are well known to be suited for indoor conditions [78]. Even Christmas tree (*Araucaria heterophylla*), Kodia purple (*Eranthemum purpureum*), Phoenix (*Phoenix roebelenii*), Song of India (*Dracaena reflexa*), Ficus (*Ficus retusa*), and Croton (*Codiaeum variegatum*) plants are also commonly used as houseplants by placing them in areas that receive abundant sunlight [78–81].

(a) Glittering wood moss (*Hylocomium splendens*)

(b) Cypress plant (*Cupressus macrocarpa*)

(c) Christmas plant (*Araucaria heterophylla*)

(d) Thuja compacta plant (*Platycladus orientalis*)

(e) Phoenix plant

(*Phoenix roebelenii*)

(f) Kodia purple plant

(*Eranthemum purpureum*)

(g) Song of India plant

(*Dracaena reflexa*)

(h) Snake plant

(*Sansevieria trifasciata*)

(i) Money plant

(*Epipremnum aureum*)

(j) Ficus plant

(*Ficus retusa*)

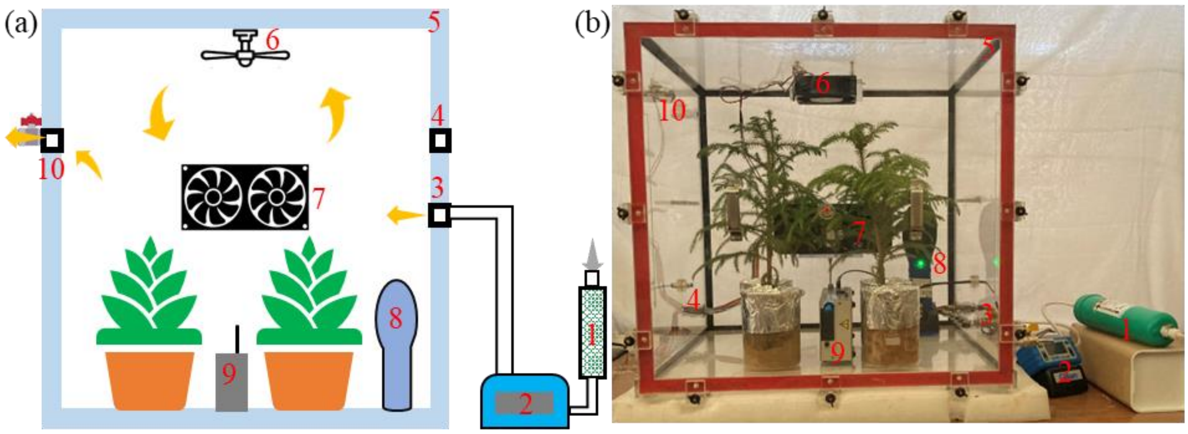
(k) Croton plant

(*Codiaeum variegatum*)

Figure 3.1. The plant species tested for passive removal of particulate matter: a) Moss, b) Cypress, c) Christmas, d) Thuja compacts, e) Phoenix plant, (f) Kodia purple, (g) Dracaena plant, (h) Snake plant, (i) Money plant, (j) Ficus plant, and (k) Croton plant.

Thuja compacta (*Platycladus orientalis*) and Cypress (*Cupressus macrocarpa*) plants are not used indoors [82,83] but were selected to add to the number of needle-leaved plants in the study. Finally, Glittering wood moss (*Hylocomium splendens*) was included to bring further plant diversity to the study. Thus, all of the eleven plant species tested, two (*Sansevieria trifasciata and Epipremnum aureum)* are well suited for indoor conditions, while the others may not be successfully used as indoors, especially when natural light is minimal.The plants' total surface area (leaves, branches, and trunk) was measured (see Table A.1 in *Appendix* A) using the methodology described in Section A.1 of *Appendix* A. The moss area could not be measured due to its complex shape. The PM uptake by those plants (through deposition and absorption) was measured by conducting experiments in an environmental chamber, as described in the following sub-sections.

3.1.1 Environmental chamber and measuring equipment



Nomenclature: 1: HEPA filter, 2: flow controller, 3: air inlet, 4: PM injection port, 5: environmental chamber, 6: mixing fan, 7: radiator, 8: temperature and humidity sensor, 9: PM monitor, and 10: air outlet.

Figure 3.2. The experimental setup: (a) schematic and (b) actual view.

We fabricated a 210-liter Plexiglass chamber (59.5 cm × 59.5 cm × 59.5 cm), as shown in Figure 3.2, in which the temperature was maintained at 26±1 °C using a thermoelectric cooling system. The chamber was supplied outdoor air using a vacuum pump with a mass flow controller (Gilair Plus, Sensidyne), such that the air exchange rate (λ) was 0.5±0.05 h^{-1}. The supply air was filtered using a high-efficiency particulate air (HEPA) filter (Coda® XtraInline® Filters-GREEN CXGR-001).

Three fans (RPM: 2600–2800) were installed in the chamber, with one at the top and two on the vertical walls, to ensure well-mixed conditions inside and generate an air velocity of 0.4 m/s (details in Section A.3 of Appendix A). The study continuously monitored the temperature and relative humidity inside the chamber by using an indoor air quality probe (Greywolf DSIAQ-PLUSTAB10-DSII). The size-resolved particle number concentration and mass were measured using a laser particle spectrometer (Grimm 11-A).

3.1.2. Experimental procedure

To study the PM removal by the different plant species, we measured the particle removal rates inside the environmental chamber, with plant (WP) and without plant (WoP) specimens. The experimental procedure included the following steps:

Step 1. Clean the chamber with distilled water, dry it, and place either four empty pots (control experiment, WoP) or four potted plants (treatment experiment, WP) inside it.

Step 2. Ventilate the chamber for about 0.5 hours, until the total particle count was below 9,000 particles/l and the total suspended particulate matter (TSPM) was below 1 μg/m^3 inside the chamber.

Step 3. Inject particles, generated using an incense stick, into the chamber until the total particle count is above 5×10^6 particles/l (TSPM was between 350–750 μg/m^3).

Step 4. Monitor the decay in particle concentration (due to ventilation and deposition on surfaces) using the laser particle spectrometer.

Step 5. Stop the experiment when the total particle count reaches below 9,000 particles/l (the starting conditions), which took about 2.5 hours from when particles were introduced into the chamber.

Following steps 1–5, we tested each plant species three times, i.e., we conducted three control and three treatment experiments to quantify the experimental uncertainties. We followed the systematic approach (see Section A.1 of *Appendix* A) to quantify the uncertainty associated with experiments.

3.1.3. Quantifying deposition velocity and clean air delivery rate (CADR)

To quantify the size-resolved particle removal rates by the different plant species, we estimated their deposition velocities for different particle sizes. To calculate the deposition velocity, we used a simple mass balance model to estimate the contributions of the chamber and plant surfaces toward particle removal.

Assumptions*:*

1. **Well-mixed conditions:** The chamber is assumed to have well-mixed air, allowing for uniform particle distribution throughout the volume same we ensured by installing mixing fans and by conducting separate experiments, for detailed approach please refer section A.3 of Appendix A.
2. **Constant parameters:** The air exchange rate (λ), particle deposition velocities on chamber surfaces (v_c), chamber surface area (A_c) and plant surface area (A_p) are considered constant over time during the measurements.
3. **Neglecting inlet concentration:** The influence of the inlet particle concentration is disregarded due to the presence of a HEPA filter, which is expected to effectively remove particles from incoming air.
4. **No particle agglomeration:** The model does not account for particle agglomeration, assuming that particles remain independent during the experiments.

5. **Sufficient mixing time:** Adequate time is provided for the establishment of well-mixed conditions before measurements, which is determined based on the mixing time derived from separate experiments, for details please refer section A.3 of *Appendix* A.

Assuming well-mixed conditions inside the chamber and neglecting the inlet particle concentration and particle agglomeration, the concentration balance for a particular particle size is given by Eq. 3.1 [84]:

$$\frac{dC_i}{dt} = -\lambda C_i - \left(\frac{v_{c,i}.A_c}{V}\right)C_i - \left(\frac{v_{p,i}.A_p}{V}\right)C_i \tag{3.1}$$

where C_i is the particle concentration (in particles/cm^3) of a particular size (denoted by the subscript *i*) at time t (in h), λ the air exchange rate (in h^{-1}), $v_{c,i}$ and $v_{p,i}$ are the deposition velocities (in cm/h) on the chamber and plant surfaces, respectively, A_c and A_p the areas (in cm^2) of the chamber and plant surfaces, respectively, and V the air volume (in cm^3) inside the chamber. As mentioned in assumptions section if λ, $v_{c,i}$, and $v_{p,i}$ are assumed constant over time, Eq. 3.1 can be integrated to obtain C_i for a particular particle size i:

$$C_i = C_{i,t=0}e^{-(\lambda+\beta_{c,i}+\beta_{p,i})t} \tag{3.2}$$

where $C_{i,t=0}$ is the initial particle concentration, $\beta_{c,i} = \frac{v_{c,i}.A_c}{V}$, and $\beta_{p,i} = \frac{v_{p,i}.A_p}{V}$. The terms $\beta_{c,i}$ and $\beta_{p,i}$ are the deposition loss coefficients for the chamber and plant surfaces, respectively.

Eq. 3.2 represents the exponential decay of particles in the chamber due to ventilation (λ term) and deposition on chamber walls ($\beta_{c,i}$ term) and plant surfaces ($\beta_{p,i}$ term). Thus, $\beta_{c,i}$ can be estimated by fitting an exponential curve between C_i and *t* to the decay of particles measured in an empty chamber (control experiment) at a known λ. Similarly, $\beta_{p,i}$ can be estimated by measuring the decay of particles in the chamber with plants (treatment experiment). From $\beta_{c,i}$

and $\beta_{p,i}$, the corresponding deposition velocities ($v_{c,i}$ and $v_{p,i}$) can be estimated. However, care must be exercised in doing so since Eqs. 3.1–3.2 are valid for well-mixed conditions only. The time duration required to achieve well-mixed conditions is dependent on the system's physical boundaries, turbulence gradients, particle size, etc. [85], and difficult to estimate a priori. Thus, we conducted separate experiments to develop a method for estimating the mixing time for the different particle sizes. Our approach (details in Section A.3 of *Appendix* A) relies on the fact that when well-mixed conditions are established in the chamber, the following criteria must be satisfied:

- An exponential curve will fit the measured decay of particles well.
- The estimates of β will be the same, irrespective of the time interval used for calculating its value.

After obtaining the deposition velocities, we also calculated the average clean air delivery rate (CADR), which is given by:

$$CADR = \overline{v_p}.A_p \tag{3.3}$$

where $\overline{v_p}$ is the size-averaged deposition velocity. The CADR parametrizes the air cleaning potential of the plants (in m^3/h) and can be compared to those of conventional filter-based air purifiers [29].

3.2. Results and discussion

This section first describes the differences in the particle decay rates in the chamber with and without plants. Subsequently, we report the size-resolved deposition velocities and CADRs for the different plant species. We conclude by estimating indoor plants' real-world PM uptake potential.

3.2.1. Particulate matter decay rates inside the environmental chamber

Figure 3.3 shows the temporal variation of the normalized concentration ($C_i/C_{i,t=0}$) of 0.35 μm diameter particles in the environmental chamber with and without the Moss plants kept inside.

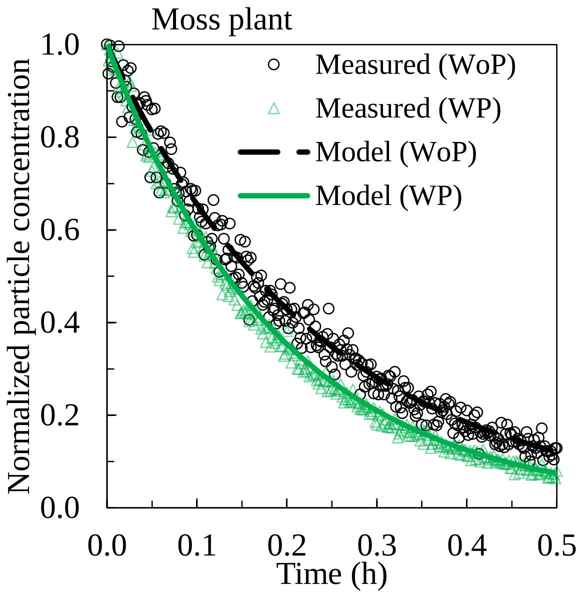


Figure 3.3. Temporal variations in the concentration of 0.35 μm diameter particles inside the environment chamber with and without Moss plant

It can be seen that when plants were present inside the chamber, the particle decay rate was noticeably higher than when they were absent, which was due to the particle uptake by the plants. Figure 3.3 also shows that the exponential model (Eq. 3.2) well represented the particle decay with and without the plants ($R^2 > 0.99$). Qualitatively similar results were obtained with the needle-leaved plants, as shown in Figure 3.4.

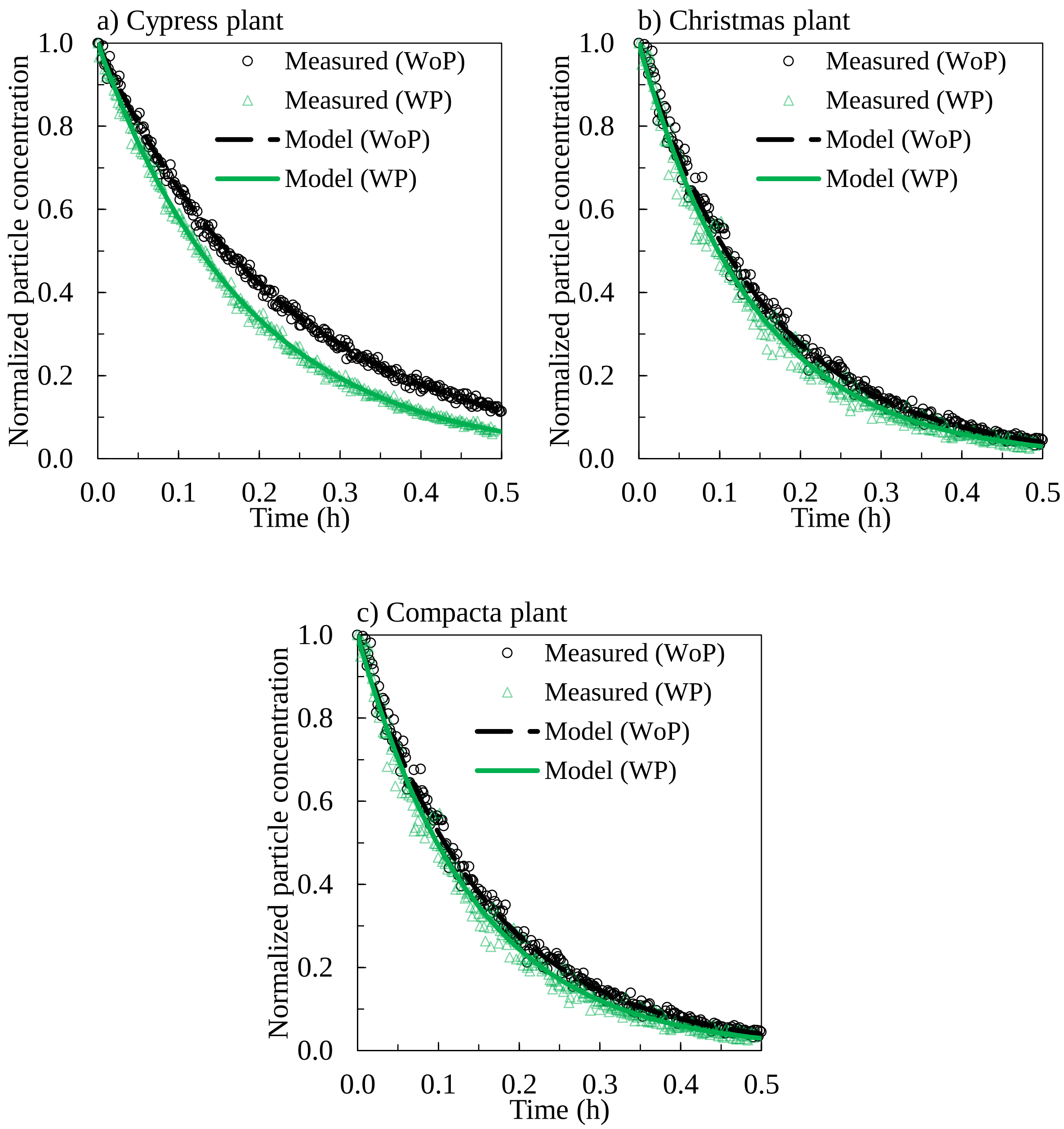


Figure 3.4. Temporal variations in the concentration of 0.35 µm diameter particles inside the environment chamber with and without: a) Cypress, b) Christmas, and c) Compacta

Overall, noticeable PM deposition was observed when needle-leaved and moss plant species were placed in the environmental chamber.

In the case of Phoenix palm (Figure 3.5a) and Kodia plants (Figure 3.5b), we observed a slight difference in the particle decay rates with and without the plants placed inside the chamber, indicating some particle removal by the plant.

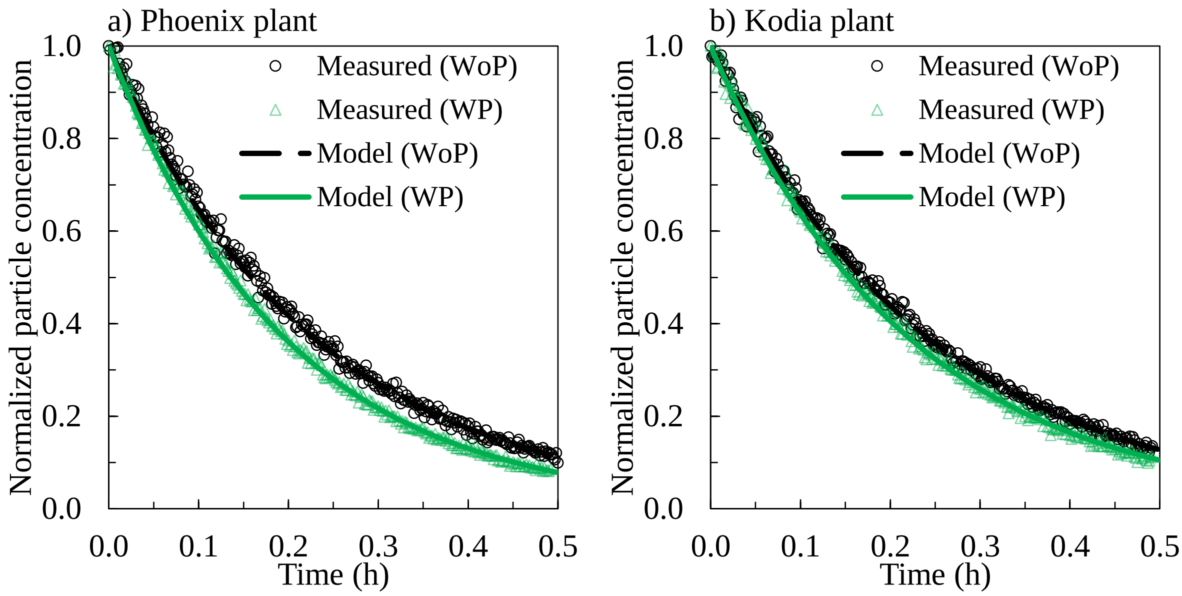


Figure 3.5. Temporal variations in the concentration of 0.35 µm diameter particles inside the environment chamber with and without:a) Phoenix plant and b) Kodia plant

However, for all other broad leaved plants (Figure 3.6 a–e) the particle decay rates were almost the same with and without the plant, indicating negligible particle uptake by the plants, likely due to the plant's surface morphology [86–88]. Factors such as the waxy cuticle, specialized trichomes, and the hydrophobic properties of the leaf surface create barriers to particle adhesion and uptake. Once again, model Eq. 3.2 well captured the particle decay trends. We observed qualitatively similar results for the different particle sizes (0.25– 0.50 µm in diameter) for all plants, which are not presented here.

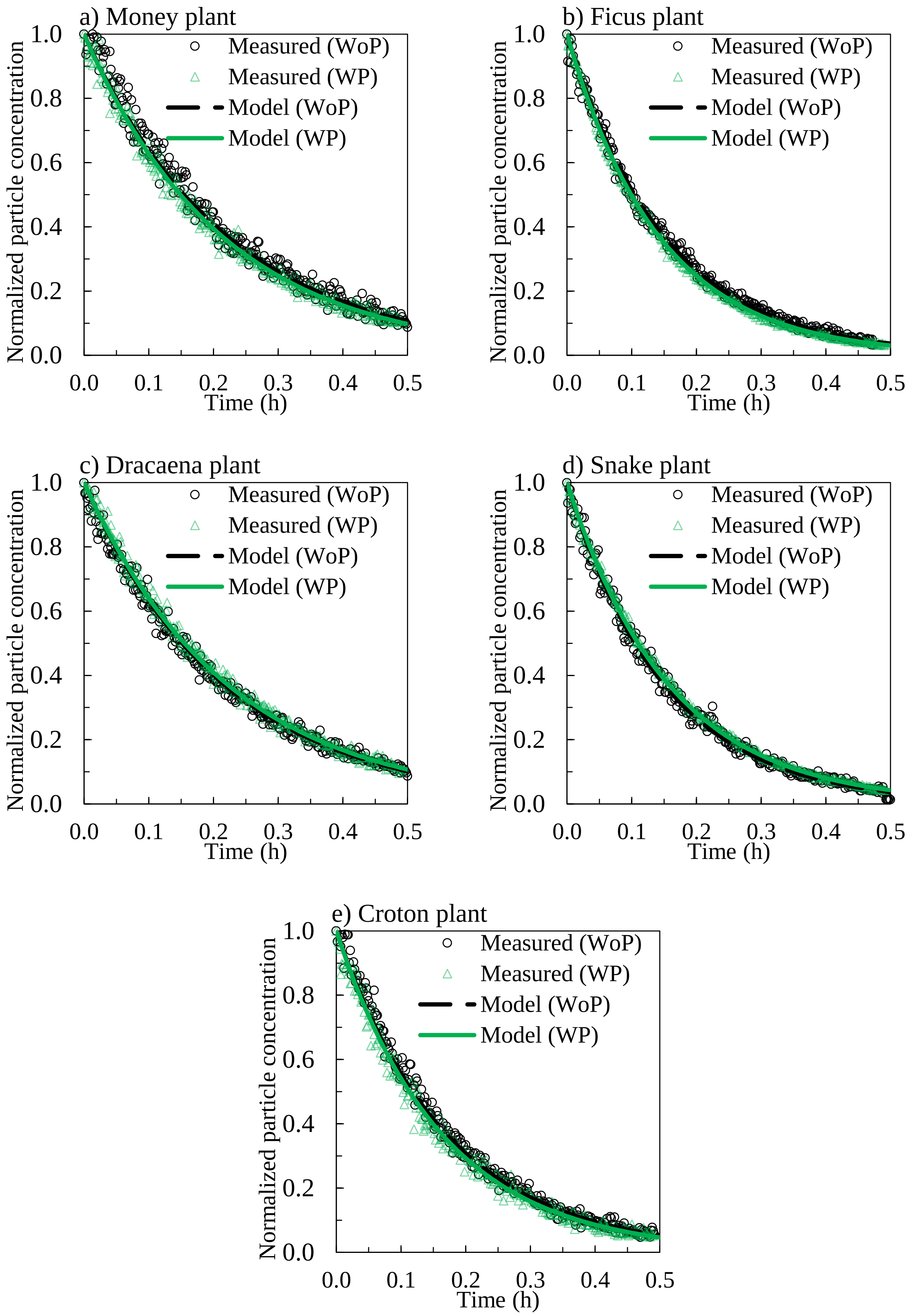


Figure 3.6. Temporal variations in the concentration of 0.35 μm diameter particles inside the environment chamber with and without: a) Money, b) Ficus, c) Dracaena, d) Snake, and e) Croton plant.

3.2.2. Particulate matter deposition velocities and CADR

From the decay tests described above, we estimated the size-resolved deposition velocities for the different plants, as shown in Figure 3.7. The deposition velocities varied significantly between the plants but remained roughly equal across all particle sizes for a particular plant. The size-averaged (average value across all particle sizes) PM deposition velocities ranged between 1±2 cm/h to 93±9 cm/h. The moss had the highest deposition velocity because we calculated it based on the frontal surface area of the moss (0.09 m^2) and not based on its actual surface area, which was much larger but could not be measured due to its irregular shape. We also found that needle-leaved plants had higher PM deposition velocities (29±3 cm/h to 37±4 cm/h) than the broad-leaved plants (1±2 cm/h to 13±2 cm/h). This difference could be due to availability of wax deposit on the leaves, and their surface structure [86–88] which may determine how strongly deposited particles are stuck to the leaf and how easily they are resuspended into the air.

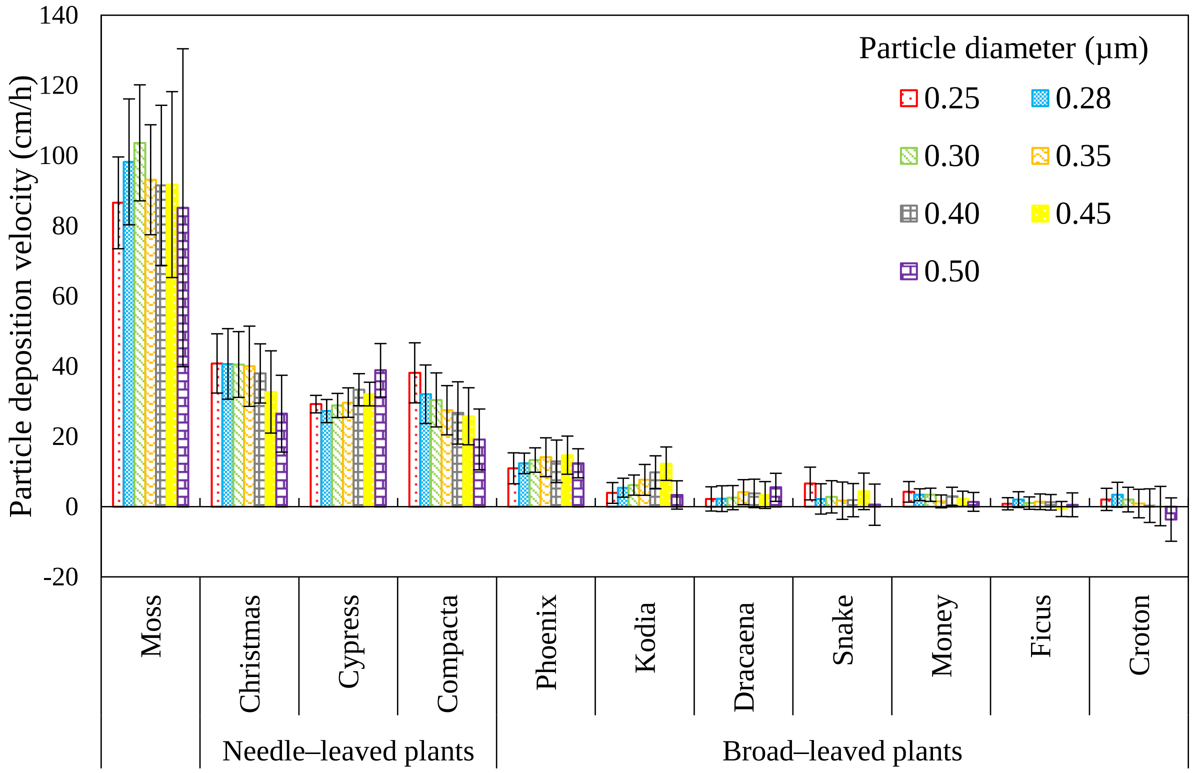


Figure 3.7. Size-resolved particle deposition velocities for the different plant species. Error bars show one standard deviation.

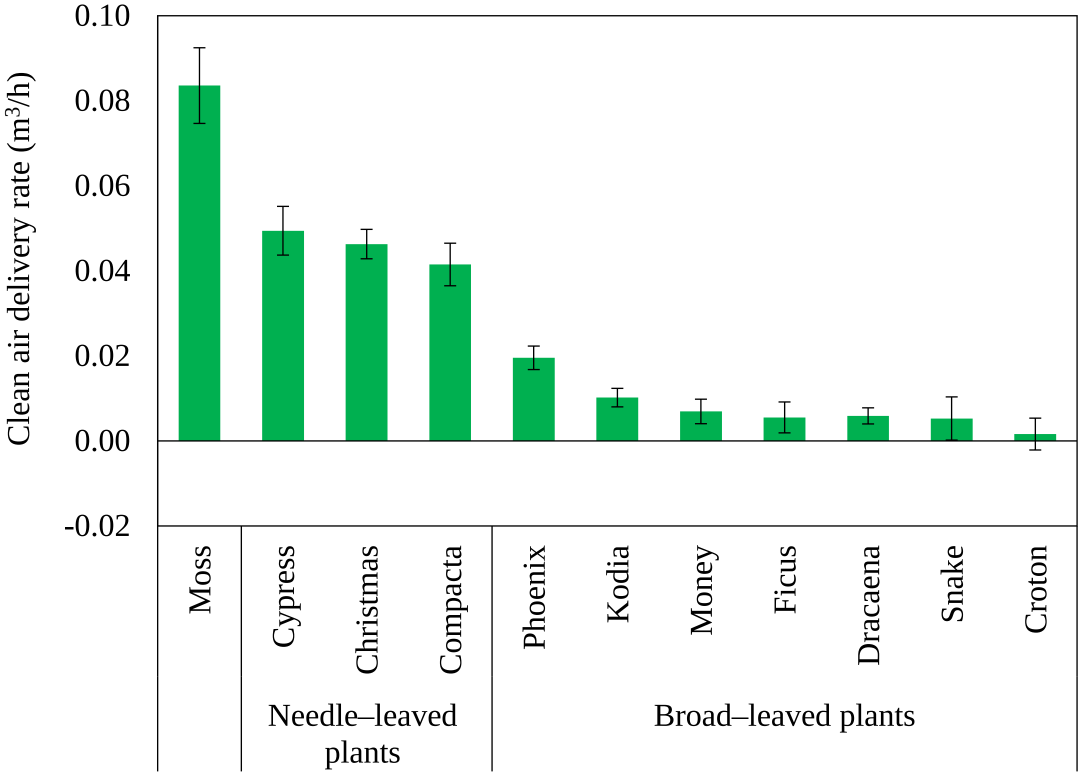


Figure 3.8. Clean air delivery rates (CADRs) for the different plant species.

Figure 3.8 shows the plants' CADRs, as obtained from Eq. 3.3. The values correspond to those obtained for a single plant (a potted plant of height ~0.45 m) or moss specimen (area = 0.09 m^2), and ranged between 0.002±0.004 m^3/h to 0.084±0.009 m^3/h.

It was observed that the moss and needle-leaved plants had significantly higher CADR values than the broad-leaved plants based on their higher PM removal rates. Still, the plants' CADRs were very small compared to conventional filter-based air purifiers, which have CADRs ranging between 170–800 m^3/h [89]. Thus, an unreasonably large quantity of plants would be required to obtain equivalent particle removal rates, indicating the limited PM uptake potential of passive plants. For example, ~107 m^2 of moss or ~2,040 Cypress plants would provide a CADR of 100 m^3/h.

Chapter 4:

Estimation of the number of plants for specific percentage particulate matter reduction in indoor spaces

This chapter presents a model to estimate the number of indoor plants needed to achieve a specific level of particulate matter (PM) reduction within realistic indoor environments. This estimation is crucial because it allows us to determine the optimal quantity of indoor plants required to reduce PM levels in indoor spaces effectively. This information is valuable for improving indoor air quality, directly impacting human health and well-being. By doing this, we thoroughly understand the challenges of using indoor plants to reduce PM. Additionally, it provides valuable insights for architects and interior designers seeking to improve indoor air quality for occupants.

4.1. Methodology

To quantify the effectiveness of indoor plants for removing particles in real-world situations, we used a simple mass balance model, with the below listed assumptions:

Assumptions:

1. **Particle deposition velocity independent of particle size**: In our model's Eq. 4.1 [84], we assumed that the deposition velocity was independent of particle size; thus, the subscript 'i' was dropped. We made this assumption since our measured deposition velocities did not significantly vary with particle size under the test conditions (see section 3.2 of chapter 3). However, indoor particle deposition velocities are known to vary with particle size and airflow conditions [90,91], but accounting for those factors was beyond the scope of our investigation. Nevertheless, Eq. (4.1) can still provide a reasonable estimate of indoor particle behaviour [84].
2. **Well-mixed room conditions**: The model assumes that the room air is well-mixed, meaning that particle concentrations are uniform throughout the space.

3. **Neglecting particle agglomeration**: The effects of particle agglomeration on the overall concentration were neglected.
4. **Constant parameters**: We assumed constant infiltration rates (λ), outdoor particle concentrations (C_{out}), and indoor particle generation rates (E).

Considering above listed assumptions and constant parameters, the PM concentration balance is given by Eq. 4.1 [92] to estimate the contributions of the room and plant surfaces toward particle removal.

$$\frac{dC}{dt} = \lambda C_{out} + \frac{E}{V} - \left(\lambda + \frac{v_R . A_R}{V} + \frac{v_p . A_p}{V}\right) C \tag{4.1}$$

where C and C_{out} are the total indoor and outdoor particle concentrations (in particles/cm^3), respectively, E the PM generation rate due to indoor sources (in particles/h), v_R the particle deposition velocity for room surfaces (in cm/h), and A_R the area of room surfaces (in cm^2).

Furthermore, as mentioned in list of assumptions assuming constant λ, C_{out},E; and constant deposition velocity irrespective of particle size we obtained Eq. 4.1 for the steady-state indoor particle concentrations with and without plants as:

$$C_{WP} = \frac{\lambda . C_{out} + \frac{E}{V}}{\lambda + \frac{v_R . A_R}{V} + \frac{v_p . A_p}{V}} \tag{4.2a}$$

and

$$C_{WoP} = \frac{\lambda . C_{out} + \frac{E}{V}}{\lambda + \frac{v_R . A_R}{V}} \tag{4.2b}$$

where C_{WP} and C_{WoP} are the steady-state particle concentrations with and without indoor plants, respectively.

To quantify the impact of presence of indoor plants on the reduction in the indoor particle concentration, we defined ε as:

$$\varepsilon = \frac{C_{WoP} - C_{WP}}{C_{WoP}} \times 100\% \tag{4.3}$$

We then calculated the required plant area (A_p) and number of plants (N) for achieving a desired value of ε by substituting C_{WP} and C_{WoP} into Eq. 4.3 from Eqs. 4.2a and 4.2b, respectively, which gives:

$$A_p = \frac{\varepsilon}{1-\varepsilon} \times \frac{\lambda + \frac{v_R . A_R}{V}}{\frac{v_p}{V}} \tag{4.4a}$$

Subsequentenlly,

$$N = \frac{A_p}{A_{p,one}} \tag{4.4b}$$

where $A_{p,one}$ is the deposition surface area of a single plant.

We can also determine the required plant area to achieve equivalent PM remove rates provided by the building's air exchange rate by equating $\frac{v_p A_p}{V}$ with λ since both terms represent the first-order loss of PM inside the building (see Eq. 4.1), as given below:

$$A_p = \frac{\lambda V}{v_p} \tag{4.5}$$

The above equation was divided by the building floor area and rearranged to obtain the required area or number densities using the following equations:

$$\rho_A = \frac{A_p}{A_f} = \frac{\lambda h}{v_p} \tag{4.6a}$$

and

$$\rho_N = \frac{N}{A_f} = \frac{\lambda h}{v_p A_{p,one}} \tag{4.6b}$$

where ρ_A is the plant area density (m^2/m^2), ρ_N the plant number density ($plants/m^2$), A_f the building floor area (m^2), and h ($h = V/A_f$) the ceiling height (in m).

4.2. Results and discussion

In this section, we explore the PM uptake capacity of indoor plants, focusing on the quantity of plants needed to achieve specific percentage reductions in PM levels within small-sized room, taking into account varying air exchange rates. Notably, our chamber experiments revealed that moss plant and Cypress plant exhibited the highest efficiency in PM removal.

To quantify this, we employed the model equations (Eq. 4.2 a–b) to calculate the required Moss area and number of plants to achieve the desired amount of particle reduction (ε) in a small residential room of volume 25.92 m^3 (3.0 m × 3.6 m × 2.4 m in size), using Eqs. 4.4a and 4.4b, respectively. The room's surface area to volume ratio (A_r/V) was taken as 3 m^{-1}, a representative value for furnished rooms [93]. The particle deposition velocity on room surfaces (v_R) was taken as 5 cm/h, which was estimated from the deposition loss coefficients reported by Riley et al. [93]. The deposition velocities (see Figure 3.7 in chapter 3) for moss and Cypress plants were taken as 93 cm/h and 31 cm/h, respectively, which are the size-averaged values obtained from our measurements. The area of a single Cypress plant was taken as 0.16 m^2, which is our measured value for a plant of about 0.45 m in height. Similarly, we calculated the required number of plants for other plants.

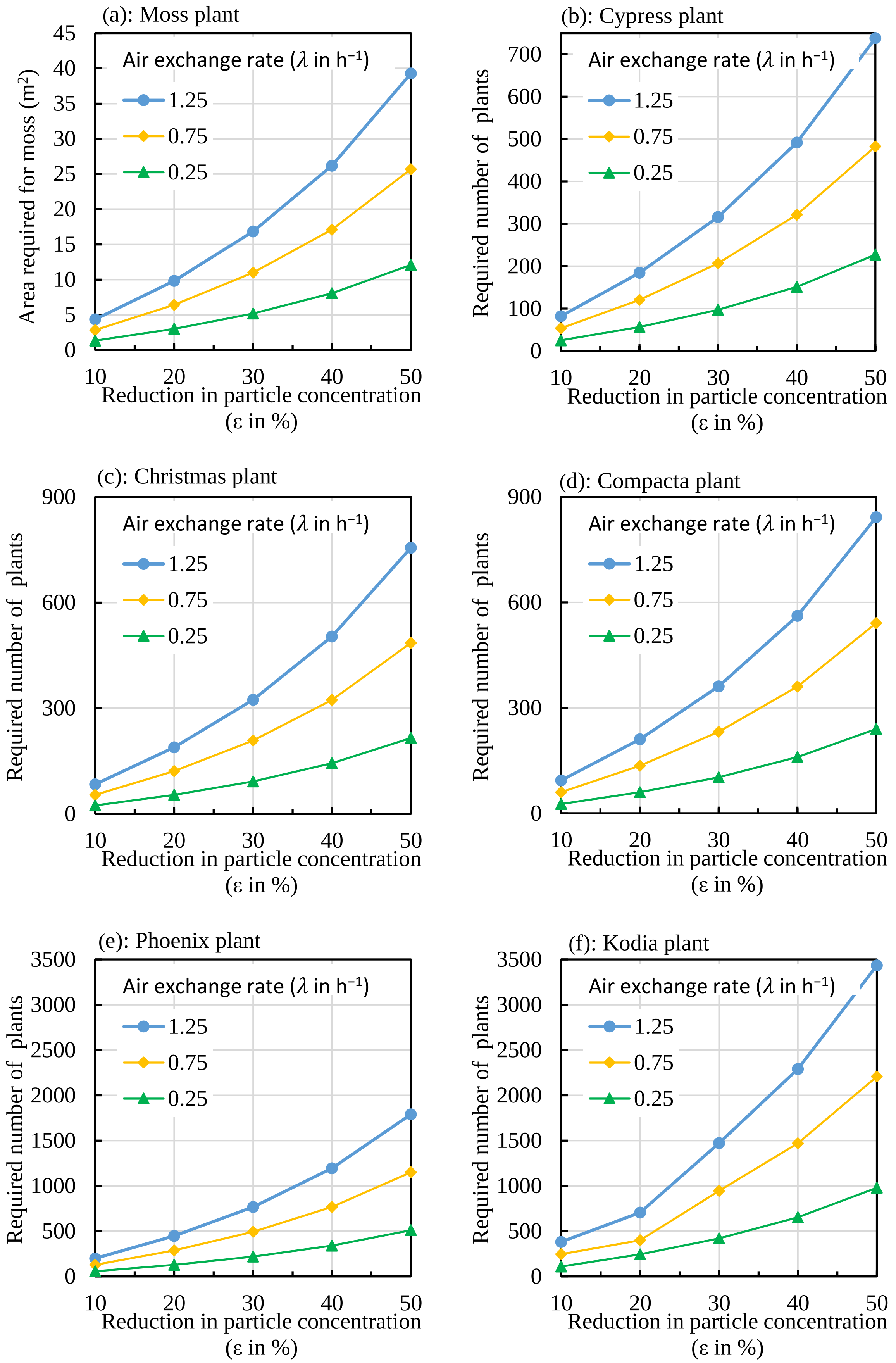


Figure 4.1. Moss area (a) or the number of plants (b: Cypress plant, c: Christmas plant, d: Compacta plant, e: Phoenix plant, and f: Kodia plant) required for desired particle reduction in a room (3.0 m × 3.6 m × 2.4 m in size) at different air exchange rates.

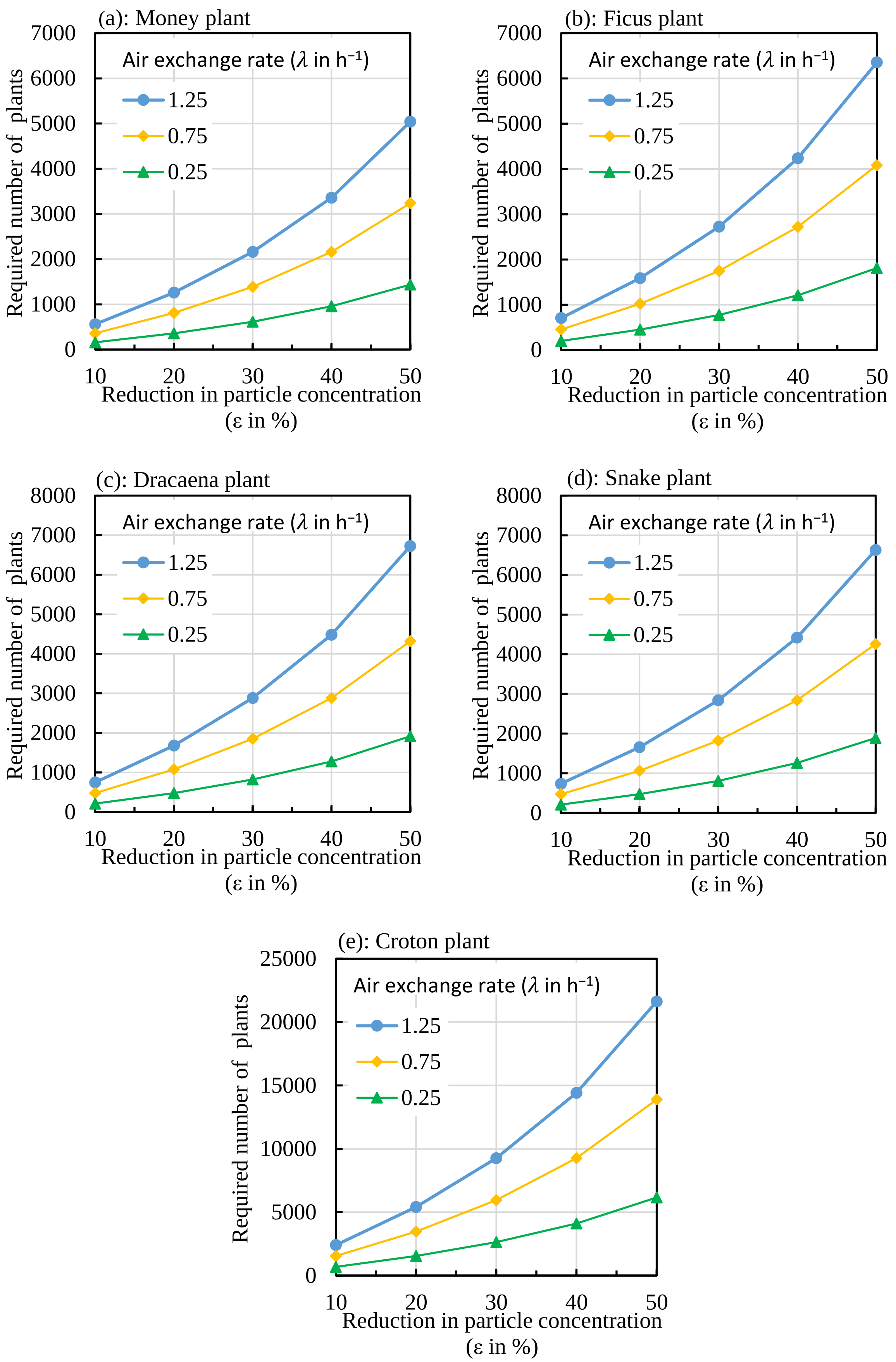


Figure 4.2. Number of plants (a: Money plant, b: Ficus plant, c: Dracaena plant, e: Sanke plant, and f: Croton plant) required for desired particle reduction in a room (3.0 m × 3.6 m × 2.4 m in size) at different air exchange rates.

We calculated the moss area (Figure 4.1a) and the number of plants (see Figure 4.1 and Figure 4.2) required to achieve desired PM reductions (ε) in the room, respectively, at different air exchange rates (λ). Note that, as ε increases, the area of moss needed and the number of plants also increase significantly. For example, for $\varepsilon = 10$ %, approximately 1.2 m^2 of moss or about 23 Cypress plants would be required at $\lambda = 0.25\ h^{-1}$. However, at the same λ, for $\varepsilon = 50$ %, the area of moss needed exceeds 10 m^2, and the number of plants is greater than 200.

Figure 4.1 and Figure 4.2 both shows that as λ increases, a much larger moss area and number of plants would be required to achieve the same particle reduction levels. This happens because as λ increases, the PM removal by air exchange also increases, meaning that more plants are needed to effectively compete with this removal mechanism and affect indoor PM levels. Similarly, as the room size is increased, the required plant quantities will also proportionally increase because of the linear relationship between the plant area (A_p) and the room air volume (V), according to Eq. 4.4a (keeping $\varepsilon, \lambda, v_R, v_p$, and A_R/V constant).

Using Eqs. 4.6 a–b, we also estimated that 0.65 m^2/m^2 of moss, or 12–15/m^2 needle-leaved plants, or 30–300/m^2 broad-leaved plants would remove equivalent PM from a building (h = 2.4 m) as that expelled by a modest air exchange rate of 0.25 h^{-1}. The required plant density will further increase (linearly with λ, as shown in Eq. 4.6 a–b) if they are to provide equivalent reductions at higher air exchange rates. Thus, an excessive number of plants would be required to even compete with PM removal provided by the building's infiltration air exchange.

Chapter 5:

Effect of indoor plants on office occupants' perception, comfort, and performance

This chapter aims to present the influence of indoor plants on occupants' emotional-state, performance, and perceived comfort within an indoor environment. To investigate this, we tested the following three hypotheses:

$H1_0$. Presence of plants indoors does not impact occupants' subjective perception of their indoor environment.

$H2_0$. Presence of plants indoors does not impact occupant affect (emotions and mood).

$H3_0$. Presence of plants indoors does not impact occupants' cognitive performance.

5.1. Methodology

The study was conducted in an air-conditioned classroom on the college campus of Birla Institute of Technology and Science, Pilani (BITS-Pilani). Pilani located in western India, in the state of Rajasthan, and it has a semi-arid climate [94]. We conducted the study in the month of April 2023. A weather station, located about 500 m from the classroom, provided the local weather data during the study days. During this period, the recorded temperature, relative humidity, and wind speed ranged between 14.5–42.6 °C, 10–86 %, and 0–6 m/s, respectively. A little rainfall (0.2, 2.5 mm) happened during a couple of days in April, but not on study days.

5.1.1. Experiment design

A between-subject design was used since the intervention consisted of having plants in the occupied space, it would not have been possible to blind the participants to the intervention. Hence, a between-subject study design was chosen to minimize any bias that could have been introduced from the physical presence of plants in only one session. Participants were blinded to the real objective of the study. They were informed that the study aimed to get occupants' feedback on indoor comfort. Each participant was part of either the without-plant group (control group, WoP) or the with-plant group (treatment group, WP).

The experiments were carried out during four successive weeks, with Sundays excluded from the schedule. The regular class schedule on campus gives students a break on Sundays (not Saturdays), so sessions were not scheduled on Sundays. Each session was scheduled from 5:30 pm – 6:25 pm to ensure the availability of the participants and the classroom.

Figure 5.1. Representative images of the indoor plant species used in this study.

Based on previous studies [52,53,95], we chose two commonly used indoor plant species: money plant (*Epipremnum aureum*) and areca palm (*Dypsis lutescens*), which can grow in medium to low-light conditions [78]. In total, five healthy money plants and three healthy areca palms were placed in earthen pots inside the indoor space (see Figure 5.1). We used a mix of plants to replicate how indoor plants may be actually placed indoors. Those plants were 1–1.2 m high so that they could be placed on the floor and still be visible to occupants seated at desks.

5.1.2. Participant recruitment

Participants needed to be at least 18 years old, have no health issues like fever, cough, or cold on the day they would participate, and should not have been diagnosed with a sleep disorder or respiratory health issues. Participants were recruited through convenience sampling. Notice board postings and email invites were used to inform the potential pool of participants on campus. Potential participants who contacted us and met the criteria listed above were recruited. We did not design to recruit matched participants for the two groups, except for maintaining the same sex ratio in both WoP and WP groups. Recruited participants were assigned at random to one of the two groups. We primarily targeted undergraduate students, excluding those in their first year of study. All participants were Indians, though they came from different states of India. They had been staying on campus for more than one year, thus well-acclimatized to the local climate. The study protocol was approved by the student welfare division of BITS Pilani.

One day before the session, an online orientation was organized. The participants signed an informed consent form, accenting their participation in the study. They were made aware that they could still withdraw from the study at any point if they did not want to continue their involvement. As a token of appreciation, after each session, five participants received a gift valued at ₹100 (~$1.2), while one randomly selected participant got a prize of ₹250 (~$3.0).

A total of 120 participants were recruited (102 males and 18 females). Each group got assigned of 60 participants. These 60 participants were further subdivided into ten subgroups. While it was intended to have five males and one female in each subgroup, due to the unavailability of enough female participants, we could not maintain this sex ratio in two of the subgroups. Two participants (one during a WoP session and the second during a WP session) could not attend the main session. To maintain a consistent set-up, we replaced the absent participant with a "dummy" participant drawing from volunteers who were conversed about the study. Their input was omitted from the analysis. Table 5.1 summarizes some key demographic measures and sleep scores on the Groningen sleep quality scale (GSQS) for the WoP and WP groups.

Table 5.1. Participants' information (n=118), median (25th percentile, 75th percentile)

Measure	**Median (25th percentile, 75th percentile)**	
Group	**WoP**	**WP**
Height (m)	1.8 (1.7, 1.8)	1.8 (1.7, 1.8)
Weight (kg)	67 (61, 80)	71 (60, 79.5)
BMI (kg/m^2)	22.4 (19.8, 25.9)	23.4 (20.1, 25.9)
Age (years)	20 (20, 21)	20 (19, 21)
Clothing (clo)	0.3 (0.23, 0.33)	0.3 (0.26, 0.33)
Sleep score (GSQS)	5 (1, 8)	3 (1, 6)

5.1.3. Experimental set-up and measurements

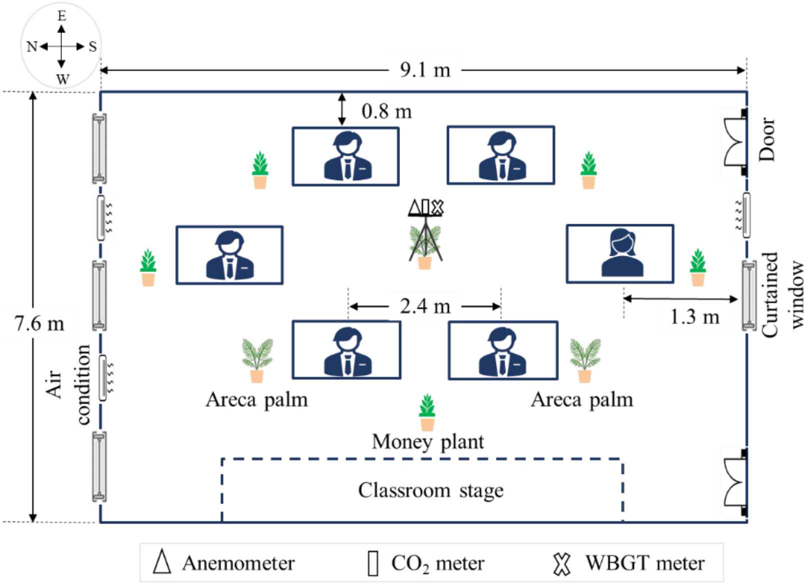
The layout in the chosen classroom was modified to simulate people in an open-plan seating space (see Figure 5.2a and 5.2b). The room (W×L×H: 7.6 m×9.1 m×3.6 m) was located on the first floor of a double storey building. The walls of the room do not receive any direct sunlight. To nullify the effect of varying outdoor conditions, windows and doors were closed and covered with white curtains/sheets.

The classroom has three split air conditioning units (see Figure 5.2a) and LED lighting. Six desks were arranged in the classroom to be seat six participants. Indoor temperature was maintained between 24–26 °C during the sessions. This temperature range conforms to the summer thermal comfort range for building occupants [96]. Lighting in the room was measured prior to sessions and provided an illuminance of 270±15 lux on the desks' work-surface, a level recommended for office desks [97].

The equipment measuring indoor environmental conditions were set-up at the centre of the room, at least 1 m away from any occupant and at a height of 1.1 meters from the ground. The height matches the breathing zone of seated occupants. Throughout the sessions, we continuously monitored and logged the air temperature, air speed, relative humidity, globe temperature, and CO_2 level at this location (marked in Figure 5.2b). Following the conclusion of each session, we measured the decay of CO_2 levels in the room, from 6:30 pm to 10:30 pm to estimate the ventilation rate.

Prior to starting the experiment in April, measurements were conducted in the room to assess uniformity of temperature, air speed, and lux level within the room where air conditions are operating. Based on this information, a hexagonal seating arrangement (please see Figure 5.2) was finalized for the participants ensuring a minimum 2.4 m distance between each participant. This distance was chosen to assure work environment privacy for the participants.

a. Representative open-plan seating space



b. Study conditions

c. Study timeline

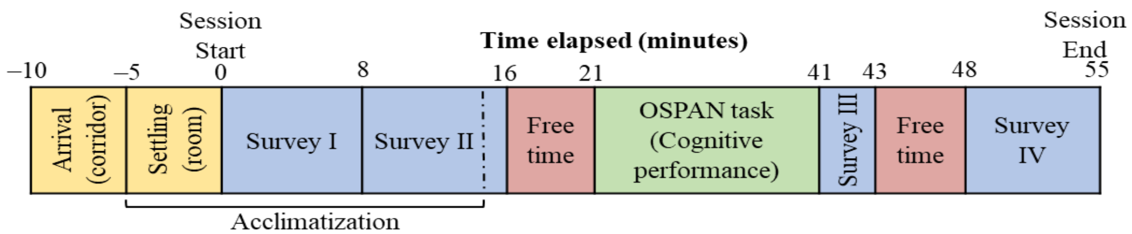


Figure 5.2. (a) The representative simulated open-plan seating space, (b) study conditions, and (c) study timeline.

The positions of potted plants were chosen such that each participant had a clear view of 2 to 3 plants in their peripheral view while sitting, without any interference with their activities. Plants were watered prior to the sessions, and their foliage was washed. We ensured that through the period of experiments, the plants remained healthy.

5.2. Experimental procedure

5.2.1. Orientation session

To familiarize the participants with the process, we organized an online orientation session, one day before their session. This involved sharing an orientation questionnaire with the participants. The questionnaire included details of the venue, session time, participant ID (an anonymized ID to use during the sessions), background questions about personality and health, and instructions for the session. The instructions also included the process for downloading and installing the Psychology experiment building language (PEBL) platform [98] for the cognitive tasks. We requested participants to practice in at least one round of the OSPAN task (details in section B.4.1 of *Appendix* B) to get familiar with the software platform and its layout.

Participants were asked not to engage in any strenuous physical activity before their session and follow their usual routine and sleep schedule prior to the session. To create a focused and distraction-free environment during the main session, we requested participants to wear plain-colored, comfortable clothing and refrain from wearing any perfume. We also asked them to keep their cell phones silent during the session and maintain silence. The session concluded with participants submitting the orientation questionnaire and confirming their willingness to participate.

5.2.2. The study session timeline

Prior to each session, the room was cleaned using cleaning agents that did not have strong odours. Participants were asked to arrive 10 minutes before the scheduled start time. This gave them some time to familiarise themselves with the space and also enabled us to start at the scheduled time. A quick note was made of participant clothing levels at this point. The participants entered the room together at 5:30 pm and were assigned a random seat. They received the survey questionnaires in their email at the specified times shown in Figure 5.2c. Survey I included questions about sleep quality and work environment. Survey II and IV were about thermal comfort, IAQ, SBS, and emotions. Survey III followed the cognitive tasks and asked specifically about their self-assessed performance.

In their free time during the sessions, participants were free to do their own work like reading, writing, etc. maintaining silence. Participants were not instructed in any manner to look toward the plants or the overall room aesthetics. The timeline of WoP and WP sessions were identical. The only difference between the two groups of sessions was the presence or absence of plants in the room.

5.2.3. Participants' feedback and assessments

In Survey I, we asked participants to assess the indoor environment, including the lighting, visual comfort, noise, aesthetics, space, cleanliness, and the overall room environment quality. Since last night's sleep can impact work performance and perception [99–101], we asked participants to rate their last night's sleep score on the GSQS. We also asked participants to provide information on their activity level for the 30 minutes before coming for the session. The complete survey questionnaires have been provided in section B.4 of *Appendix B.*

Surveys II and IV were identical and asked participants to assess their thermal perception, including thermal sensation vote (TSeV), thermal satisfaction vote (TSaV), thermal preference vote (TPV), humidity sensation vote (HSeV), and humidity satisfaction vote (HSaV) with the room's thermal, humidity, and air movement. We evaluated IAQ perception under the following categories: air freshness, odours, and overall air quality. A series of questions related to SBS symptoms were used to assess the impact of the indoor climate on occupant well-being. There were nine questions (see section B.4.4 of *Appendix* B) in this section related to ailments of eye, nose, and throat.

During Survey II and Survey IV, participants also rated their assessment of their current emotional state on the circumplex model of affect [102]. “Affect” is an individual’s immediate expression of their emotional state, as in how they might be feeling at a given moment. The model contains eight categories (octant) of emotions: high arousal positive (HAP), positive (P), low arousal positive (LAP), low arousal (LA), low arousal negative (LAN), negative (N), high arousal negative (HAN), and high arousal (HA) (see Figure B.1 in *Appendix B*). Each category has three to four adjectives (words) associated with it.

We used the Operation Span (OSPAN) [103] to assess cognitive performance of the participants. OSPAN targets working memory. Working memory is one of the core executive functions [104] and as such, an important measure of cognitive performance. In previous research, OSPAN has been shown to be able to distinguish performance under different indoor environmental conditions [105]. OSPAN was administrated using the PEBL platform. PEBL was installed by the participants on their laptops one day before the main session. OSPAN involves memorizing a series of letters while solving simple additions and subtractions (arithmetic distractor). The intervening arithmetic tasks are intended as a distractor that increases cognitive load. The OSPAN task in the PEBL platform is set-up so that participants have a complete a practice round of tasks before proceeding to the actual test. In Survey III, participants were asked to self-assess their performance in the OSPAN task via a series of questions, using 5-point Likert scales. The questions covered the following five items: Task difficulty, Effort level, Time pressure, Fraction of capacity work was performed at, and self-rated performance.

5.2.4. Data processing and statistical analysis

From the various sources, e.g., instruments, PEBL, Google forms for subjective questionnaire, the data was collated using Microsoft Excel spreadsheets. All statistical analysis was carried out using R, on the R Studio platform. The responses collected from the two "dummy" participants were removed prior to analysis. For the cognitive performance task, three (one from WoP session and two from WP session) responses were removed because the respective participants could not complete their test due to a software glitch. One response (from the WoP session) was further removed as the scores were an outlier.

When checking for significant differences, we used the t-test for continuous variables (e.g. indoor temperature) and Mann−Whitney U test (paired and unpaired) for categorical variables (e.g. subjective votes) [106]. The subjective perceptions of thermal environment, air quality, SBS were compared between WoP and WP sessions were compared using the responses to Survey IV. By that time participants would have spent over 30 minutes in the room and would have adjusted to this indoor environment [107]. The participants provided feedback on the indoor climate first within 10 minutes of entering the space (Survey II) and then at the end of the session, having spent over 40 minutes in the space (Survey IV). Hence, we also compared how the indoor climate perception evolved, between Surveys II and IV, within each type of session. These two surveys were the same in terms of their content. The intention was to understand if the evolution was different for WoP vs WP sessions.

We set a level of significance (α) equal to 0.05 for all tests of significance. Effect sizes (Mann-Whitney *r*, and Cohen's *d*) were calculated for all tests of significance using the R package "rcompanion" [108]. Here, the calculated *r* and *d* value is the general effect size statistic for the Mann−Whitney test and t-test, respectively. Effect size were interpreted as- negligible: $|r| < 0.1$, $d < 0.2$; small: $0.1 \leq |r| < 0.3$, $0.2 \leq d < 0.5$; moderate: $0.3 \leq |r| < 0.5$, 0.5

≤ *d* < 0.8; and large: |*r*| ≥ 0.5, *d* ≥ 0.8 [109,110]. For all tests, both *p* values and the effect size have been reported and no adjustments were made to α.

5.3. Results

5.3.1. Environmental conditions

The indoor environmental conditions and outdoor conditions from the WoP and WP sessions are summarized in Table 5.2.

Table 5.2. Indoor and outdoor conditions during sessions

Measure	**Median (25th percentile, 75th percentile)**		**Measurement uncertainty**
Group	**WoP**	**WP**	
Indoors			
Air temperature (°C)	24.9 (24.5, 25.3)	24.7 (24.3, 25.3)	±0.8
Globe temperature (°C)	24.9 (24.4, 25.4)	24.7 (24.2, 25.2)	±0.6
Relative humidity (%)	36 (33, 39)	37 (34, 42)	±3
Air speed (m/s)	0.05 (0.01, 0.12)	0.05 (0.00, 0.15)	±0.1
CO_2 (ppm)	949 (868, 1014)	956 (885, 1019)	±35
Ventilation rate (h^{-1})	0.10 (0.09, 0.13)	0.11 (0.11, 0.13)	NA*
Outdoors			
Air temperature (°C)	33.9 (32.6, 36.6)	34.3 (33.2, 35.2)	±21
Relative humidity (%)	17 (15.2, 21.3)	17 (14.5, 23.5)	±2.5
Air speed (m/s)	0.2 (0, 0.3)	0.1 (0.1, 0.5)	±1.1

*Ventilation rate calculated from CO_2 decay measurements after each session.

The room's air and globe temperatures were between 24–26 °C, and humidity ranged between 30–45 %. Thermal conditions were within the summer thermal comfort zones [96]. Like the indoor conditions, the outdoor conditions during WoP and WP sessions were also comparable.

5.3.2. Participant demographics and personality

Participants in the two groups did not have significantly different age (*d* = 0.24, *p* = 0.2), height (*d* = 0.21, *p* = 0.2), weight (*d* = 0.05, *p* = 0.7), or BMI (*d* = 0.03, *p* = 0.8). Between the two sessions, the clothing resistance of ensembles worn by participants also did not differ significantly (*d* = 0.19, *p* = 0.3). Both groups had similar sex ratios (M:F::5:1; excluding one session for each WP and WoP session where there were no females). The sleep scores for the WoP and WP groups were not significantly different (*r* = 0.17, *p* = 0.06). The test results from the Big Five personality test questions showed that the participants in the two groups did not have significantly different scores under the different personality ($|r|$ = 0.04–0.12, and *p* = 0.13–0.65), except for Conscientiousness (*r* = −0.23, *p* = 0.01). The responses of the WP group were slightly higher on the Conscientiousness questions scale (3 vs 3.5, median). The two groups of participants thus had similar anthropometric and demographic features. Their personality types and last night's sleep scores were also similar.

5.3.3. Plants effect on work environment perception

Of the questions examining participants' perception of their work environment, significant differences in responses were noted for the question on "room decoration (*r* = −0.42, $p < 0.0001$)" and "overall visual comfort (*r* = −0.22, *p* = 0.01)". The WP group felt the room decoration and overall visual comfort were better. We did not observe any significant impact of plants on the remaining questions on work environment perception. Results for these comparisons have been detailed in Table B.2 of *Appendix B.*

5.3.4. Plants effect on subjective responses regarding indoor climate and well-being

Other than thermal sensation and humidity sensation, no significant differences were noted for the responses obtained under other measures of thermal environment, IAQ, and SBS symptoms between the WoP and WP groups. Among SBS symptoms, WP session participants felt their breathing to be slightly easier (r = 0.11), though this difference was not statistically significant (p = 0.11).

Fig. 5.3 provides the TSeV for the two groups from Surveys II and IV. In this and subsequent figures, the rectangle within each box represents the mean value of the votes. After spending just over 30 minutes in the space, the TSeV of the WoP group got significantly warmer between Surveys II and IV (r = −0.61, p = 0.001). However, TSeV of the WP group did not change significantly (r = −0.08, p = 0.36) over this duration. By the end of the session, the WP group felt their environment to be slightly cooler (mean TSeV difference = 0.42, r = 0.18, p = 0.02) than the WoP group.

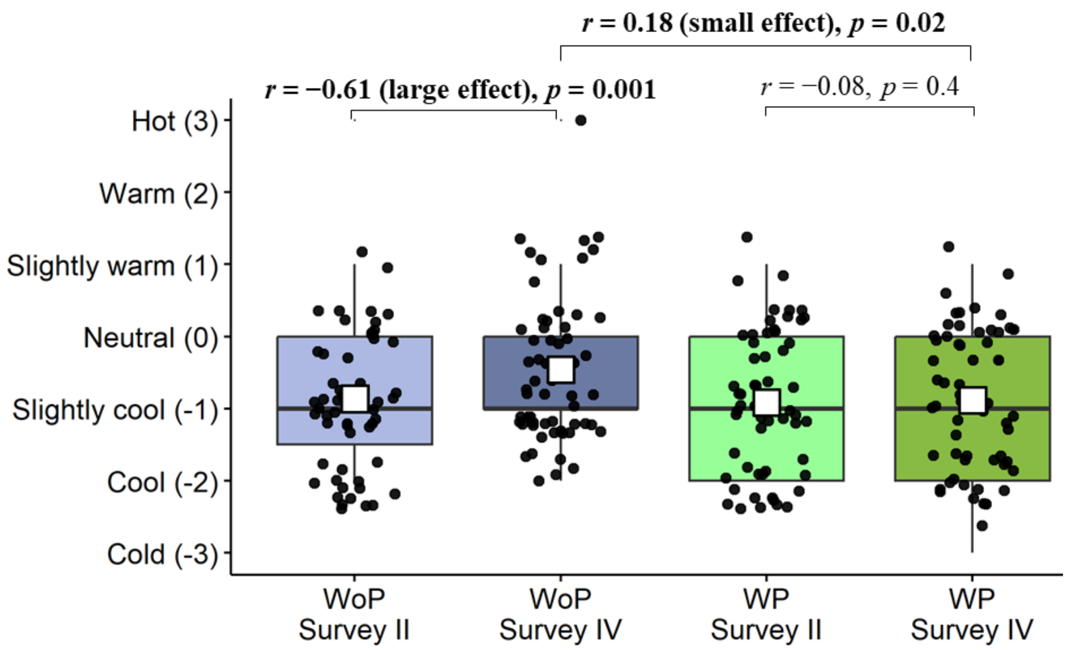


Figure 5.3. Comparison of thermal sensation votes (TSeV), for the sessions without (WoP) and with plants (WP).

After 40 minutes in the room, thermal satisfaction votes (TSaV) of the WP session remained about the same while the WoP session TSaV reduced (r = 0.34, p = 0.02), as illustrated in Fig. 5.4. Comparing Surveys II and IV, we did not find any significant evolution of participants' perception for any of the other subjective measures of indoor climate. HSeV did not change significantly throughout the session for either group, as shown see Figure B.2

in *Appendix* B. The HSeV was slightly drier for the WoP group in Survey IV (r = 0.18, p = 0.03) than the WP group.

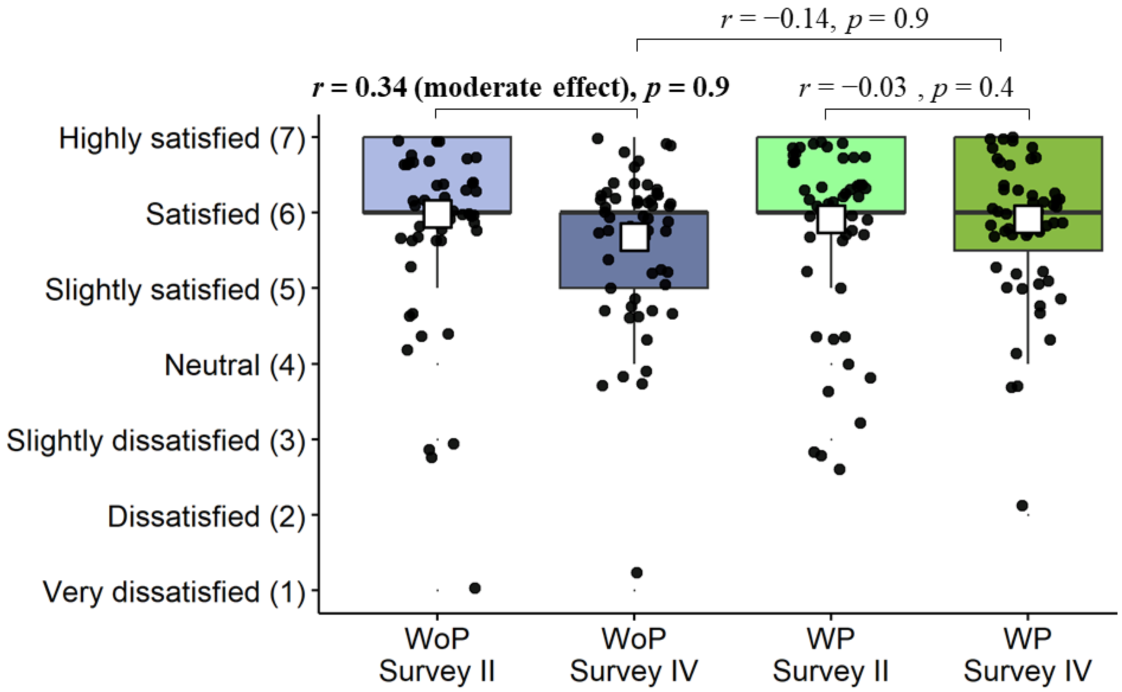


Figure. 5.4. Comparison of thermal satisfaction votes (TSaV), across each session type and between WoP and WP sessions.

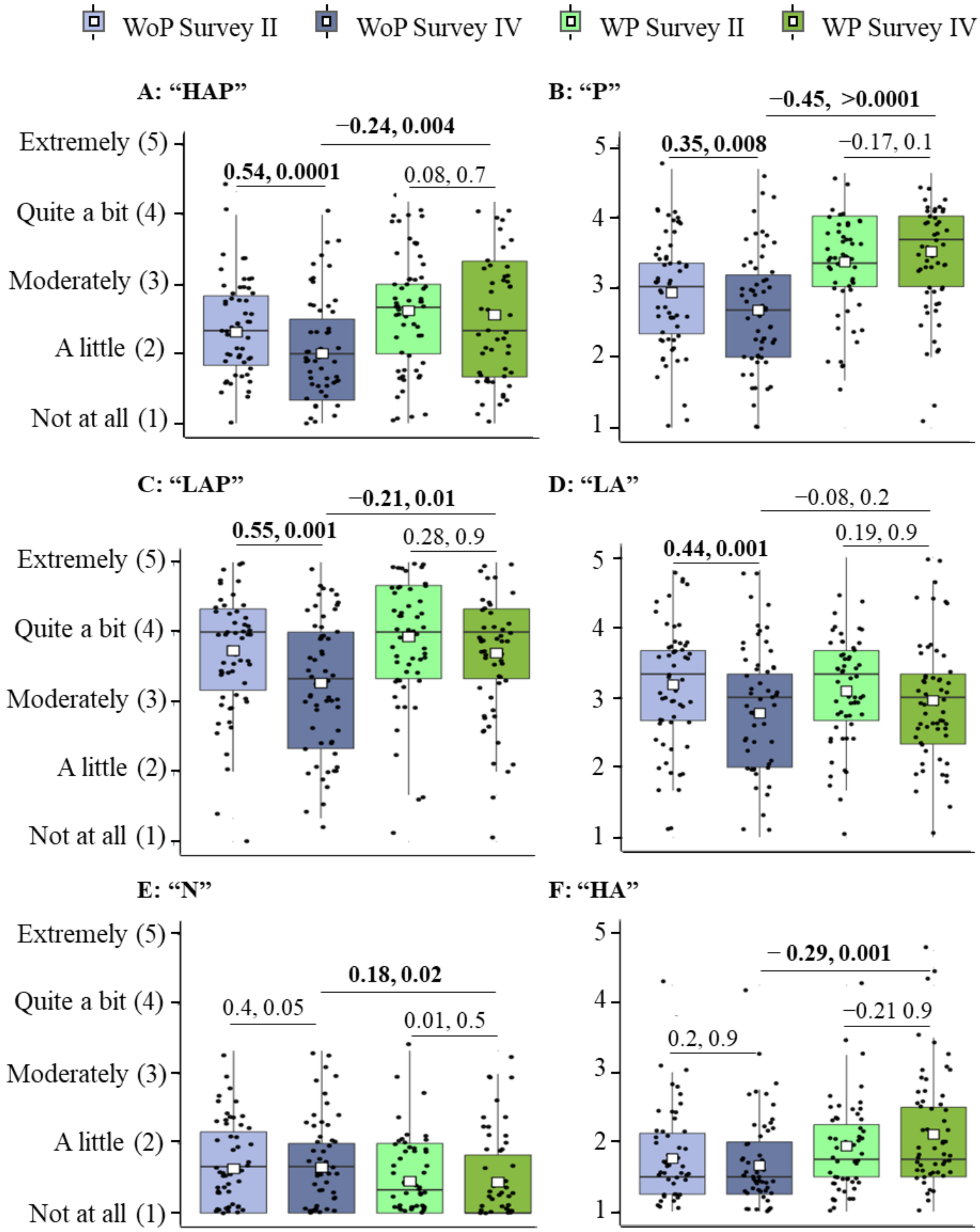


Figure. 5.5. Comparison of affect votes, across each session type and between WoP and WP sessions. Note: The two values written above the horizontal lines connecting two box plots are r value followed by p value.

5.3.5. Plants effect on participant affect

A comparison of the mean votes of WoP and WP groups, under the different affect categories in the circumplex model, has been summarized in Fig. 5.5. Comparing the responses between Survey II and Survey IV, participants felt sustained positive affect when plants were present. For the WoP sessions, participant responses on the HAP, LAP, and LA affects dropped significantly between Survey II and Survey IV, indicating a drop in positive emotions. A similar change was not found in WP participants' affect. Between the WoP and WP group, participants were found to have started off on a higher rating for the HAP, P, and LAP affects. In Survey IV, the WP group rated significantly more positive (HAP, P, and LAP) and less negative (N) affect. The WP participants were also likely to feel more stimulated/alert (HA).

5.3.6. Plants effect on cognitive performance

We evaluated performance in the OSPAN task under three headings: percentage score in the working memory task (WMT), percentage score in the distractor task (the arithmetic problems, DT), and average response time for the distractor task. The PEBL platform concurrently calculated all three metrics as the test was administered. The average response time for distractor tasks was used as an indicator of the time response for the task. No significant difference was observed for the three metrics between WoP and WP sessions, as summarized in Fig. 5.6.

5.3.7. Plants effect on self-assessed performance

The participant's self-assessed performance, on all five metrics used for evaluation, did not differ significantly between WoP and WP sessions. The results of these comparisons have been summarized in Figure 5.7.

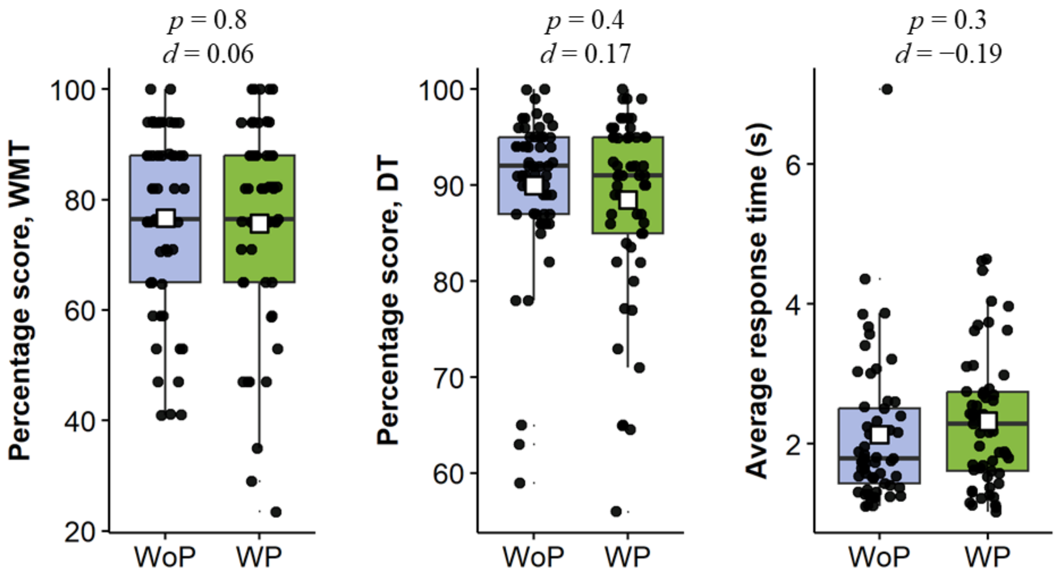


Figure. 5.6. Comparison of cognitive performance between WoP and WP sessions.

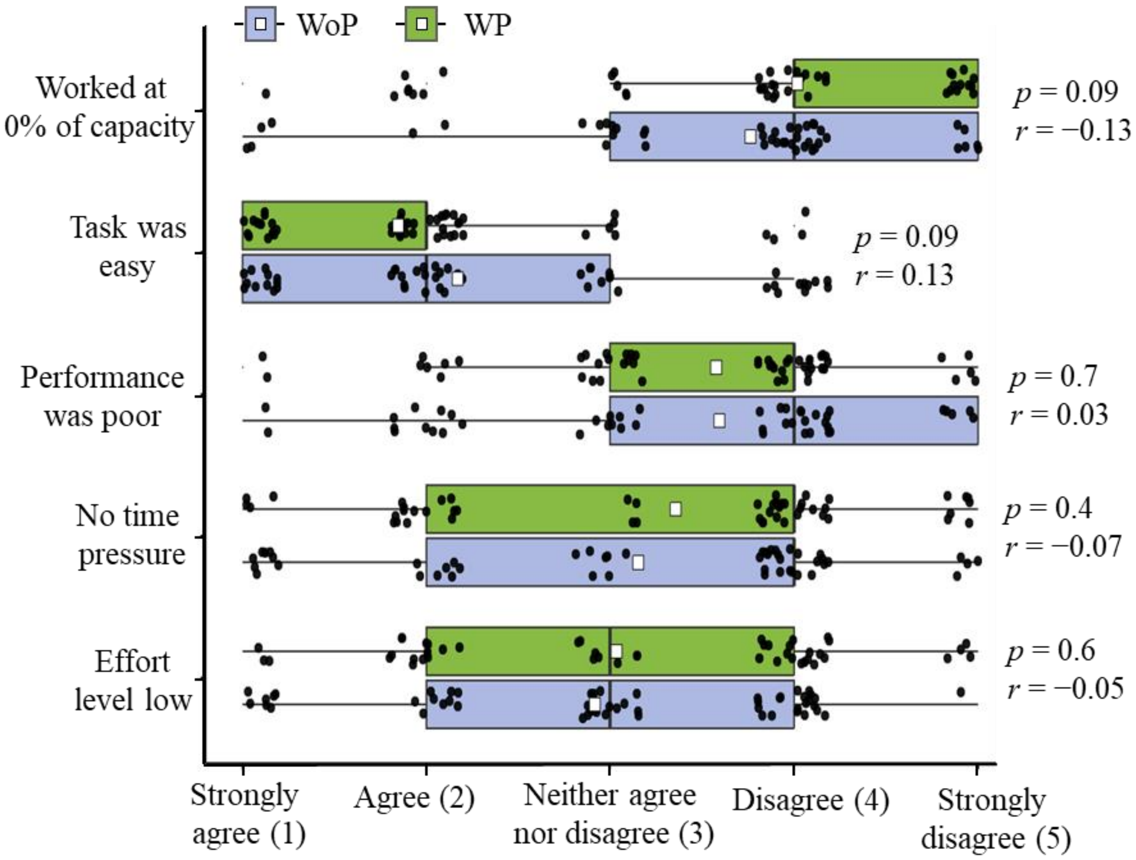


Figure 5.7. Comparison of self-assessed performance between WoP and WP sessions.

5.4. Discussions

Indoor plants have been a part of interior design and décor for a long time. Recent realizations for including biophilic elements have renewed the investigations to understand the impact of indoor plants on the perception of the indoor thermal environment, IAQ, and productivity. Plants can have co-benefits for occupants, e.g., improved appreciation of the indoor space, more positive emotions, and improved work performance. We designed the current study, involving human participants, to test for some of those possible benefits. Unlike most previous works studying the impact of indoor plants, we performed an a priori power analysis, the study met the requirements of intention-to-treat analysis, and both groups had similar demographics. Participants were blinded to the intervention, viz. plants and indoor conditions were maintained similarly for WoP and WP groups.

5.4.1. Plants effect on work environment perception

In addition to the change in indoor environmental perception, the plants also improved the perception of "room decoration ($r = -0.42$, $p < 0.0001$)" and "overall visual comfort (r: −0.22, p: 0.01)". The improved perception of room decoration and visual comfort was an expected result, considering the biophilic nature of indoor plants [46]. Participants of the WP session noticed the presence of plants and appreciated their aesthetic and visual impact.

5.4.2. Plants effect on subjective responses regarding indoor climate and well-being

Based on responses received in Survey IV, when participants had been in the room for over 40 minutes, they experienced the WP conditions as slightly cooler ($r = 0.18$, $p = 0.02$) and less dry ($p = 0.03$, $r = 0.18$) than WoP conditions. Although these differences in perception between WoP and WP sessions corresponded to small effect sizes but perceptible and hold practical significance in the context of occupant thermal comfort. These changes were likely only in participants' subjective perception since the temperature and humidity conditions during both sessions were within similar bounds. The mean thermal sensation vote between WoP and WP sessions differed by 0.4 scale points. For a 0.4 point thermal sensation difference on the Predicted Mean Vote (PMV) scale, with all other parameters remaining the same, a change of 1 °C would be needed [111]. The thermal conditions between WoP and WP sessions did not differ as much. Hence, we rejected $H1_0$.

We also compared how perceptions evolved during the sessions (Survey II vs Survey IV). Without plants, the TSaV worsened as the session progressed. It did not change significantly with plants present. Similarly, without plants, TSeV got warmer, while it did not change with plants. Humidity sensation was always significantly drier without plants. The physical presence of plants caused a cooler and less dry perception, while the absence of plants led to a gradual worsening of thermal satisfaction and a warming of thermal sensation. It is plausible that the participants interpreted the presence of plants to mean a cooler, less dry, more satisfying space. Outdoor urban green spaces are known to create physically cooler and more moist environments that attract people [112]. In the minds of the participants, this association may have been extended to indoor greenery even without an objective change in the thermal environment. It could also be that viewing plants provided a positive distraction, improving participants' perception in the WP session [50,113].

The difference in thermal sensation we noticed aligns with the findings of Ko et al. [114]. In their work, view through a window (of plants outdoors) made participants feel slightly cooler than the control condition where window views were blocked (small effect sizes, $r = 0.29$). The study of Ko et al. [114] also had a similar exposure duration as our work, though their study design was within subjects. It stands to reason that viewing plants outdoors could have similar impacts on perception as the presence of plants indoors.

5.4.3. Plants effect on participant affect

We used a standardized measure called the circumplex of affects, focusing on the "right now" emotional state of occupants, otherwise known as affect. The circumplex model is an easy-to-use, consistently repeatable measure, that has been extensively used in relevant literature [114–117]. It can be a useful instrument for future similar studies involving plants/indoor greenery.

With plants, participants experienced more positive emotions, felt more stimulated, and less negative emotions compared to those without plants. The biggest observed impact was for the average score on positive affect adjectives – the P octant ($r = -0.45$, $p < 0.0001$). During the WoP sessions, participant responses even showed a drop in positive affect, while in WP sessions participants felt sustained positive affect. We thus rejected $H2_0$. Similar to our findings, Ko et al. [114] also reported more positive emotions when participants had the window view, i.e., better ratings for HAP, P, LAP, LAN, and N octants of the affects circumplex. Further, the maximum impact in their study was also on the P octant ($r = 0.36$, $p = 0.0007$).

5.4.4. Plants effect on cognitive performance and self-assessed performance

The presence of plants did not significantly impact the self-reported or objectively measured cognitive performance of participants. With plants, the participants' performance in the distractor test was slightly worse (lower accuracy and increased response time); however, the effect sizes were small ($|d| = 0.17$–0.19, $p = 0.3$–0.4). Due to a lack of significant differences, we fail to reject $H3_0$. These results were similar to previous studies [52,55,72,75], which showed no effect on subjectively or objectively assessed cognitive performance. They were contrary to studies that reported enhancement in subjective [55,57,59] or objective performance [55,59]. The effect of plants on performance and productivity can be task-dependent [10, 25], and depend on the density, location, and arrangement of plants [58,118]. Other factors like indoor conditions (lighting, air quality, noise), participant characteristics (gender, age), and preference of being connected to nature are also liable to modulate the impact of plants on work performance [55].

5.4.5. Indoor plants and possible indoor conditioning energy savings

Assuming plants can lead to a reduction in air conditioning set-point up to 1 °C, over current set-points, in an optimistic scenario and up to 0.5 °C in a more conservative scenario, we estimated potential energy savings utilizing adaptive cooling degree days (ACDD) [119]. ACDD is a metric that is proportional to the cooling energy consumption, and it depends on indoor and outdoor temperature. We used the Indian Model of Adaptive Comfort (IMAC) [120] and PMV model [111] to calculate ACDDs. To compare the effect of set-point temperature change by 0.5–1 °C on ACDDs we used five different scenarios : i) a baseline of 24.5 °C (PMV Baseline), ii) baseline temperature increased by 0.5 °C with plants, over 24.5 °C (PMV+0.5 °C); plant adjusted baseline temperature by 1.0 °C, over 24.5 °C (PMV+1 °C); the IMAC model predicted comfort temperature (IMAC); and IMAC model predicted comfort temperature adjusted by 0.5 °C (IMAC+0.5 °C). The details of the method use for these evaluations have been provided in the Supplementary Information. As we conducted the study in Pilani, which comes under the composite climate region of India [121], we further calculated the ACDDs for four other major Indian cities with composite climate, New Delhi, Gwalior, Hyderabad, and Kota.

Figure 5.8 represents the estimated ACDDs for the five cities, across the five scenarios. The IMAC+0.5 °C scenario provides the lowest ACDDs. This scenario performs even better than assuming plants can lead to a reduction in set-point of 1 °C (Section 4.2). The percentage reduction in ACDDs, with PMV Baseline as reference, has been provided in Table 3.

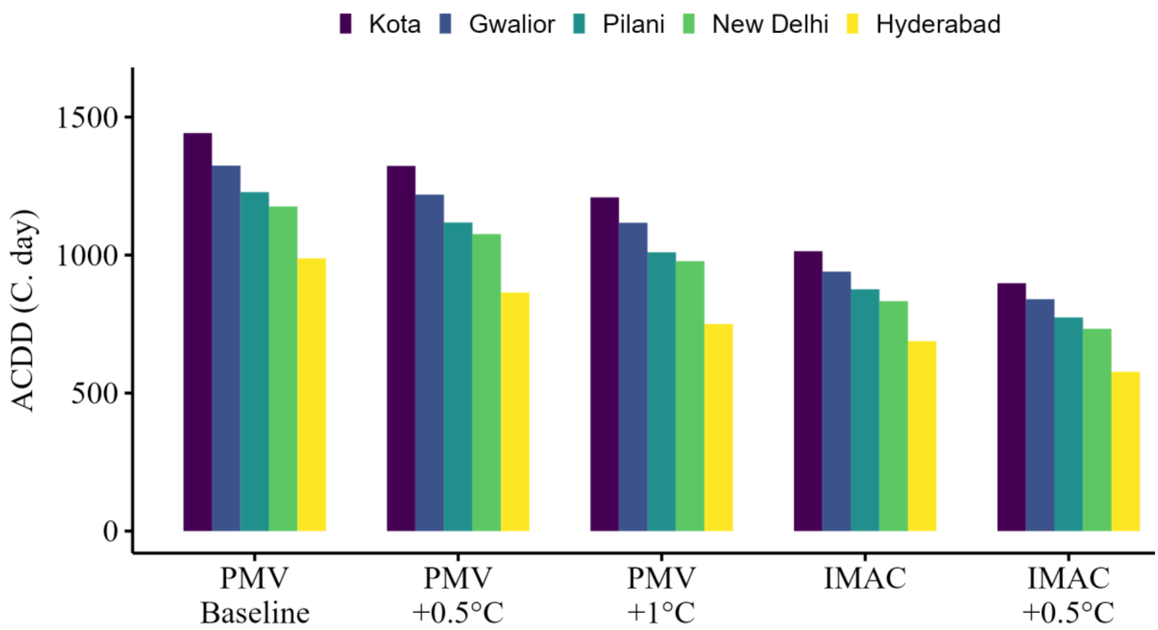


Fig 5.8. ACDD calculated for mixed mode buildings located in composite climate of India.

Table 5.3. Percentage reductions in ACDDs, with PMV Baseline as reference

City	PMV+ 0.5°C	PMV+ 1°C	IMAC	IMAC + 0.5°C
Hyderabad	13	24	30	42
New Delhi	9	17	29	38
Pilani (town)	9	18	29	37
Gwalior	8	16	29	37
Kota	8	16	30	38

Energy simulation models [122] predicted that increasing the AC set-point temperature by 0.5–1°C can achieve an average savings of approximately 6–11% in cooling energy for the AC office building in San Francisco. Similarly using plants for biophilia indoors could lead to a reduction of 8–42% (considering all the above discussed five scenarios) ACDDs for mixed mode buildings in the composite climate of India, specific value being climate dependent.

5.4.6. Overall effect of indoor plants on occupants' perception

The differences noted during our study between WoP and WP group participants have been summarized in the form of a heatmap in Fig. 5.9. For the heatmap, we have used effect sizes for the color gradient. We have included p values up to 0.15 in the heatmap as future studies employing larger sample sizes may find these items to reach statistical significance. We rejected two of our three of our null hypotheses ($H1_0$: The presence of indoor plants does not impact occupants' subjective perception of their indoor environment and $H2_0$: The presence of plants indoors does not impact occupants' affect). Plants positively impacted aesthetics, thermal perception, and occupant affect on five of the eight categories (octants). These differences lend credence to the co-benefits for occupants of having plants in a space. Future research can explore whether such a biophilic design would significantly impact HVAC energy use as well. While some effect sizes are small, it would come down to space design and organizational policies as to if the small effect size, relevant to thousands of occupants, can still provide meaningful benefits.

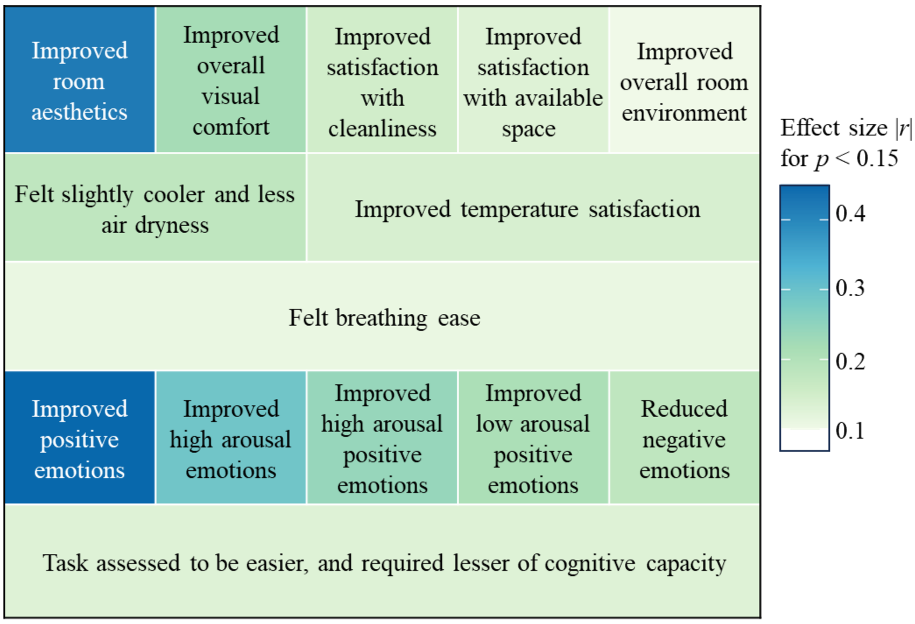


Figure.5.9. Heat map showing impact of indoor plants on occupants, graded by the effect size.

Chapter 6:
Conclusion

This study was motivated primarily by the desire to find out plausible solutions to improve indoor environment quality (IEQ). The study was divided into two parts, first part has focused on assessment of indoor plants for their effectiveness in removing particulate matter (PM) and second part is focused on influence of indoor plants on occupants' emotional-state, performance, and perceived comfort within an indoor environment. In the former investigation, experiments were conducted in environment-controlled chamber (*Section 6.1*) and mathematical model (*Section 6.2*) was developed to estimate fruitful results. Later, in the latter investigation (*Section 6.3*), a between-group study was performed, combining subjective participant surveys with objective measurements to find the effect of plants on occupants.

6.1. The impact of indoor plants on particulate matter reduction within the experimental chamber

This investigation estimated the size-resolved particle deposition velocities and clean air delivery rates (CADRs) for eleven different plant species by comparing PM removal rates in an environmental chamber with and without the plant specimen. The deposition velocities varied significantly between the plants, but remained roughly equal across all particle sizes for a particular plant. The size-averaged deposition velocities were found 93±9 cm/h for the Moss plant, between 29±3 to 37±4 cm/h for the needle-leaved plants, and between 1±2 to 13±2 cm/h for the broad-leaved plants. The plants' CADRs were between 0.002±0.004 m^3/h to 0.084±0.009 m^3/h, which are significantly lower than those of conventional filter-based air purifiers (CADR = 170–800 m^3/h).

6.2. The estimation of number of indoor plants for specific PM reduction in indoor spaces

This investigation estimated the number of required plants for specific PM reduction in a small indoor space by using PM deposition velocities obtained from experiments. The required number of plants varied significantly for the type of plant species, air exchange rates, and desired PM reduction.

We found that only small reductions in indoor PM levels can be achieved by keeping a reasonable number of indoor plants. An increase in the air exchange rate or the room size further increases the quantity of plants to achieve the same reduction in the PM levels. Thus, it is concluded that passive phytoremediation systems can only provide minimal PM reductions in real-world conditions and can neither compete with traditional filter-based air purifiers nor with the building's infiltration air exchange.

6.3. Effects of indoor plants on occupants' emotional-state, performance, and perceived comfort in an open-plan seating space

We investigated the effects of indoor plants on the perceived indoor environment (thermal environment and IAQ), occupants' cognitive performance, well-being, and mood. Analysis of the data from our study and led to the following conclusions:

- The WP (with plant) group felt cooler (0.4 points on the seven-point ASHRAE thermal sensation scale) and less dry than the WoP (without plant) group, even when thermal conditions experienced by both groups were similar. This could present an avenue for increasing the set-point temperature of air conditioning systems in the presence of plants, by 0.5–1 °C, leading to significant cooling energy savings.

- Indoor plants also enhanced positive affect ($|r| = 0.21$ to 0.45, $p < 0.0001$ to 0.02) and reduced negative affect ($|r| = 0.18$; small effect, $p = 0.02$) of participants significantly.

- The plants improved perception of the room's decoration ($r = -0.42$, $p < 0.0001$) and overall visual comfort ($r = -0.22$, $p = 0.01$), as may be expected. The observed effect of plants on occupants' perceived SBS symptoms, self-assessed performance, and cognitive performance was not notable.

6.4. Study novelty, research applications, limitations, and future scope

6.4.1. Novelty of work

This research contributes to the field of indoor environmental quality by quantitatively assessing the effectiveness of various indoor plant species in PM reduction. It not only measures particle deposition velocities and clean air delivery rates (CADRs) in a controlled environment but also integrates subjective and objective measures to evaluate indoor plants' emotional and psychological impacts.

6.4.2. Research Application

The findings of this study have practical applications in the design and maintenance of indoor environments, particularly in settings like offices, schools, and healthcare facilities. Although plants have limited capacity to reduce PM levels, indoor plants significantly enhanced occupants' perceived comfort, allowing for a potential increase in air conditioning set-point temperatures by 0.5–1 °C, which could lead to substantial energy savings. Additionally, plants improved positive affect and visual comfort while reducing negative affect, highlighting their value in enhancing indoor environments' overall well-being and satisfaction.

6.4.3. Limitations

In the first part of this research, we estimated the number of plants based on deposition velocities measured in specific environmental conditions, which may vary by climate. We also assumed ideal well-mixed indoor conditions which may not reflect real-world scenarios.

Further, we used constant deposition velocity irrespective of particle size, which can lead our model to either underestimate or overestimate the CADR and number of plants required to remove desired PM level.

The second part of this study investigated the importance of the indoor plants appearance on people's emotional responses and perceptions. As this study was conducted in an academic campus and participants were recruited through convenience sampling, all our participants were young undergraduate students (average age of 20). This represents an important segment of future workforce but is a narrow demographic. The participants had no major health issues or disabilities, and only 15% of them were females. Due to the limited number of female participants, we were unable to conduct a meaningful comparison of responses between male and female participants. Consequently, the participant population was not very diverse, making it difficult to extrapolate the results to the general population. The participants of the WP session reported slightly better sleep scores for last night's sleep than WoP participants; however, the difference corresponded to a small effect size. Similarly, the WP group scored higher on the Conscientiousness questions scale of the Big Five personality test. While both these differences were minor, it is possible that they could have had a confounding effect on the participant's subjective evaluation of plants in their environment.

6.4.4. Future Scope

Future research should consider a broader demographic to enhance the generalizability of the findings from both parts of this study. For the first study on PM reduction, investigating the effectiveness of a wider variety of plant species, including those with different leaf structures and physiological characteristics, could provide deeper insights into their capabilities for particulate matter filtration. Additionally, similar study can be conducted to estimate the VOC removal potential of indoor plants that will help assess the practical applicability of indoor plants in real-world settings. In the second study, using post hoc power calculations in G*Power, with 59 participants, α = 0.05 and medium-sized effect, we obtained a power of 84%. However, our results indicated that most observed effect sizes were small. For small effect sizes, to reach a power of 80%, with α=0.05, a sample size of 325 would be required. Such a sample size can be prohibitive for laboratory studies and may need to be assessed in field conditions; however, field studies may provide less control over indoor conditions. Hence, this is an important challenge for future work.

We chose a specific measure targeting working memory to understand plants' impact on cognitive performance. A more in-depth investigation covering different dimensions of cognition (attention, inhibition, task-switching, etc.) could provide a better understanding of how indoor plants impact occupants' performance. Our study design was focused on the presence or absence of plants while thermal conditions were comfortable. Under warm or cool thermal conditions, the occupants' perception towards the presence of plants could be different. Similarly, another form of greenery, like green walls, could impact occupants differently. Additionally, future studies with bigger sample size could benefit from examining the effects of indoor plants on male and female participants, as well as differentiating between participants who wear glasses and those who do not.

Appendix A:

The impact of indoor plants on particulate matter reduction within the experimental chamber

A.1. Systematic approach to quantify uncertainty

To minimize the uncertainty associated with values of particulate matter (PM) deposition velocity and clean air delivery rate (CADR), we conducted three replicates for control (with plant) and treatment (without plants) experiments for the assessment of each type of plant species. We conducted a propagation of error analysis using a systematic approach considering all major sources of uncertainty. We considered three primary sources of uncertainty: (1) the uncertainty associated with the slope value (total particle loss coefficient) of decay curve, (2) the uncertainty associated equipment's (refer to Table B.1 in *Appendix* B), and (3) the measurement of plant surface area (refer to Table A.1 in *Appendix* A). The uncertainty in plant surface area ranged between 3.5–5.2 % depending on the type of plant species.

To calculate uncertainties associated with the control experiments, we used the following steps:

Step 1: Get three sets of decay data ($D_{j=1,2,3}$) from three repeated experiments and calculate uncertainty associated with the total environment chamber loss coefficient $u(\alpha_{ci})_j$ for i micron particle size and for jth experiment number. We used the LINSET function on the natural logarithm of the decay data.

$$u(\alpha_{ci})_j = \text{LINSET}(\ln(D_j)) \quad \text{(A.1)}$$

Step 2: Calculate the standard uncertainties related to the measurement of chamber air volume (V). This includes assessing the uncertainties associated with measuring both the empty chamber volume $u\ (V)$ and the volumes of the things ($u(V_t)$) like equipment and pots, placed inside the chamber.

$$\mathrm{u}(V) = u(V_c) - u(V_t) \tag{A.2}$$

$$\mathrm{u}(V) = \sqrt{u(V_c)^2 + u(V_t)^2} \tag{A.3}$$

Step 3: Calculate standard uncertainties associated with air flow rate (Q).

$$\mathrm{u}(Q) = u\ \text{(air flow controller accuracy)} \tag{A.4}$$

Step 4: Calculate fraction uncertainties associated with chamber air volume (f_V) and air flow rate and combine them to get fraction uncertainty associated with air exchange rate (f_λ).

Fraction uncertainties:

$$\text{for chamber air volume } (f_V) = \left(\frac{u(V)}{V}\right) \tag{A.5}$$

$$\text{for air flow rate } (f_Q) = \left(\frac{u(Q)}{Q}\right) \tag{A.6}$$

$$\text{Combined uncertainty for air exchange rate } u(\lambda) = \sqrt{{f_V}^2 + {f_Q}^2} \tag{A.7}$$

Step 4: Calculate the standard uncertainty associated with the PM filtration (λ_f) which is assumed to be equivalent to accuracy of sampling pump of Laser particle spectrometer.

$$\mathrm{u}(\lambda_f) = \mathrm{u}\ \text{(accuracy of sampling pump of Laser particle spectrometer)} \tag{A.8}$$

Step 5: Calculate uncertainties associated with the chamber deposition coefficient $u(\beta_{c,i})_j$ using uncertainties associated with total chamber loss coefficient $(u(\alpha_{ci})_j)$, filter deposition coefficient $u(\lambda_{f,i})$ and air exchange rate $u(\lambda)$.

$$u(\beta_{c,i})_j = u(\alpha_{ci})_j - u(\lambda_{f,i}) - u(\lambda) \quad (A.9)$$

$$u(\beta_{c,i})_j = \sqrt{u(\alpha_{ci})_j{}^2 + +u(\lambda_f)^2 + u(\lambda)^2} \quad (A.10)$$

Step 6: Calculate fraction uncertainties (f_β) associated with the chamber deposition coefficient $u(\beta_{c,i})_j$.

$$(f_\beta) = \left(\frac{u(\beta_{c,i})_j}{\beta_{c,i}}\right) \quad (A.11)$$

Step 7: Obtain uncertainties associated with chamber deposition velocity $u\,(v_{c,i})_j$ using fraction uncertainties of chamber air volume (f_V), air flow rate (f_Q), and chamber deposition coefficient (f_β).

$$u\,(v_{c,i})_j = \sqrt{f_\beta{}^2 + f_V{}^2 + f_Q{}^2} \quad (A.12)$$

Step 8: Calculate uncertainty associated with repeatability $u(r)$, that is standard deviation (σ) of three values of uncertainty associated with chamber deposition velocity.

$$u(r) = \sigma\,[u\,(v_{c,i})_j] \quad (A.13)$$

Step 9: Calculate combined standard uncertainties $u\,(v_{c,i,std})_j$ associated with chamber deposition velocity by adding common value of uncertainty associated with repeatability ($u(r)$) to each value of uncertainty associated with chamber deposition velocity ($u\,(v_{c,i})_j$).

$$u\,(v_{c,i,std})_j = u\,(v_{c,i})_j + u(r) \quad (A.14)$$

$$u\,(v_{c,i,std})_j = \sqrt{u\,(v_{c,i})_j{}^2 + u(r)^2} \quad (A.15)$$

Step 10: Calculate total average standard uncertainty ($u\ (v_{c,i})_{average}$) associated with average chamber deposition velocity (m/h).

$$u\ (v_{c,i})_{average} = \text{Average}\ (u\ (v_{c,i,std})_j) \qquad \text{(A.16)}$$

Similar steps we followed to calculate uncertainty associated with experiments that were conducted with plants.

A.2. Plant area measurements

The leaf areas of broad-leaved plants and Thuja compacta (needle-leaved plant with flattened fan-shaped leaves) were estimated using an image processing software (ImageJ). The above methodology could not be used for the other two needle-leaved plants (Cypress and Christmas plants) since they had irregular shapes. Thus, we sampled ten needles from those plants and measured their length and base thickness values using a Vernier caliper. We then computed the surface area of each needle by assuming it to be a right circular cone and then calculated the average across all sampled needles. The total area of plant needles was then estimated by multiplying the average area of a needle with the total number of needles. Next, we calculated the plants' trunk and branch areas from their measured thickness and length values, by assuming them to be of cylindrical shape. Finally, the total area of plants was obtained by summing the leaf (or needle), trunk, and branch areas, as given in Table A.1.

Table A.1. Surface areas of the plants

	Plant name	Leaf type	Plant surface area (m^2)	Number of leaves/needles**
a)	Glittering wood moss (*Hylocomium splendens*)	Feather-like fronds	0.090±0.003*	Not applicable
b)	Cypress (*Cupressus macrocarpa*)	Needle-leaved	0.16±0.01	21,440
c)	Christmas (*Araucaria heterophyllas*)		0.13±0.01	15,750
d)	Thuja compacta (*Platycladus orientalis*)		0.15±0.02	Not available
e)	Phoenix (*Phoenix roebelenii*)	Broad-leaved	0.15±0.02	176
f)	Kodia purple (*Eranthemum purpureum*)		0.15±0.01	44
g)	Song of India (*Dracaena reflexa*)		0.17±0.01	32
h)	Snake (*Sansevieraia trifasciata*)		0.18±0.01	5
i)	Money (*Epipremnum aureum*)		0.26±0.01	28
j)	Ficus (*Ficus retusa*)		0.61±0.02	198
k)	Croton (*Codiaeum variegatum*)		0.22±0.01	13

* Frontal area of the moss, ** typical numbers in the chosen plant specimen.

A.3. Estimation of mixing time

As mentioned in the Section 3.1.3, our method to quantify particle deposition velocities relies on establishing well-mixed conditions in the environmental chamber. However, the time duration required to achieve well-mixed conditions after particles were injected into the chamber was difficult to estimate a priori. Thus, we devised a method to determine when well-mixed conditions were present in the chamber. In this method, we split the particle decay data into time intervals of 15 minutes and determine the total loss coefficient ($\alpha_i = \lambda + \beta_{c,i} + \beta_{p,i}$) for each of those intervals.

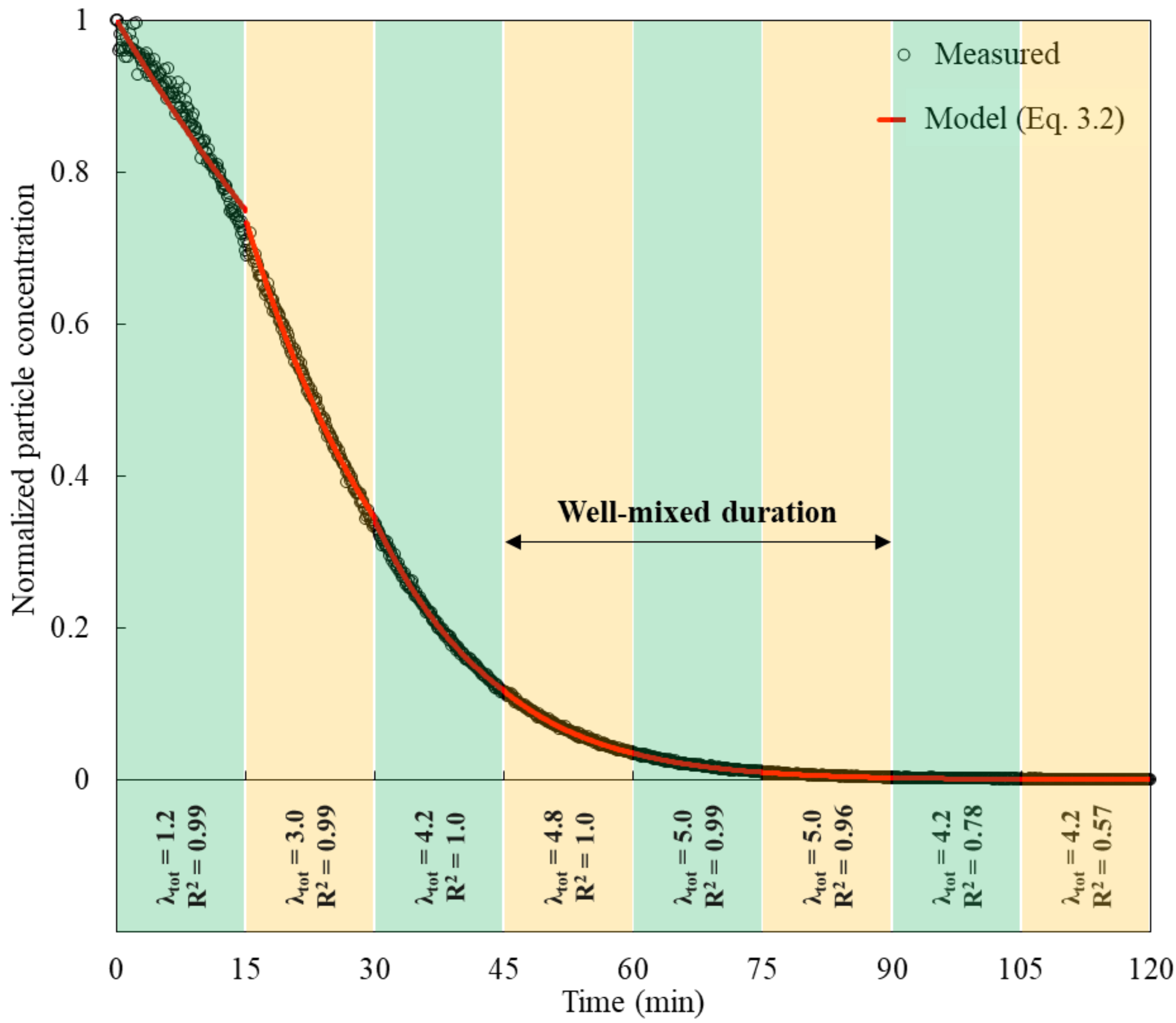


Figure A.1. Total loss coefficients (α) for 0.35 µm diameter particles, estimated for different time intervals.

For example, Figure A.1 shows the particle decay rates for 0.35 µm diameter particles in an empty chamber, along with the estimated α values for different time intervals. Note that during 45–90 minutes, the α values were stable (4.8 h^{-1}, 5.0 h^{-1}, and 5.0 h^{-1}), and the R^2 values (coefficient of determination) were above 0.95. Thus, the exponential decay model (Eq. 3.2) seems valid only for this duration (other data points can be discarded), and well-mixed conditions existed during this period. This approach, termed the stable-α approach, was used to estimate the mixing time and the deposition loss coefficients for all particle sizes in our experiments.

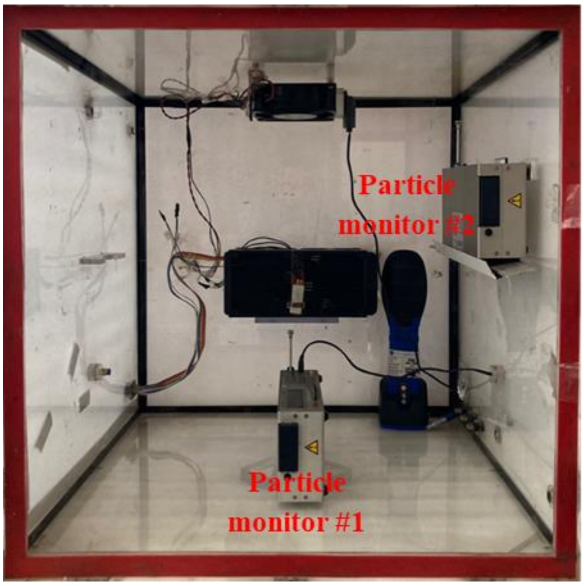


Figure A.2. Empty chamber with two particle monitors to determine the well-mixed duration.

To validate the above approach, we conducted additional experiments, in which we placed two identical particle monitors inside the chamber, one at the center and another at the side, as shown in Figure A.2. Next, we injected particulate matter (PM) inside the chamber, and monitored the size-resolved concentration of particles at both locations. Well-mixed conditions

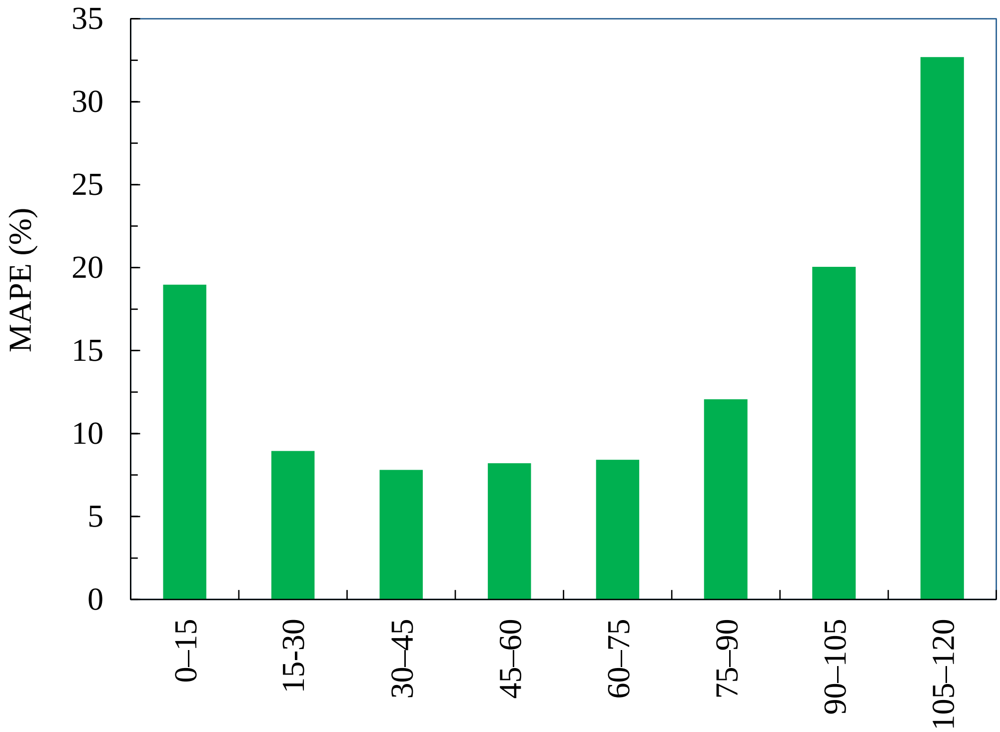


Figure A.3. The mean absolute percentage errors (MAPEs) obtained for 0.35 µm particles.

were said to be established when the two particle monitors displayed the same concentrations.

Figure A3 shows the mean absolute percentage errors (MAPEs) at different time durations between the particle concentrations measured at the two-location for 0.35 µm particles. As seen in the figure, the MAPE was relatively low between 15–90 minutes, indicating that the particle concentrations were roughly equal at both locations or well-mixed conditions existed. We call this approach for determining well-mixed conditions, the low-MAPE approach. Note that the well-mixed duration estimated from the stable-α approach (45–90 minutes in Figure A1) falls within the range calculated from the low-MAPE approach (15–90 minutes in Figure A3).

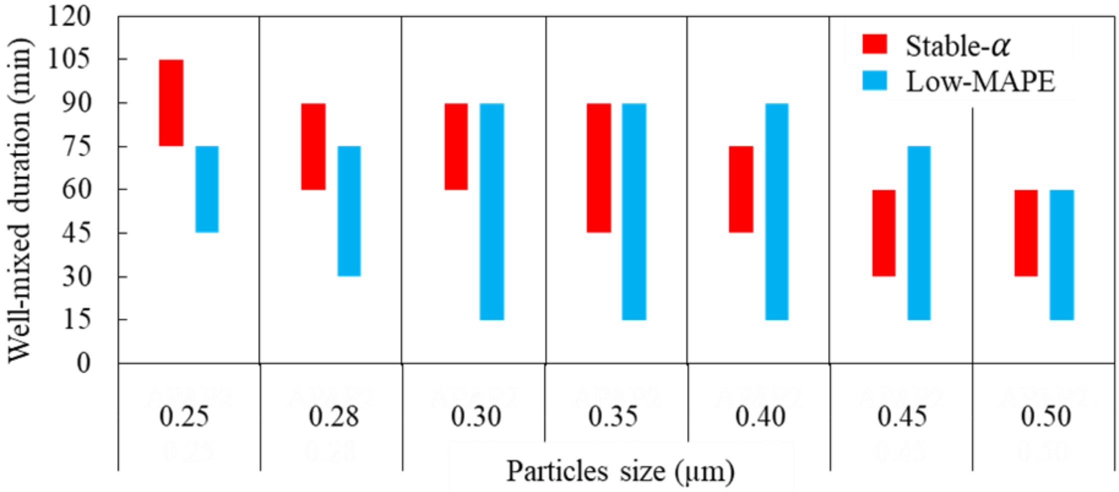


Figure A.4. Estimates of well-mixed durations for different particle sizes in the empty chamber obtained using stable-α and low-MAPE approaches.

Similarly, we estimated the well-mixed durations for particle decay in an empty chamber (Figure A.2) with both approaches for the different particle sizes. Figure A.4 shows that for particle diameters between 0.30–0.50 µm, the well-mixed region obtained from the stable-α method lies within that obtained from the low-MAPE approach; thus, justifying the use of the stable-α approach for estimating the mixing times for those sizes. In the case of 0.25 and 0.28

μm particles, the two methods gave slightly different estimates of the well-mixed durations, probably due to the higher experimental uncertainties in measuring the smaller-sized particle.

Figure A.5. Chamber with plants and two particle monitors to determine the well-mixed duration.

A similar procedure was followed to estimate the mixing time for conditions when plants were placed inside the chamber, as shown in Figure A5. The well-mixed durations obtained with both approaches were around the same (see Figure A6), thus validating the stable-α approach that was followed for determining the well-mixed duration in all our experiments.

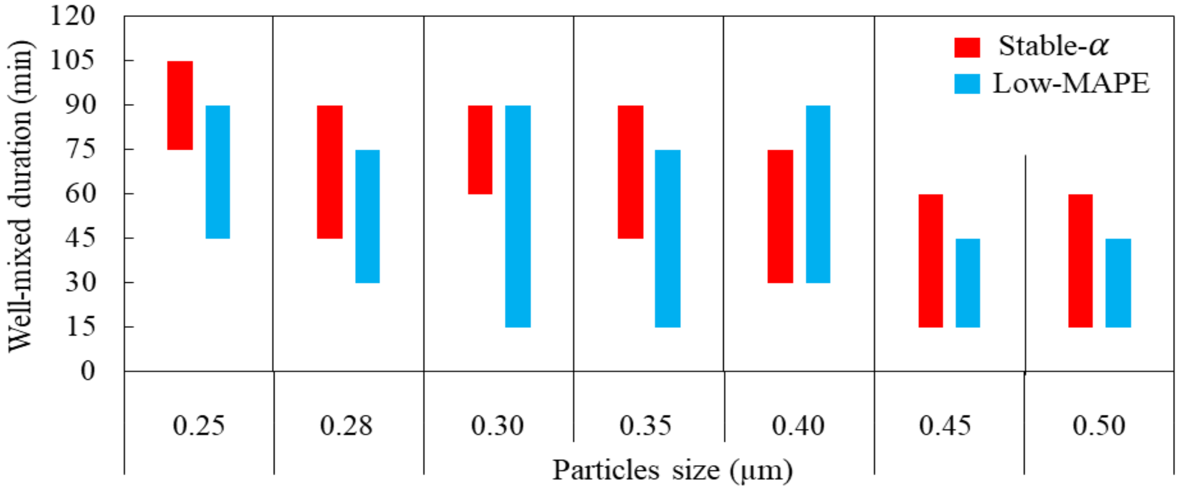


Figure A.6. Estimates of well-mixed durations for different particle sizes in the chamber with plants obtained using stable-α and low-MAPE approaches.

B.1. Methods

Table B.1. Equipment specifications

Parameter	Equipment/Sensor	Make (model)	Range (resolution)	Accuracy
Indoor air temperature	Heat index WBGT meter	Lutron (WBGT-2010SD)	0–50 °C (0.1°C)	± 0.8 °C
Indoor humidity			5–95 % (0.1%)	±3 %
Globe temperature			0–80 °C (0.1°C)	±0.6 °C
Air speed	Hot wire anemometer	Testo (405i)	0–30 m/s (0.01 m/s)	±(0.1 m/s + 5 % of mv)
Horizontal illuminance	Light meter	CHY (CHY-332)	20–20K lux (0.1 lux)	±5 %
Outdoor solar radiation	Silicon pyranometer	HOBO (S-LIB-M003)	0–1280 W/m^2 (1.25 $W/m^{2)}$	± 10 W/m^2
Outdoor air temperature	Temp sensor (12-bit) w/2m cable with solar radiation shield	HOBO (S-THB-M003)	−40–70 °C (0.02°C)	± 0.21 °C
Outdoor humidity	RH sensor (12-bit) w/2m cable with solar radiation shield		0–100 % (0.1%)	± 2.5 %
Outdoor air speed	Cup type anemometer	HOBO (S-WSB-M003)	0–76 m/s (0.5 m/s)	± 1.1 m/s
Precipitation	Rain gauge smart sensor	HOBO (S-RGF-M002)	0–10.2 cm (0.2 mm)	±4 %
Particulate matter	Particulate matter monitor	Grimm Aerosol (11-A)	1–3,000,000 particles/litre (Sampling	±3 % (for counts)

			pump flow rate 1.2 l/m)	±5 % (for sampling flow rate)
Air flow rate	Air sampling pump	Gilair Plus, Sensidyne	1–5100 cc/min (1 cc/min)	±5 % of set flow or ±3 cc/min whichever is higher
CO_2	NDIR CO_2 sensor	Greywolf (TVSPL-CL-DSII-5)	350–1500 ppm (1 ppm)	±35 ppm
Temperature	SEN-SMT-TRH3		0–50 ℃ (0.1°C)	0.66–1.09%
Humidity			5–95 % (0.1%)	0.73–0.75%

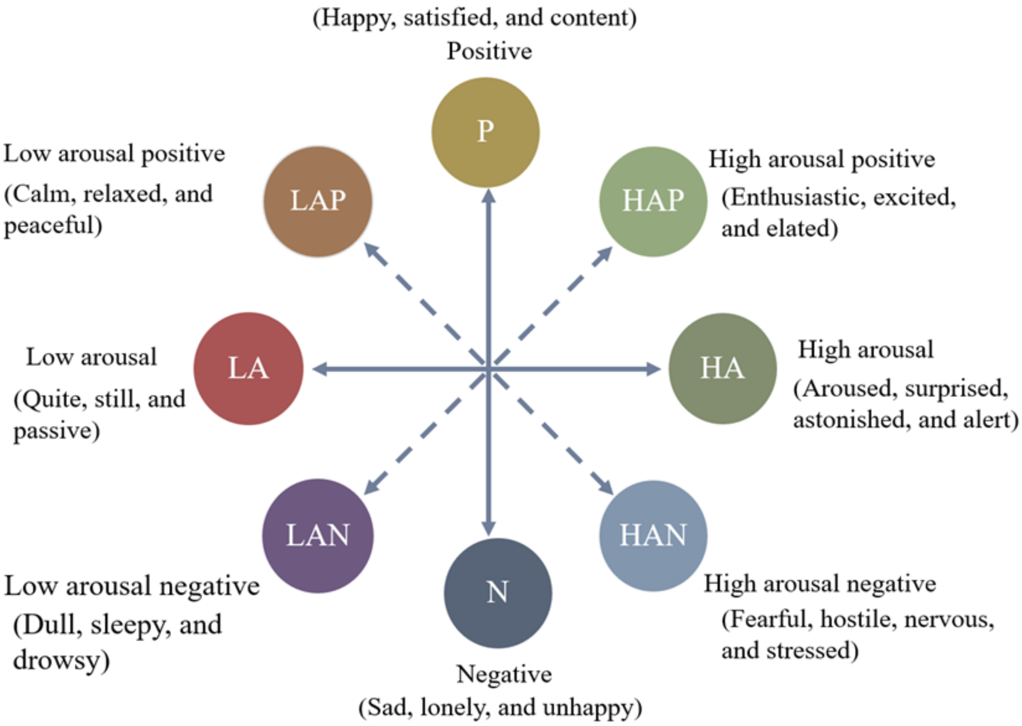


Figure B.1. The circumplex model of affect

B.2. Results

B.2.1. Subjective responses regarding indoor climate and well-being

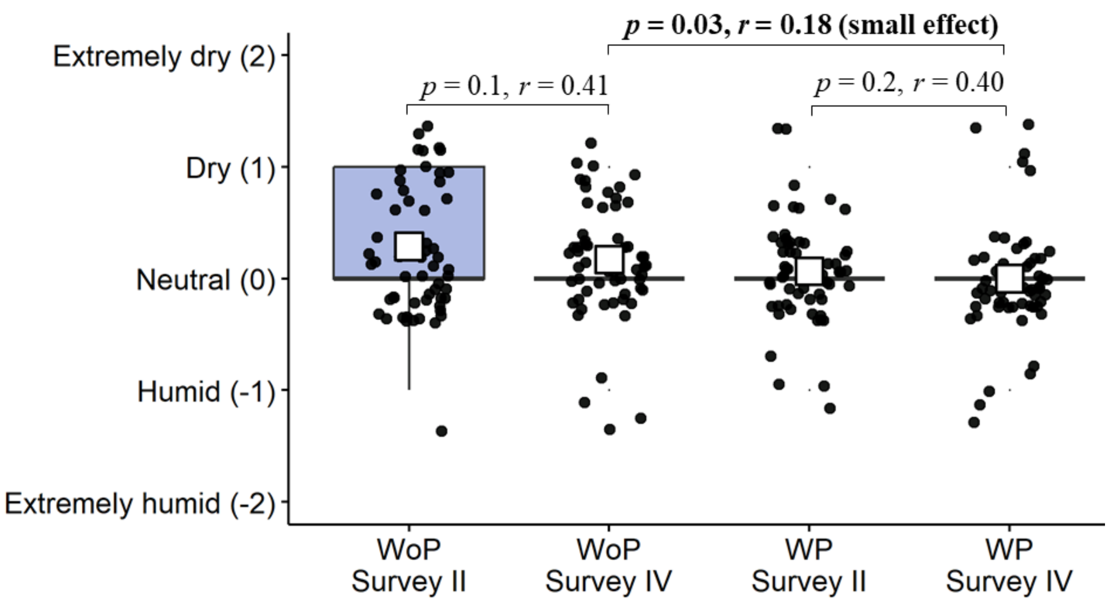


Fig. B.2. Comparison of humidity sensation votes (HSeV), across each session type and between WoP and WP sessions.

Table B.2. Effect of indoor plants on perceived work environment

Measure	*r* value	*p*-value
Lighting	−0.08	0.21
Glare and reflection	0.05	0.70
Space available	−0.14	0.07
Furnishing	−0.08	0.20
Room decoration	−0.42 (medium)	>0.0001
Room cleanliness	−0.16 (small)	0.06
Noise	0.02	0.58
Overall visual comfort	−0.22 (small)	0.01
Overall room environment	−0.10	0.14

B.3. Discussions

B.3.1. Indoor plants and possible energy savings in indoor conditioning

To estimate savings in indoor cooling energy-use, we used adaptive comfort degree days (ACDDs). ACDDs are similar to normal cooling degree days calculation except, instead of a constant reference temperature, the reference temperature is based on an adaptive thermal comfort model. In this case, we used the Indian Model of Adaptive Comfort (IMAC) [120]. To calculate ACDDs, we accessed weather data for a typical meteorological year of the cities from the epw files [123]. The ACDDs reflect the cooling energy needs under these scenarios, for the different cities.

The IMAC model proposes a variation for mixed mode buildings and this is what we used for our estimations as the study set-up had split AC units. The proposition is that, either with plants or following the IMAC model for mixed mode buildings, the AC units are brought into play only when the indoor temperature breaches the warmer set-points.

Table B.3. ACDDs calculation for different types of scenarios

Scenario type	Comfort temperature/ equation	ACDD
1. Baseline (PMV model)	24.5°C, for seated occupants engaged in typing work, dressed in trousers and long-sleeve shirts.	ACDD= $\sum_{i=1}^{N}(24.5 - DMT)^{+}$ where T is the daily mean ambient temperature, DMT is daily mean temperature, and N the number of days in the year. The '+' superscript denotes that only positive values contribute to the adaptive degree-day calculations.
2. Plant-adjusted baseline temperature by 0.5°C (PMV+ 0.5°C)	24.5°C+0.5°C = 25°C	ACDD= $\sum_{i=1}^{N}(25 - DMT)^{+}$
3. Plant-adjusted baseline temperature by 1°C (PMV+ 1°C)	24.5°C+1.0°C = 25.5°C	ACDD= $\sum_{i=1}^{N}(25.5 - DMT)^{+}$
4. Indian Model of Adaptive Comfort (IMAC)	T_n= 0.28*RMT+17.87	ACDD= $\sum_{i=1}^{N}(T_n - DMT)^{+}$
5. Plant-adjusted IMAC temperature by 0.5°C (IMAC+ 0.5°C)	$T_{n1} = T_n + 0.5°C$	ACDD= $\sum_{i=1}^{N}(T_{n1} - DMT)^{+}$

From these files we get hourly recorded temperature, which was then processed to obtain day-wise mean temperature (DMT) and running mean temperature (RMT)

$$(\mathrm{RMT})_t = \frac{1}{30}\sum_{i=1}^{30}(DMT)_{t-i+2}$$

The above formula calculates the average temperature over the specified the last thirty days, excluding the current day. Where, $(\mathrm{RMT})_t$ is the running mean temperature of day t, $(DMT)_{t-i+2}$ is the day mean temperature on day t–i+2, where ‘i' ranges from 1 to 30.

B.4. Notice board posting to inform the potential pool of participants on campus

Inviting Volunteer for a research study:

"Indoor environment and occupant comfort "

Register here

Our team is working on a new research study in collaboration with IIT Kanpur and University of Galway, Ireland. We need you as a volunteer for a continuous 55-minute session. During the session, you will be answering some survey questions and participating in some cognitive tests. **We plan to conduct the session during April 2023, Monday to Saturday between 17:30–18:25**. ***One participant can participate in one session only***.

"One lucky draw prize will be given to every six student participants in every session, while every participant will receive a token gift."

Who can participate?

First-degree students, BITS Pilani students who are 18 years of age or older can participate.

With best regards,
Research Team
BITS Pilani, IIT Kanpur, and the University of Galway, Ireland.

Approved
27/03/23
ASSOCIATE DEAN
PILANI (RAJASTHAN)

B.5. Complete survey questionnaires

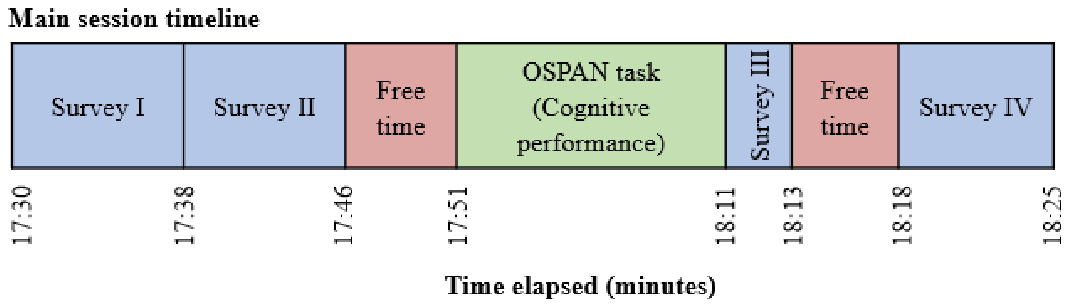
B.5.1. Orientation session questionnaire

Dear partcipants, thank you for agreeing to participate in our survey session!

Note: Dear partcipants please fill out the questionnaire below which contains participants handouts, participant consent, demographic and personality related questions followed by instructions related to installation of PEBL software and practice of cognitive task i.e. OSPAN.

Participant handouts (Do's and Don'ts) for the main session

1. You need to bring your laptop in fully charged condition
2. Carefully read the instructions (at page No. 05 of this questionnaire) about installation of the PEBL software. Based on the provided instruction, please practice the one round of cognitive task before coming to the main session.
3. Mobile phones to be in silent/switched-off mode.
4. Talking or whispering during the session is not permitted.
5. No computer gaming and loud music allowed.
6. You will not be allowed to change your seating position during the session.
7. You will not be allowed to adjust the window, light, fan, or AC settings.
8. You will not be allowed to go outside the room for bio-break or any other reason except for emergency conditions. Once you go outside, the experiment ends for you.
9. Wear plain color comfortable clothing that you normally wear to the institute for classes; the same can be self-adjusted to ensure comfort.
10. Please do not use any strong-smelling cosmetics or personal hygiene products during the session.
11. No eatables allowed, but you can drink water.
12. Please don't engage yourself in any physically strenuous activity just before coming to the session.
13. Please do not to change your usual daily routine and sleep schedule around the session day.



Participation consent (please read carefully):

I have gone through the Do's and Don'ts in the recruitment email. I understand that my participation in this research is voluntary, and I may withdraw at any time from the study. The study will not expose me to any potentially harmful ambiance or any indoor environment that I do not come across during my regular life. My name or any other identifiable information, associated with me (like email, registration number etc.) will not be used as part of the study reports. While the researchers will make every effort to prevent any leak of personal data, there is always a small chance that this may happen.

I understand that the duration of this session is 55 minutes. During this session, I will be providing my feedback through questionnaires. I will not be stepping out of the room unless it is an emergency. If I do need to step out, my participation in the session ends there. My responses will all be processed anonymously.

If I have concerns or complaints regarding the way the research is or has been conducted, I can contact the institute management team, BITS Pilani, Pilani campus. I understand that information gathered will be used to work towards more energy efficient and comfortable indoors.

I agree to participate in the studies described above. [If you do not agree, do not submit this form]

- ○ Agree

1. Participant ID number provided to you by our team? ____________________

3. What is your weight (in kg e.g. 72)? ____________________

4. During the past month, how would you rate your sleep quality, overall?

- ○ Very good
- ○ Fairly bad
- ○ Fairly good
- ○ Very bad

5. What is your current state of health?

- ○ Sick
- ○ Good
- ○ Not too bad

6. Have you been diagnosed with these health disorders?

- ☐ Asthma
- ☐ Sleep apnoea
- ☐ Diabetes
- ☐ Low/high blood pressure
- ☐ Any other chronic disease
- ☐ None

7. Do you smoke?

- ○ No, never smoked
- ○ Yes, < 10 a day
- ○ No, give up within the last year
- ○ Yes, > 10 a day

8. How much do you usually perspire (sweat)?

○ Not at all
○ Very little
○ Somewhat
○ Very much

9. How many minutes do you exercise per day? ___________________________

10. Is there any other information about yourself, which may affect your perception of an indoor space, that you would like the researchers to know? If so, please state in the space provided below:

____

11. How well do the following statements describe your personality?

I see myself as someone who..	Disagree strongly	Disagree a little	Neither agree nor disagree	Agree a little	Agree strongly
..is reserved	○	○	○	○	○
..is generally trusting	○	○	○	○	○
..tends to be lazy	○	○	○	○	○
..is relaxed handles stress well	○	○	○	○	○
..has few artistic interests	○	○	○	○	○
..is outgoing, sociable	○	○	○	○	○
..tends to fault with others	○	○	○	○	○
..does a thorough job	○	○	○	○	○

..gets nervous easily	○	○	○	○	○
..has an active imagination	○	○	○	○	○

12. Please read below information about the cognitive task (OSPAN) that you have to practice before coming to the main session

"As part of the session, we will be using a cognitive task called OSPAN, which is a computer-based working memory task. To ensure that you are well-prepared for the session, we have provided some instructions and practice materials below.

Instructions for Downloading and Installing the PEBL Software:

1. Please click on below link to see the instructional video to install and practice the software on your laptop.

https://drive.google.com/file/d/12Iv8ntlByCQrhisFdEGwO8gsNCxj94mW/view? usp=share_link

2. If you face any issues with the installation or use of the PEBL software or the OSPAN task, contact us for assistance

If you have any questions about the OSPAN task or the PEBL software, please contact us at mukesh.budaniya@pilani.bits-pilani.ac.in.

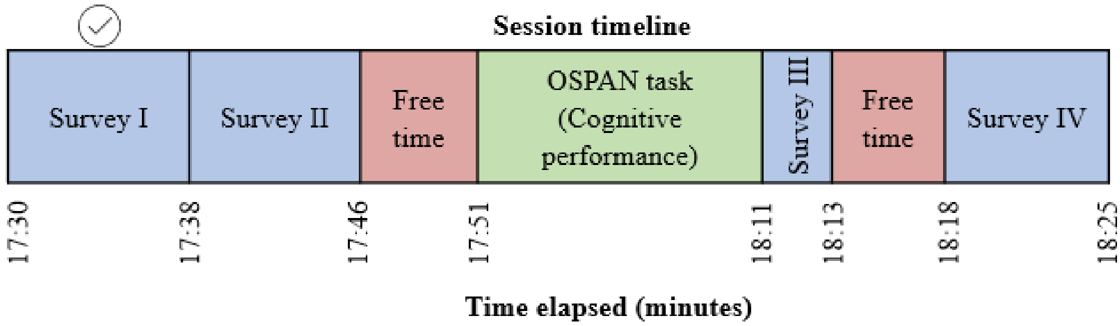
We appreciate your participation and look forward to seeing you at the main session!

With best regards,

Research Team (BITS Pilani, IIT Kanpur, and the University of Galway, Ireland)"

B.5.2. First round questionnaire of main session

Note: This questionnaire is about the participant's sleep quality, followed by what the participant feels about the room noise level, layout, lighting, aesthetics, and overall indoor environment.



1. Participant ID number? ______________________

2. What you were doing in the most part of the last 30 minutes?

- ○ Walking
- ○ Running
- ○ Sitting
- ○ Relaxing
- ○ Washing
- ○ Eating
- ○ Reading or writing

3. The questionnaire is used to evaluate how well you slept last night. Please answer True or False to the best of your recollection.

	TRUE	FALSE
I had a deep sleep last night	○	○
I feel like I slept poorly last night	○	○
It took me more than half an hour to fall asleep last night	○	○
I felt tired after waking up this morning	○	○

	TRUE	FALSE
I woke up several times last night	○	○
I feel like I did not get enough sleep last night	○	○
I got up in the middle of the night	○	○
I felt rested after waking up this morning	○	○
I feel like I only had a couple of hours of sleep last night	○	○
I feel I slept well last night	○	○
I did not sleep a wink last night	○	○
I did not have any trouble falling asleep last night	○	○
After I woke up last night, I had trouble falling asleep again	○	○
I tossed and turned all night last night	○	○
I did not get more than 5 hours sleep last night	○	○

4. In general, how satisfied are you with each of the following aspects of the room?

	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied
Lighting	○	○	○	○	○
Glare and reflections	○	○	○	○	○
The amount of space available to you	○	○	○	○	○
The Furnishings (Chair desk, equipment, etc)	○	○	○	○	○
Room decor	○	○	○	○	○
Room cleanliness	○	○	○	○	○

5. If you are dissatisfied with the lighting aspect of this room, which of the following do you think are (is) causing it? (Check all that apply)

- ☐ Too dark
- ☐ Without lighting control
- ☐ Glare
- ☐ Too bright
- ☐ Reflections on the laptop screen
- ☐ Not applicable
- ☐ Not enough daylight
- ☐ Shadows on the workspace
- ☐ Flicker lighting
- ☐ Too much daylight
- ☐ Undesirable lighting colour
- ☐ Other

6. In general, how satisfied are you with noise level aspect of this room?

	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied
Noise	○	○	○	○	○

7. If you are dissatisfied with the noise levels aspect of this room, which of the following do you think are (is) causing it? (Check all that apply)

- ☐ Noise from equipment
- ☐ Noise from outdoor
- ☐ Noise from people
- ☐ Noise from the air-conditioning system
- ☐ Not applicable

8. If you are dissatisfied with room cleanliness or decoration, which of the following do you think are (is) causing it? (Check all that apply)

- ☐ Surface dust on other surfaces you might touch like doorknobs & handles
- ☐ Dust on table and chair surfaces
- ☐ Dirty floors
- ☐ Significant source of odor
- ☐ Other, please specify

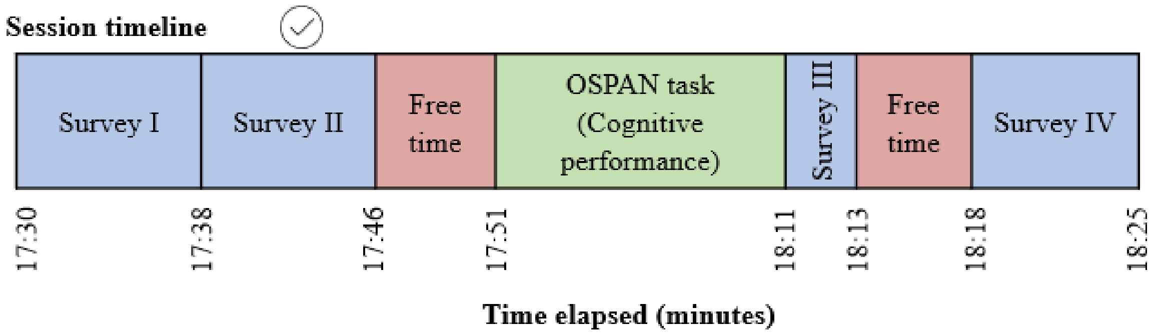
9. In general, how satisfied are you with each of the following aspect of this room?

	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied
Overall visual comfort	○	○	○	○	○
Overall indoor environment quality	○	○	○	○	○

10. If you are feeling discomfort in this room, please describe about the sources of discomfort.

B.5.3. Second round questionnaire of main session

Note: This questionnaire about what you feel about the thermal environment, indoor air quality, mood, and sick building syndrome.



1. Participant ID number?

____

2. How do you feel about room air temperature right now?

	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
Air temperature	○	○	○	○	○	○	○

3. How do you feel about room air humidity right now?

	Extremely dry	Dry	Neutral	Humid	Extremely humid
Room air humidity	○	○	○	○	○

4. Would you prefer to feel?

	Cooler	No change	Warmer
Room air temperature	○	○	○

5. How satisfied are you with the following aspects of this room right now?

	Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Highly satisfied
Temperature	○	○	○	○	○	○	○
Air movement	○	○	○	○	○	○	○
Air freshness	○	○	○	○	○	○	○
Odors	○	○	○	○	○	○	○
Humidity	○	○	○	○	○	○	○
Overall air quality	○	○	○	○	○	○	○

6. If you are dissatisfied with the temperature and/or air movement in this room. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ My area is too hot
- ☐ My area is too cold
- ☐ Humidity too high (damp)
- ☐ Air movement too strong
- ☐ Air movement too weak
- ☐ Not applicable
- ☐ Other

7. If you feel any unpleasant odor in the room air, which of the following do you think is the reason? (Check all that apply)

- ☐ Furniture
- ☐ Other people
- ☐ Perfumes/Deodorants
- ☐ Cleaning products
- ☐ Mold
- ☐ Odors from outdoor
- ☐ Not applicable
- ☐ Other

7. If you feel any unpleasant odor in the room air, which of the following do you think is the reason? (Check all that apply)

- ☐ Furniture
- ☐ Other people
- ☐ Perfumes/Deodorants
- ☐ Cleaning products
- ☐ Mold
- ☐ Odors from outdoor
- ☐ Not applicable
- ☐ Other

8. Right now, do you feel any?

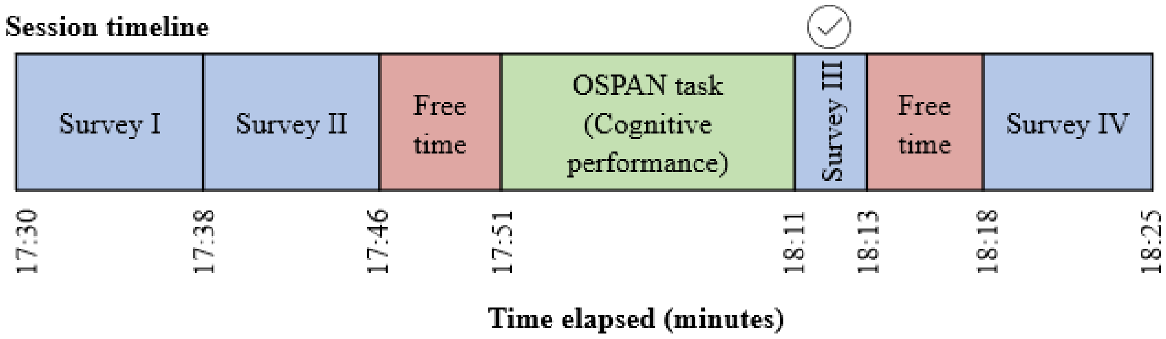
	Not at all	Light	Moderate	Strong	Very strong	Overwhelming
Eye dryness, Itchy or watery eyes	○	○	○	○	○	○
Nose/throat irritation or dryness	○	○	○	○	○	○
Difficulty breathing	○	○	○	○	○	○
Lethargy and/or tiredness	○	○	○	○	○	○
Headache	○	○	○	○	○	○
Dry, itching or irritated skin	○	○	○	○	○	○
Dizziness	○	○	○	○	○	○
Difficulty concentrating	○	○	○	○	○	○
Sleepiness	○	○	○	○	○	○

9. Read each item and indicate to what extent you feel this way right now.

	Very slightly or not at all	A little	Moderately	Quite a bit	Extremely
Enthusiastic	○	○	○	○	○
Sleepy	○	○	○	○	○
Happy	○	○	○	○	○

	Very slightly or not at all	A little	Moderately	Quite a bit	Extremely
Sad	○	○	○	○	○
Calm	○	○	○	○	○
Fearful	○	○	○	○	○
Quiet	○	○	○	○	○
Aroused	○	○	○	○	○
Excited	○	○	○	○	○
Dull	○	○	○	○	○
Satisfied	○	○	○	○	○
Lonely	○	○	○	○	○
Relaxed	○	○	○	○	○
Hostile	○	○	○	○	○
Still	○	○	○	○	○
Surprised	○	○	○	○	○
Elated	○	○	○	○	○
Drowsy	○	○	○	○	○
Content	○	○	○	○	○
Unhappy	○	○	○	○	○
Peaceful	○	○	○	○	○
Nervous	○	○	○	○	○
Passive	○	○	○	○	○
Astonished	○	○	○	○	○
Alert	○	○	○	○	○
Stressed	○	○	○	○	○

B.5.4. Third round questionnaire of main session



Note: This questionnaire is about what you feel about the cognitive task you just performed.

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
They were very easy	○	○	○	○	○
Your effort level was very low	○	○	○	○	○
There was no time pressure	○	○	○	○	○
You worked at 0% of your capacity	○	○	○	○	○
Your performance was poor	○	○	○	○	○

B.5.5. Fourth round questionnaire of main session

Note: The fourth round of the questionnaire was a duplicate of the second round of the questionnaire.

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International journals

1. **Budaniya, M.,** & Rai, A. C. (2022). Effectiveness of plants for passive removal of particulate matter is low in the indoor environment. Building and Environment, 222, 109384. https://doi.org/10.1016/j.buildenv.2022.109384. **(SCI-E, Impact factor = 7.4, H-index: 189, published)**

2. **Budaniya, M.,** Mishra, A. K., Rai, A. C., Dasgupta, M.S. (2024). Effects of Indoor Plants on office Occupants' Comfort, Perception, and Performance in the Composite Climatic regions of India. **(submitted in journal "Building and Environment", SCI-E, Impact factor = 7.4)**

International conference

Budaniya, M., & Rai, A. C. (2021). Phytoremediation of airborne particulate matter in indoor environments. In Healthy Buildings 2021–Europe. Proceedings of the 17th International Healthy Buildings Conference 21–23 June 2021. https://hdl.handle.net/11250/2839336. (**Long paper of distinction award**)

Book Chapter

Budaniya, M., & Dasgupta, M. S. (2023). Effects of Indoor Plants on Occupants' Perceptions of Indoor Climate, Sick Building Syndrome, Emotional State, Self-Assessed Performance, and Overall Space Satisfaction: A Systematic Review. In *Lecture Notes on Energy Transition: Challenges and Opportunities*. Indian Institute of Chemical Engineers, Jadavpur University Campus, Kolkata, India.

1. Long paper of distinction award – Our paper titled "Phytoremediation of airborne particulate matter in indoor environments" awarded by "long paper of distinction award" in Healthy Buildings 2021–Europe. Proceedings of the 17th International Healthy Buildings Conference 21–23 June 2021.

2. Our study "Effectiveness of plants for passive removal of particulate matter is low in the indoor environment" received media coverage from the British Broadcasting Corporation (bbc.com/news/business-66186492).

Conferences

1. I presented an article titled “Phytoremediation of airborne particulate matter in indoor environments” presented in 17th International Healthy Buildings 2021–Europe Conference held on 21–23 June 2021.

2. I participated as an organizing committee member in the 28th CIRP conference on life cycle engineering (LCE 2021), Jaipur, India from 10–12 March 2021.

Courses/ workshops

1. I attended a course one week Global Initiative of Academic Networks (GIAN) course on “Urban air quality assessment, modelling and management”" at IIT Madras from September 25th to September 29th, 2023.

2. I attended a one day workshop on “Teaching-Leraning workshop for next generation academicians” organized by teaching learning centre, BITS Pilani-Pilani Campus held on 27th November, 2021.

3. Participated in an online FDP “Traffic emissions, urban air quality, and sustainable solutions” scheduled for December 11th to 15th, 2023, at NIT Warangal, India.

4. Participated in Solar Decathlon India 2023-24 and I have successfully completed the self-learning modules on “Net Zero Energy and Water Buildings”.

About the Candidate (Mukesh Budaniya)

Mukesh Budaniya graduated with a Bachelor of Technology (B.Tech.) in Mechanical Engineering from Rajasthan Institute of Engineering and Technology, Bhankrota (Jaipur), in 2012. He is Graduate Aptitude Test in Engineering (GATE) qualified with a GATE score of 447. He then completed his Master in Technology (M.Tech.) in Thermal Engineering from the Government Engineering College Bikaner, Rajasthan, in 2018. In January 2020, he joined the Department of Mechanical Engineering at BITS Pilani, Pilani campus, as a Ph.D. research scholar.

He is member of Air Quality Management Association (AQMA), IIT madras, Tamil Nadu (India). His research includes quantifying various indoor plant species' particulate matter (PM) removal potential through controlled experiments conducted in an environmental chamber. Furthermore, he has developed a model to estimate the number of plants required to achieve a specific level of PM reduction in real indoor settings. In addition, his work involves assessing the impact of indoor plants on occupants' emotional state, performance, and perceived comfort under real-world conditions by conducting controlled experiments within a simulated open-plan seating space. During his Ph.D., he received funding support from the Science and Engineering Research Board (SERB) under the Department of Science and Technology (DST), Government of India, under grant no. ECR/2018/000330 until May 2022. From June 2022 to the Ph.D. viva voce exam, he received funding support from institute doctoral research fellowship from BITS Pilani. During his Ph.D., he collaborated with Dr. Asit Kumar Mishra (Healthy Buildings Researcher at School of Public Health, University College Cork, Ireland).

His web page is https://www.bits-pilani.ac.in/research_scholars/mukesh-budaniya/

About the Supervisor (Prof. Shyam Sunder Yadav)

Prof. Shayam Shyam Sunder Yadav is an Associate Professor in the Department of Mechanical Engineering at BITS Pilani, Rajasthan. He received a Ph.D. in 2015 from the Indian Institute of Science Bangalore (IISc Bengaluru). Prior to that, he completed his B. Tech. in Mechanical Engineering from the National Institute of Technology Kurukshetra in 2004 and M.E. from the Indian Institute of Science Bangalore in 2010. He has over 07 years of teaching and research experience at graduate and post-graduate levels, in addition, he has 04 of industry experience. He works in the areas of computational fluid dynamics of multiphase flows, two-phase electrohydrodynamic flows, high-performance scientific computing, etc., mostly with open-source codes for scientific computing. He has published more than 20 research papers in national, international journals and proceedings. He also has two research projects for DST India and the National Supercomputing Mission.

His web page is https://www.bits-pilani.ac.in/pilani/shyam-sunder-yadav/

About the Co-supervisor (Prof. M. S. Dasgupta)

Prof. M S Dasgupta has about thirty years of teaching and research experience at BITS Pilani, India at the Mechanical Engineering Department. He has mentored and motivated several students who subsequently grew to be among the highest achievers across the globe, both in the corporate world and in research. Prof. Dasgupta served as Departmental head of Mechanical Engineering for 8 years in two double terms and as faculty in charge of Campus placement for 8 years. He is currently serving as Coordinator of internal quality assurance cell (IQAC) for the University and had served as the same capacity earlier for 2 years. He had participated in 10 NAAC peer team visits in various capacities.

Prof. Dasgupta has primary research interest in environment-friendly technologies, specifically in CO_2 Trans-critical systems and natural refrigerants, and has worked in several funded research projects, including two in partnership with SINTEF Ocean Norway and NTNU Norway. He has more than 80 publications in peer-reviewed international journals and conferences and has given keynote addresses at various conferences in India and abroad.

His web page is https://www.bits-pilani.ac.in/pilani/m-s-dasgupta/