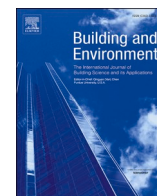


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Indoor plants' effect on occupants' performance, perceived comfort, and affect in an open-plan space in composite climatic regions, India

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ABSTRACT

Biophilic designs with indoor plants are being increasingly recognized for their potential to enhance indoor environmental quality (IEQ) and occupant satisfaction. This can contribute to sustainable and green buildings. However, evidence on the specific benefits of indoor plants remains ambiguous. Particularly, for the buildings in India, there is dearth of evidence of the impact of plants on occupants. We conducted a between-subjects study, with (WP) and without plants (WoP), to investigate effect of indoor plants on Indian building occupants in the composite climatic region of India. Subjective questionnaires queried participants' indoor climate perception, sick building syndrome (SBS) symptoms, emotional state, self-assessed performance, and overall satisfaction with the space. Participants undertook a cognitive task targeting working memory (Operations Span). Air quality perception, SBS symptoms, and subjectively and objectively assessed performance did not differ significantly between WP and WoP groups. The WP group perceived the space to be better decorated ($|r|$, effect size = 0.42, $p < 0.0001$), cleaner ($|r| = 0.16$, $p = 0.04$), visually more comfortable ($|r| = 0.22$, $p = 0.01$), and cooler ($r = 0.18$, $p = 0.02$). The WP group also had enhanced positive emotions ($|r| = 0.21$ to 0.45 , $p < 0.0001$ to 0.02) and reduced negative emotions ($r = 0.18$, $p = 0.02$). Our findings indicated that potted plants improved occupant perception of indoor environment and can potentially lower cooling energy use by over 8 %.

1. Introduction

The indoor environment intimately impacts occupant comfort, well-being, work performance, and overall satisfaction with space [1,2]. Buildings underperforming in terms of indoor environmental quality (IEQ) can have an adverse economic and health impact [3]. Targeting sustainability and low-energy building designs, researchers are exploring methods to improve thermal comfort and air quality for occupants [4], in an energy-efficient manner [5]. One direction of such explorations is inclusion of biophilic features in buildings [6,7], particularly indoor plants [8–10], that connect occupants to nature [11]. Indoor plants, with their potential to improve IEQ, can offer a sustainable and energy-efficient complementary solution for reducing energy used by HVAC (Heating, Ventilation, and Air Conditioning) systems. HVAC systems regulate indoor thermal comfort and air quality (IAQ) at

significant energy costs [12]. Integrating biophilic elements such as indoor plants may make it possible to enhance occupant satisfaction with the indoor climate (thermal environment and IAQ) while reducing dependency on energy intensive HVAC usage.

Previous studies have examined green plants inculcated indoors in the form of green walls [13–15] and indoor potted plants (hanging, tabletop, or kept on the floor) [16–21]. The evidence favoring plants improving indoor environment and occupant perception remains equivocal. Plants may reduce stress and improve occupants' mental health [22,23], improve perceived indoor air quality (IAQ) [24,25] and thermal comfort [9,13,26], and improve task performance [19,21,25]. At the same time, multiple works have failed to find a significant impact of plants on mood [27–29], perceived IAQ [10,30], or thermal comfort and task performance [29,30].

An analysis of the impact of plants on indoor particulate matter

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removal showed low to insignificant clean air delivery rates (CADRs; 0.002–0.08 m³/h) [31], as was also observed when using plants for VOCs removal indoors [32]. While plants may not significantly impact the indoor climate through PM and VOC removal, their effects on occupants could also be influenced by other factors, such as the potential influence on indoor temperature and humidity through transpiration [33,34]. In buildings with HVAC and typical plant density, the impact of plants is likely to stem from biophilia [35] and improved aesthetics [36].

Buildings in India consume 33 % of the country's energy use [37]. More than half of the buildings that will be in use in India by 2050 are yet to be built [38]. This presents a unique opportunity as well as challenges for the future of sustainable design and operation of buildings in this country of over 1.4 billion people, including the use of biophilic elements like indoor plants. Placing plants indoors requires space and upfront investment and their care. There are also issues like increased humidity [39], allergens [40], and volatile organic compounds (VOCs) emitted by the plants [41]. Hence widespread implementation requires carefully weighing the evidence of how plants impact the indoor environment and the occupants.

Composite climatic [42] regions account for about 30 % of India's geographical extent and 450 million of its population [43]. They combine characteristics of hot and dry, warm and humid, and cold climatic regions and are hence referred to as composite climates. In these regions of India, office buildings dedicate 50 % or more of their energy use for indoor conditioning [44].

For the new buildings being designed for the composite climate of India, the design intervention of indoor plants can prove to be advantageous. It can 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..."

To the best of our knowledge, no previous work has explored the multifaceted impact of plants on indoor climate and occupants in India [45–47], and only one study has been conducted in South Asia [30]. Perusing reviews of studies [45–48] related to how indoor plants impact occupant perception, we identified the following limitations:

- 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 and report indoor conditions of the spaces.
- 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.

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. Our study was conducted in a classroom modified to simulate an open-plan seating space (with and without plants), while keeping consistent thermal environmental parameters (air temperature, air speed, ventilation). A between-subjects design ensured that the participants were blinded to the intervention – physical presence of plants. 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. Methodology

The study was conducted over 20 days between April 04, 2023, to April 28, 2023, in an air-conditioned classroom on the campus of Birla Institute of Technology and Science, Pilani (BITS-Pilani). Pilani, in the state of Rajasthan, has a composite climate. A weather station, located about 500 m from the classroom, provided the local weather data. During this 20-day 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 rain (0.2 mm and 2.5 mm) fell on a couple of days but not on the study days. A flowchart illustrating the methodological steps has been presented in Fig. 1.

2.1. Experiment design

The intervention consisted of having plants in the occupied space. Participants were blinded to the 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

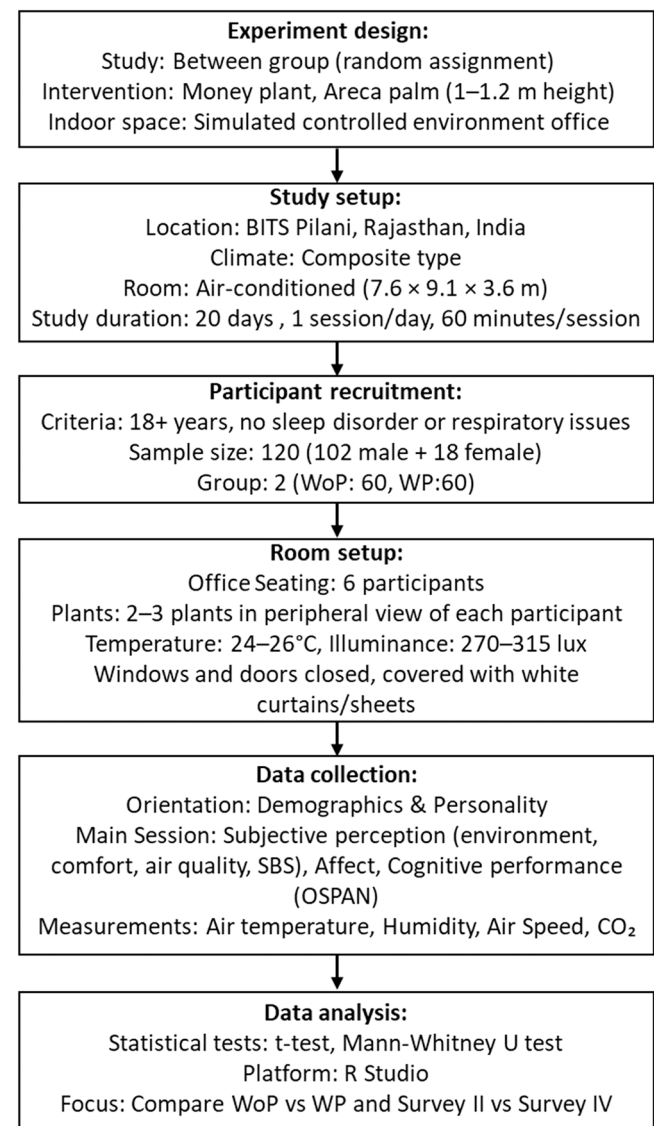


Fig. 1. The research methodology.

(control group, WoP) or the with-plant group (treatment group, WP). The experiments were carried out over four consecutive 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 5:30pm – 6:25pm to ensure the availability of the participants and the classroom.

Based on previous works [18,19,49], we chose two commonly used indoor plant species in India: money plant (*Epipremnum aureum*) and areca palm (*Dypsis lutescens*). Both species can grow in medium to low-light conditions [50]. They have been used in horticultural studies in India [51,52] and are considered to be suitable choices for indoor use in the Indian popular media [53]. In total, five money plants and three areca palms were placed in earthen pots inside the classroom. We used a mix of plants to replicate how indoor plants may be practically used 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.

We established the following null hypotheses (H_0) for the study, following the Fisher significance testing framework [54]:

H1. The presence of indoor plants does not impact occupants' subjective perception of the indoor environment.

H2. The presence of indoor plants does not impact occupants' affect (emotional state).

H3. The presence of indoor plants does not impact occupants' cognitive performance.

A priori power analysis using G*Power [55] showed that a minimum of 53 participants would be required for the significance testing. Hence, 60 participants were recruited in each WP and WoP group. More details have been provided in Supplementary information (SI).

2.2. 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 from students in the campus. Recruited participants were assigned at random to one of the two groups, WoP or WP. The study protocol was approved by the student welfare division of BITS Pilani. More information on recruitment has been provided in SI.

A total of 120 participants were recruited (102 males and 18 females), 60 participants in each group. Two participants (one during a WoP session and the other 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. Table 1 summarizes some key demographic measures and sleep scores on the Groningen Sleep Quality Scale (GSQS) [56], on the day of their participation, for the two groups.

2.3. Experimental set-up and measurements

The layout in the chosen classroom was modified to simulate people

Table 1
Participants' information ($n = 118$), median (25th percentile, 75th percentile).

Measure	Median (25th percentile, 75th percentile)	
	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)
Body mass index (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)

in an open-plan seating space (see Fig. 2a and 2b). The room (width $\times$ length $\times$ height: 7.6 m $\times$ 9.1 m $\times$ 3.6 m) was located on the first floor of a two-storey building. The walls of the room do not receive any direct sunlight. The room has three split air conditioning units (see Fig. 2a) and LEDs for lighting.

ASHRAE Standard 55 defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. As the objective of this study was to understand the impact from presence of indoor plants on occupant's thermal comfort and perception, air conditioning was used to maintain consistent thermal conditions in the room. We focused on differences, if any, on the perceived thermal comfort, task performance and affects of the occupants, in presence of indoor plants. Usage of AC removed any confounding effect of fluctuating indoor temperature/humidity. The study design did not intend to detect the impact of plants on indoor thermal conditions.

Six desks were arranged in the classroom to seat six participants. To nullify the effect of varying outdoor conditions, windows and doors were closed and covered with white curtains/sheets.

Through the sessions, we continuously monitored and logged the air temperature, air speed, relative humidity, globe temperature, and CO₂ level at the location marked in Fig. 2a. Instrument specifications have been provided in Table S1, as part of SI. Indoor temperature was maintained between 24 and 26 °C during the sessions, and conforms to the summer thermal comfort range for building occupants [57]. Lighting in the room was measured prior to sessions and provided an illuminance of 270–315 lux on the desks' work-surface, a level recommended for office desks [58].

2.4. Experimental procedure

To familiarize the participants with the process, we organized an online orientation session, one day before their session. This involved an orientation questionnaire (details in SI) and the instructions for downloading and installing the Psychology Experiment Building Language (PEBL) platform [59] for the cognitive tasks.

Participants were asked to arrive 10 mins before the scheduled start time. This gave them some time to familiarise themselves with the space and 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 5:25pm and were assigned a random seat. They received the survey questionnaires (details in SI) through email at the specified times shown in Fig. 2b. The questionnaires were based on standardized scales and questionnaires widely used in similar works. The sources for the different portions of the questionnaire have been provided in Table S5. Survey I included questions about sleep quality and work environment. This survey was taken while participants were still within the initial 20-minute period marked for acclimatization to the room (Fig. 2b). The 20-minute acclimatization duration for the thermal environment was chosen based on the available literature related to outdoor-indoor transition or transition between two indoor spaces [60]. Before the participants started with the cognitive tasks, they had spent over 25 mins in the room. Surveys 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.

2.5. Participants' feedback and assessments

Details regarding the content of each Survey and the complete set of questions have been provided as part of SI. In Survey I, we asked participants to assess the indoor environment, including lighting, visual comfort, noise, room decoration, space, cleanliness, and the overall room environment quality. Since last night's sleep can impact work performance and perception [61–63], we asked participants to rate their last night's sleep score on the GSQS [64]. We also asked participants to

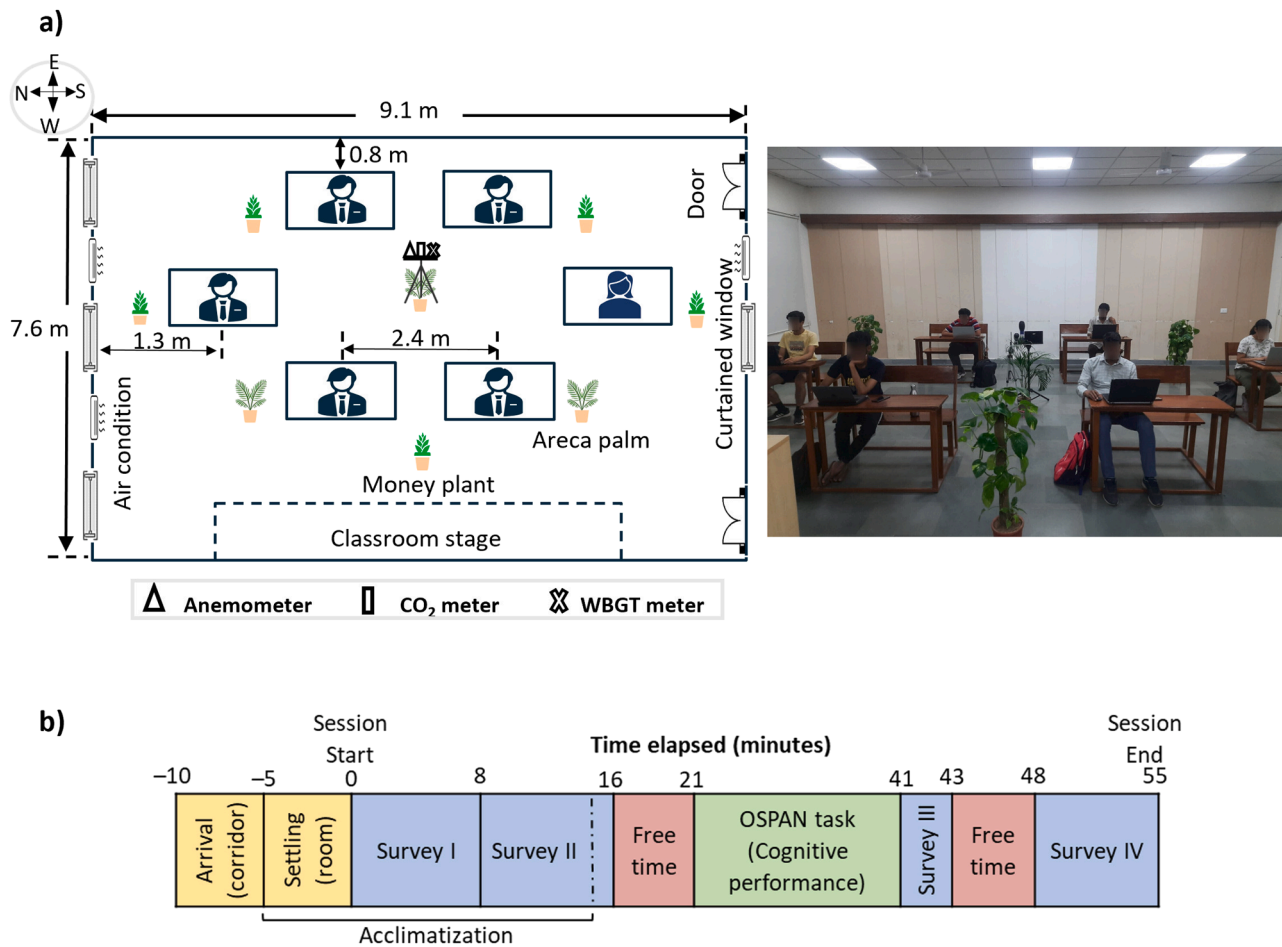


Fig. 2. a. The representative simulated open-plan seating space and study conditions, and b. study timeline.

provide information on their activity level for the 30 mins before coming to the session.

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). We also evaluated IAQ perception and SBS symptoms.

In Survey II and Survey IV, participants also rated their assessment of their current emotional state on the circumplex model of affect (more information is SI), under eight categories or octants [65]. “Affect” is an individual’s immediate expression of their emotional state, as in how they might be feeling at a given moment. We used the OSPAN [66] to assess the participants’ cognitive performance. 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.

2.6. Data processing and statistical analysis

From the different sources, e.g., data logged in indoor environment monitors, PEBL, Google forms for subjective questionnaire, the data was collated using Microsoft Excel spreadsheets. All statistical analysis was carried out on the R Studio platform. Data and R scripts used for this work have been made available at <https://github.com/asitkm76/IndoorPlantsPilani>.

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

removed as the scores were an outlier.

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) [67]. Participants provided feedback on the indoor climate, first within 15 mins of entering the space (Survey II) and then at the end of the session, having spent over 45 mins in the space (Survey IV). The subjective perceptions of thermal environment, air quality, SBS were compared between WoP and WP sessions, using the responses to Survey IV. By that time, participants would have spent over 30 mins in the room and would have adjusted to this indoor environment [68]. We also compared how the indoor climate perception evolved between Surveys II and IV within each type of session. The intention was to understand if the evolution was different for WoP vs WP sessions.

For *p* values less than 0.05, the null hypothesis was rejected. However, since the *p*-value is the conditional probability, given the null hypothesis is true, in addition to the *p*-value, we also calculate and report the effect sizes. While a *p*-value can indicate whether an effect is present or not, it doesn’t reveal the magnitude of that effect. The effect size, on the other hand, provides more information about the magnitude of the difference we observe [69]. Effect sizes (Mann–Whitney *r*, and Cohen’s *d*) were calculated for all tests of significance using the R package “rcompanion” [70].

Here, the calculated *r* and *d* values are the general effect size statistics for the Mann–Whitney test and *t*-test, respectively. Effect size was interpreted as negligible: $|r| < 0.1$, $|d| < 0.2$; small: $0.1 \leq |r| < 0.3$, $0.2 \leq |d| < 0.5$; medium: $0.3 \leq |r| < 0.5$, $0.5 \leq |d| < 0.8$; and large: $|r| \geq 0.5$, $|d| \geq 0.8$ [71,72].

3. Results and discussions

We designed the current study, involving human participants, to test for some of the possible co-benefits of plants for occupants, e.g., improved aesthetics and positive emotions. 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.

3.1. Environmental conditions

The indoor environmental conditions and outdoor conditions from the WoP and WP sessions have been summarized in Table 2. The room's air and globe temperatures were between 24 and 26 °C, and humidity ranged between 30 and 45 %. Thermal conditions were within the summer thermal comfort zones [57]. Like the indoor conditions, the outdoor conditions during WoP and WP sessions were also comparable.

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 two groups of participants thus had similar anthropometric and demographic features.

The sleep scores for the WoP and WP groups, on the GSQS, 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 characteristics ($|r| = 0.04$ – 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).

3.3. Effect on work environment perception

Significant differences in responses were noted for the question on “room decoration ($|r| = 0.42, p < 0.0001$)”, “room cleanliness ($|r| =$

$0.16, p = 0.04$)”, 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 – Table S2 of SI. The improved perception of room decoration and visual comfort was an expected result, considering the biophilic nature of indoor plants [6].

3.4. 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. 3a provides the TSeV for the two groups from Surveys II and IV. Since the response scales were ordinal and not continuous, we have chosen to present the data in terms of stacked bar charts (with percentages in different points of the scale) or grouped scatter plots to represent the data. This helps clearly visualize the change across the points in the scale between control and intervention or over time, in the same session. After spending ~30 mins 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 ($|r| = 0.08, p = 0.4$) 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.

After over 30 mins in the room, 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. 3b. HSeV did not change significantly throughout the session for either group (data plotted in Figure S2). The HSeV was slightly drier for the WoP group in Survey IV ($r = 0.18, p = 0.03$) than the WP group. 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.

The differences in perceptions were likely entirely subjective since the temperature and humidity conditions during both sessions were within similar bounds. Previous studies conducted without occupant presence have noted that plants did not impact indoor temperature [33] but may impact humidity levels [33,73]. In this study, the humidity levels between WoP and WP did not differ significantly though RH for WP was slightly higher (1 %). This would indicate that evapotranspiration from plants can impact indoor humidity levels, but the effect may not be significant when there are other sources of humidity to consider, e.g., occupants.

Other works have also noted the impact of indoor plants on indoor thermal perception, like an improvement in thermal comfort votes [74] and thermal satisfaction [8]. In the current work, the differences thermal sensation between WoP and WP sessions corresponded to small effect sizes but hold practical significance in the context of occupant thermal comfort. The mean TSeV 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 in operative temperature would be needed [75]. The thermal conditions between WoP and WP sessions did not differ as much. Hence, we rejected H1₀.

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 [76]. 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

Table 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 °C
Globe temperature (°C)	24.9 (24.4, 25.4)	24.7 (24.2, 25.2)	±0.6 °C
Relative humidity (%)	36 (33, 39)	37 (34, 42)	±3 %
Air speed (m/s)	<0.10 (<0.10, 0.12)	<0.10 (<0.1, 0.15)	±0.1 m/s
CO2 (ppm)	949 (868, 1014)	956 (885, 1019)	±35 ppm
Ventilation rate (h ⁻¹)	0.10 (0.09, 0.13)	0.11 (0.11, 0.13)	±0.04 h ⁻¹
Outdoors			
Air temperature (°C)	33.9 (32.6, 36.6)	34.3 (33.2, 35.2)	±0.21 °C
Relative humidity (%)	17 (15.2, 21.3)	17 (14.5, 23.5)	±2.5 %
Air speed (m/s)	Under uncertainty limits		±1.1 m/s

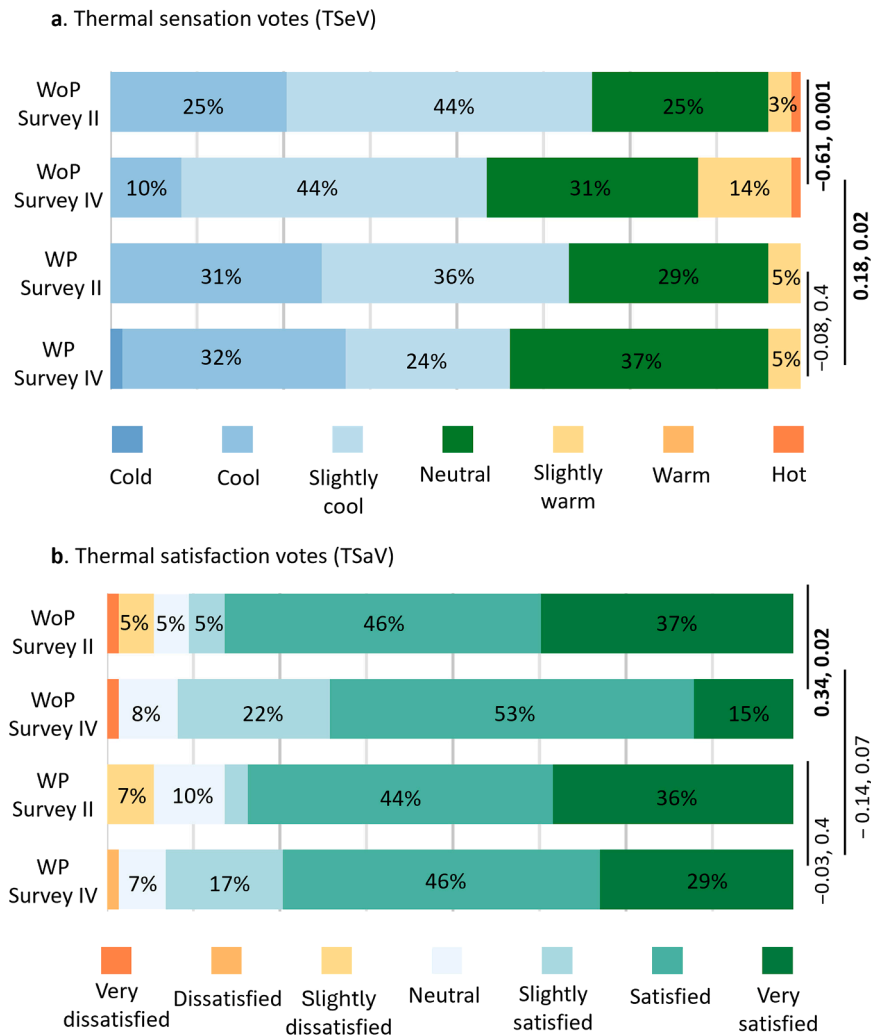


Fig. 3. a. Comparison of thermal sensation votes (TSeV), and b. Comparison of thermal satisfaction votes (TSaV), across each session type and between WoP and WP sessions. Note: The two values written above the vertical lines connecting two percentage vote plots are *r* value followed by *p*-value.

positive distraction, improving participants’ perception in the WP session [77].

The difference in thermal sensation we noticed aligns with the findings of Ko et al. [78]. In their work, view through a window (of plants outdoors) made participants feel slightly cooler than the control condition where window views were blocked ($r = 0.29$). The study of Ko et al. also had a similar exposure duration as our work, though their study design was within-subjects. It is reasonable that viewing plants

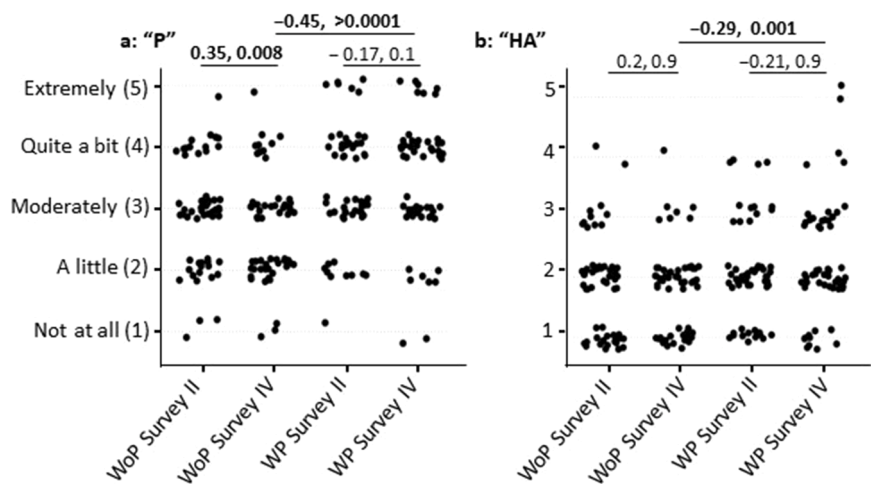


Fig. 4. a. Comparison of affect votes for P affect and b. Comparison of affect votes for HA affect, across each session type and between WoP and WP sessions. Note: The two values written above the horizontal lines connecting two scatter plots are *r* value followed by *p* value.

outdoors could have similar impacts on perception as the presence of plants indoors.

3.5. Effect on participant affect

A comparison of the mean votes under the different affect categories in the circumplex model, for WoP and WP groups, has been summarized in Fig. 4. Comparing the responses between Survey II and Survey IV, WP participants felt sustained positive affect. For the WoP sessions, participant responses on the high arousal, positive (HAP), positive (P), low arousal, positive (LAP), and low arousal (LA) octants dropped significantly between Survey II and Survey IV, indicating a drop in positive emotions over time (see Figure S3).

This decrement was not found for WP participants. 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). The biggest observed impact was for the average score on the P octant ($|r| = 0.45, p < 0.0001$). We thus rejected H_{20} .

Similar to our findings, Ko et al. [78] 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 ($|r| = 0.36, p = 0.0007$). The circumplex model is an easy-to-use, consistently repeatable measure, that has been extensively used in relevant literature [79–81]. It can be a useful instrument for future similar studies involving plants/s/indoor greenery and indoor climate and conditioning.

3.6. Effect on cognitive performance and self-assessed 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, as obtained from the PEBL platform. The average response time for distractor tasks was used as an indicator of the time response for the task. No significant differences ($|d| = 0.06–0.19, p = 0.3–0.8$) were observed for the three metrics between WoP and WP sessions, as summarized in Figure S4. The participants' self-assessed performance on all five metrics used for evaluation did not differ significantly between WoP and WP sessions, as shown in Figure S5.

Due to a lack of significant differences, we fail to reject H_{30} . There have been previous works which similar to our results, did not find an impact of plants on task performance [18,21,29,30] while there also have been works which found a positive effect [21,23,25]. The effect of plants on performance and productivity can be task-dependent, and depend on the density, location, and arrangement of plants [24,82]. 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 [21].

3.7. Indoor plants and possible indoor conditioning energy savings

The mean TSeV between WoP and WP sessions differed by 0.4 scale points, which corresponds to a difference in indoor conditioning temperature of 1 °C [75]. 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 (ACDDs) [83]. Like the cooling degree days metric, the ACDD metric also correlates with cooling energy consumption. We used the Indian Model of Adaptive Comfort (IMAC) [84] and PMV model [75], as references, to calculate ACDDs.

To compare the effect of set-point temperature change on cooling energy use, we used five different scenarios, for buildings operating in mixed mode ventilation:

- (i) PMV Baseline: a constant set-point temperature of 24.5 °C,
- (ii) PMV+0.5 °C: baseline temperature increased by 0.5 °C, with plants,
- (iii) PMV+1 °C: baseline temperature increased by 1 °C, with plants,
- (iv) IMAC model predicted comfort temperature, and
- (v) IMAC model predicted comfort temperature increased by 0.5 °C, with plants, (IMAC+0.5 °C).

Unlike the cooling degree days though, the ACDDs do not use a constant reference temperature. They use a variable reference temperature, based on an adaptive thermal comfort model. In this case, we used IMAC. To calculate ACDDs, we accessed weather data for a typical meteorological year of the cities from the epw files [85]. The ACDDs reflect the cooling energy needs under these scenarios, for the different cities.

The IMAC model proposes a variation for mixed mode buildings. We used this 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.

From the epw files we get hourly recorded temperature, which was then processed to obtain daywise mean temperature (DMT) and running mean temperature (RMT)

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

The above formula calculates the average temperature over the last thirty days, excluding the current day. Where, $(RMT)_t$ 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.

The details of the method used for these evaluations have been provided in the Table S3. As we conducted the study in Pilani, which comes under the composite climate region of India [86], we further calculated the ACDDs for four other major Indian cities with composite climate: New Delhi, Gwalior, Hyderabad, and Kota.

Fig. 5 presents the estimated ACDDs for the five cities in India's composite climate zone, calculated under five distinct scenarios. The scenarios represent varying cooling strategies, including constant set-point adjustments (PMV+0.5 °C and PMV+1 °C) and adaptive comfort thresholds derived from the Indian Model of Adaptive Comfort (IMAC). The IMAC+0.5 °C scenario achieves the lowest ACDDs across all cities, outperforming even the PMV+1 °C scenario, which assumes a 1 °C setpoint increase facilitated by indoor plants.

These reductions reflect potential energy savings, as ACDD correlates with cooling energy needs. Notably, the ACDD variations across cities (e. g., higher in Hyderabad and lower in Gwalior) result from differences in local climate, such as temperature profiles and cooling seasons. A detailed percentage reduction in ACDDs, using the PMV Baseline as a reference, is provided in Table S4. This analysis underscores the potential of combining adaptive thermal comfort standards with plant based strategies to reduce cooling energy use.

The calculation of Adaptive Cooling Degree Days (ACDDs) in this study follows established methods, including the integration of variable comfort setpoints derived from the IMAC. Similar to the approach described by McGilligan et al. (2011), the ACDD metric reflects cooling energy needs under different scenarios, correlating with cooling degree days but using adaptive comfort temperatures. Our analysis utilized verified weather data from epw files and processed it to calculate running mean temperatures, ensuring consistency with adaptive comfort methodologies.

The ACDD predictions are supported by building performance simulations from prior works [87], which indicate that setpoint increases of 0.5–1 °C can achieve average cooling energy savings of 6–11 %. Our findings, suggesting potential reductions of 8–42 % in ACDDs for mixed mode buildings with indoor plants, align with these predictions,

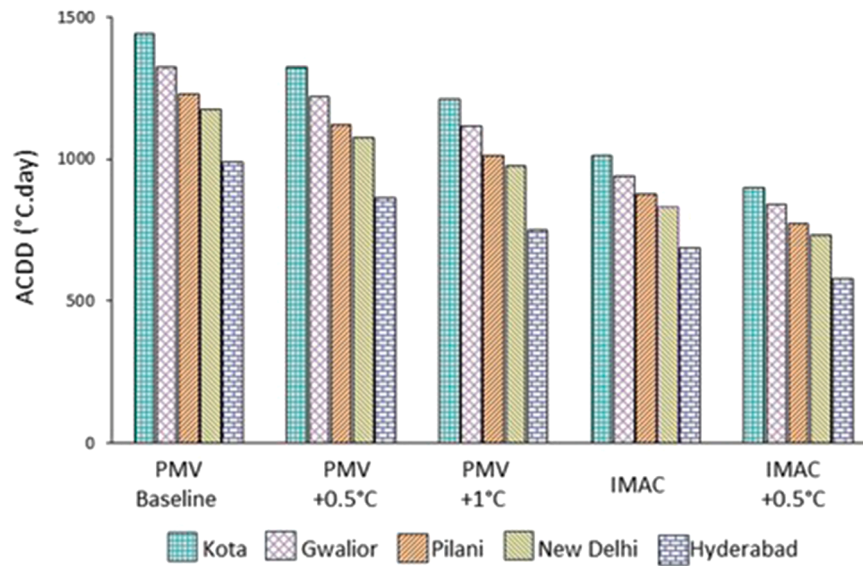


Fig. 5. ACDD calculated for mixed mode buildings located in composite climate of India.

reflecting the influence of adaptive thermal comfort models and operational patterns. While this study demonstrates theoretical consistency, future validation under real world building conditions would be needed to substantiate these results. The specific values would depend on the operational pattern used for the systems, building size, occupant density etc. However, the implication is that indoor plants can help with reducing cooling energy use and contribute to UN Sustainable Development Goal 13, Target 13.1, “Strengthen resilience and adaptive capacity to climate related hazards...” like heatwaves.

3.8. Overall effect of indoor plants on occupants’ perception

In the heatmap (Fig. 6), we included attributes with p values up to 0.15 and effect sizes of 0.1 or greater. Some of these differences are more exploratory and do not yet provide strong statistical support [69]. The smaller effect sizes can yet prove to be relevant considering the large population of office occupants. Future works, with greater number of participants may ascribe statistical significance to some of these findings.

We have discussed the $p < 0.05$ results in earlier sections,

highlighting the stronger effects observed in attributes like “Improved positive emotions” ($|r| = 0.45$) and “Improved high arousal emotions” ($|r| = 0.29$) in presence of plants. These findings align with the positive impact of viewing plants on occupant wellbeing, as found in multiple previous works, discussed in the Introduction. Presence of plants did appear to improve perceived thermal comfort providing slightly cooler and less dry perception.

Attributes such as “Improved overall room environment” ($|r| = 0.10$), “Felt breathing ease” ($|r| = 0.11$), “Improved satisfaction with available space” ($|r| = 0.14$), and “Task assessed to be easier” ($|r| = 0.13$) had p values > 0.05 . They may contribute to improving the overall room environment, breathing ease, and performance for a large population.

Overall, the improvements related to affects, temperature satisfaction, breathing ease, and satisfaction with room IEQ could contribute to creating a comfortable indoor environment using biophilic elements, complimenting HVAC systems and saving energy. While some effect sizes are small to medium, it would come down to space design and organizational policies as even a small effect size, relevant to thousands of office occupants, could provide meaningful benefits.

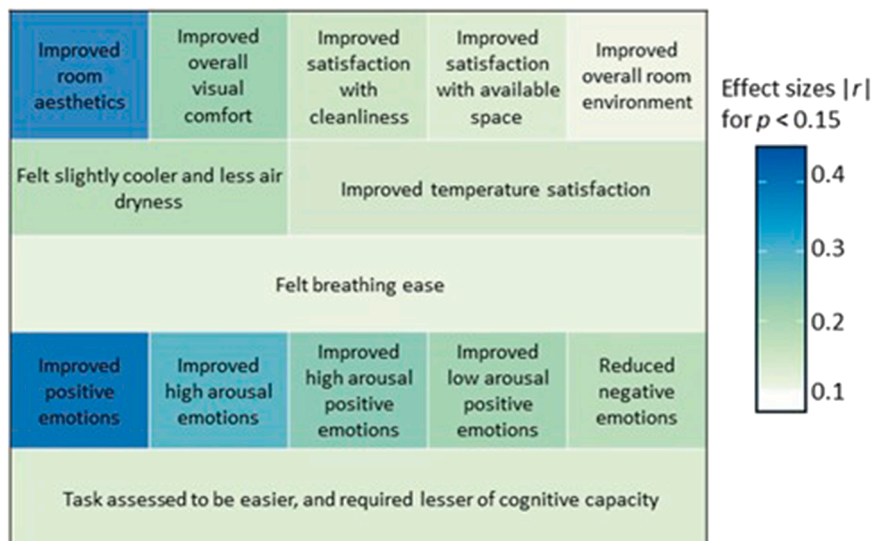


Fig. 6. Heat map showing impact of indoor plants on occupants.

4. Study limitations and future works

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 the 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. The participant population was representative of the campus population.

A statistically significant difference with small effect size in conscientiousness scores between the two groups (WP group scoring slightly higher) was observed. This may have influenced the subjective responses though there is no known effect of conscientiousness on thermal preferences. Future studies may need to inculcate larger and more diverse groups of participants to avoid such potential confounding effects.

Using post hoc power calculations in G*Power, with 59 participants, $\alpha = 0.05$ 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 $\alpha = 0.05$, 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 provide less control over indoor conditions. Hence, this is an important challenge for future works.

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 within comfort-bounds. Under warm or cool discomfort, the occupants' perception towards the presence of plants could be different. Similarly, another form of greenery, like green walls, could impact occupants differently.

Based on resource constraints and participant feedback regarding duration and measures (from a smaller scale pre-study organized six months prior to the main study) we designed the study to be of 60 min duration and without any physiological measures of thermal comfort and stress. We could not include objective indicators of discomfort and stress such as heart rate variability and cortisol or salivary α -amylase. Instead, we focused on ensuring participant numbers as per a priori power calculations. Future studies could incorporate these objective measures alongside subjective indicators to enhance the scientific validity and credibility of the findings, in consultation with participant needs and comfort.

5. Conclusions

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 (8–42 %).
- Indoor plants enhanced positive affect ($|r| = 0.21$ to 0.45 , $p < 0.0001$ to 0.02) and reduced negative affect ($|r| = 0.18$; small effect, $p = 0.02$) significantly. This indicates psychological benefits of

incorporating indoor plants that may improve well-being and productivity, contributing to a healthier working environment.

- The plants improved occupants' perception of the room's decoration ($|r| = 0.42$, $p < 0.0001$), room cleanliness ($|r| = 0.16$, $p = 0.04$), and overall visual comfort ($|r| = 0.22$, $p = 0.01$), as may be expected.
- The observed effect of plants on occupants' perceived SBS symptoms particularly felt breathing ease ($|r| = 0.11$, $p = 0.11$), improved overall room environment ($|r| = 0.10$, $p = 0.14$), improved satisfaction with available space ($|r| = 0.14$, $p = 0.07$), and "Task assessed to be easier" ($|r| = 0.13$, $p = 0.09$). These aspects lack statistical significance and require future research with large sample sizes.

CRedit authorship contribution statement

Mukesh Budaniya: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Asit Kumar Mishra:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aakash C. Rai:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **M.S. Dasgupta:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2025.112785](https://doi.org/10.1016/j.buildenv.2025.112785).

Data availability

Data and codes shared as a GitHub repository which is given in Methods section.

References

- [1] F. Liu, L. Yan, X. Meng, C. Zhang, A review on indoor green plants employed to improve indoor environment, *J. Build. Eng.* 53 (2022) 104542, <https://doi.org/10.1016/j.jobee.2022.104542>.
- [2] F. Felgueiras, Z. Mourão, A. Moreira, M.F. Gabriel, Indoor environmental quality in offices and risk of health and productivity complaints at work: a literature review, *J. Hazard. Mater. Adv.* 10 (2023), <https://doi.org/10.1016/j.hazadv.2023.100314>.
- [3] W.J. Fisk, Health and productivity gains from better indoor environments and their relationship with building energy efficiency, *Annu. Rev. Energy Environ.* (2000) 537–566.
- [4] T. Al Mindeel, E. Spentzou, M. Eftekhari, Energy, thermal comfort, and indoor air quality: multi-objective optimization review, *Renew. Sustain. Energy Rev.* 202 (2024) 114682, <https://doi.org/10.1016/j.rser.2024.114682>.
- [5] I. Andric, A. Kamal, S.G. Al-Ghamdi, Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: case study of Qatar, *Energy Reports* 6 (2020) 2476–2489, <https://doi.org/10.1016/j.egy.2020.09.006>.

- [6] M. Mehaffy, Biophilic design: the theory, science, and practice of bringing buildings to life, *Proc. Inst. Civ. Eng. Urban Des. Plan.* 165 (2012), <https://doi.org/10.1680/udap.11.00035>, 193–193.
- [7] M. Mannan, S.G. Al-Ghamdi, Life cycle embodied energy analysis of indoor active living wall system, *Energy Reports* 6 (2020) 391–395, <https://doi.org/10.1016/j.egy.2020.11.180>.
- [8] J. Ayuso Sanchez, T. Ikaga, S. Vega Sanchez, Quantitative improvement in workplace performance through biophilic design: a pilot experiment case study, *Energy Build.* 177 (2018) 316–328, <https://doi.org/10.1016/j.enbuild.2018.07.065>.
- [9] G. Mangone, S.R. Kurvers, P.G. Luscuere, Constructing thermal comfort: investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment, *Build. Environ.* 81 (2014) 410–426, <https://doi.org/10.1016/j.buildenv.2014.07.019>.
- [10] R. Elnaklah, I. Walker, S. Natarajan, Moving to a green building: indoor environment quality, thermal comfort and health, *Build. Environ.* 191 (2021) 107592, <https://doi.org/10.1016/j.buildenv.2021.107592>.
- [11] M. Richardson, C.W. Butler, Nature connectedness and biophilic design, *Build. Res. Inf.* 50 (2022) 36–42, <https://doi.org/10.1080/09613218.2021.2006594>.
- [12] H.B. Awbi, Ventilation for good indoor air quality and energy efficiency, *Energy Procedia* 112 (2017) 277–286, <https://doi.org/10.1016/j.egypro.2017.03.1098>.
- [13] X. Ma, M. Du, P. Deng, T. Zhou, B. Hong, Effects of green walls on thermal perception and cognitive performance: an indoor study, *Build. Environ.* 250 (2024), <https://doi.org/10.1016/j.buildenv.2024.111180>.
- [14] X. Meng, L. Yan, F. Liu, A new method to improve indoor environment: combining the living wall with air-conditioning, *Build. Environ.* 216 (2022) 108981, <https://doi.org/10.1016/j.buildenv.2022.108981>.
- [15] M.A. Kenai, L. Libessart, S. Lassue, D. Defer, Impact of green walls occultation on energy balance: development of a TRNSYS model on a brick masonry house, *J. Build. Eng.* 44 (2021), <https://doi.org/10.1016/j.jobe.2021.102634>.
- [16] K. Li, A. Perrault, W.A. DeYoung, E. Cameron, C.T. Miller, A.S. O'Connor, M. Gu, B. Braun, Impact of biophilic design on college student perception of mental health and environmental benefits: a dose-response study, *Build. Environ.* 267 (2025), <https://doi.org/10.1016/j.buildenv.2024.112318>.
- [17] S. Seyam, The impact of greenery systems on building energy: systematic review, *J. Build. Eng.* 26 (2019) 100887, <https://doi.org/10.1016/j.jobe.2019.100887>.
- [18] S. Shibata, N. Suzuki, Effects of the foliage plant on task performance and mood, *J. Environ. Psychol.* 22 (2002) 265–272, <https://doi.org/10.1006/jevp.2002.0232>.
- [19] V.I. Lohr, C.H. Pearson-Mims, G.K. Goodwin, Interior plants may improve worker productivity and reduce stress in a windowless environment, *J. Environ. Hortic.* 14 (1996) 97–100, <https://doi.org/10.24266/0738-2898-14.2.97>.
- [20] R.K. Raanaas, K.H. Evensen, D. Rich, G. Sjøstrøm, G. Patil, Benefits of indoor plants on attention capacity in an office setting, *J. Environ. Psychol.* 31 (2011) 99–105, <https://doi.org/10.1016/j.jenvp.2010.11.005>.
- [21] A. Thatcher, K. Adamson, L. Bloch, A. Kalantzis, Do indoor plants improve performance and well-being in offices? Divergent results from laboratory and field studies, *J. Environ. Psychol.* 71 (2020) 101487, <https://doi.org/10.1016/j.jenvp.2020.101487>.
- [22] G. Carrus, M. Scopelliti, R. Laforteza, G. Colangelo, F. Ferrini, F. Salbitano, M. Agrimi, L. Portoghesi, P. Semenzato, G. Sanesi, Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting urban and peri-urban green areas, *Landsc. Urban Plan.* 134 (2015) 221–228, <https://doi.org/10.1016/j.landurbplan.2014.10.022>.
- [23] T. Bringslimark, T. Hartig, G.G. Patil, Psychological benefits of indoor plants in workplaces: putting experimental results into context, *HortScience* 42 (2007) 581–587, <https://doi.org/10.21273/hortsci.42.3.581>.
- [24] D. Jumeño, H. Matsumoto, The effects of indoor foliage plants on perceived air quality, mood, attention, and productivity, *J. Civ. Eng. Archit. Res.* 3 (2016) 1359–1370.
- [25] M. Nieuwenhuis, C. Knight, T. Postmes, S.A. Haslam, The relative benefits of green versus lean office space: three field experiments, *J. Exp. Psychol. Appl.* 20 (2014) 199–214, <https://doi.org/10.1037/xap0000024>.
- [26] J. Qin, C. Sun, X. Zhou, H. Leng, Z. Lian, The effect of indoor plants on human comfort, *Indoor Built Environ.* 23 (2014) 709–723, <https://doi.org/10.1177/1420326X13481372>.
- [27] D.L. Rich, Effects of Exposure to Nature and Plants On Cognition and mood: a Cognitive Psychology Perspective, Cornell University, New York, 2007. <http://digi.lib.unila.ac.id/4949/15/BABII.pdf>.
- [28] C.K. Coleman, R.K. Mattson, Influences of foliage plants on human stress during thermal biofeedback training, *Horttechnology* 5 (1995) 137–140, <https://doi.org/10.21273/horttech.5.2.137>.
- [29] N. van den Bogerd, S.C. Dijkstra, S.L. Koole, J.C. Seidell, J. Maas, Greening the room: a quasi-experimental study on the presence of potted plants in study rooms on mood, cognitive performance, and perceived environmental quality among university students, *J. Environ. Psychol.* 73 (2021) 101557, <https://doi.org/10.1016/j.jenvp.2021.101557>.
- [30] N.M. Jamaludin, N. Mahyuddin, F.W. Akashah, Assessment on indoor environmental quality (IEQ) with the application of potted plants in the classroom: case of university Malaya, *J. Des. Built Environ.* 17 (2017) 1–15, <https://doi.org/10.22452/jdbe.vol17no2.1>.
- [31] M. Budaniya, A.C. Rai, Effectiveness of plants for passive removal of particulate matter is low in the indoor environment, *Build. Environ.* 222 (2022) 109384, <https://doi.org/10.1016/j.buildenv.2022.109384>.
- [32] B.E. Cummings, M.S. Waring, Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies, *J. Expo. Sci. Environ. Epidemiol.* 30 (2020) 253–261, <https://doi.org/10.1038/s41370-019-0175-9>.
- [33] J. Jiang, P. Irga, R. Coe, P. Gibbons, Effects of indoor plants on CO2 concentration, indoor air temperature and relative humidity in office buildings, *PLoS One* 19 (2024) 1–13, <https://doi.org/10.1371/journal.pone.0305956>.
- [34] J. Berger, E. Essah, T. Blanus, The impact of plants on the humidity of naturally-ventilated office indoor environments, *J. Build. Eng.* 86 (2024) 108814, <https://doi.org/10.1016/j.jobe.2024.108814>.
- [35] S. Sugano, M. Tazaki, H. Arai, K. Matsuo, S. ichi Tanabe, Characteristics of eye movements while viewing indoor plants and improvements in occupants' cognitive functions, *Japan Archit. Rev.* 5 (2022) 621–632, <https://doi.org/10.1002/2475-8876.12284>.
- [36] N.L. Mintz, A.H. Maslow, Effects of esthetic surroundings: initial effects of three esthetic conditions upon perceiving “energy” and “well-being” in faces, *J. Psychol.* 41 (1956) 247–254, <https://doi.org/10.1080/00223980.1956.9713000>.
- [37] R. Rawal, P. Vaidya, V. Ghatti, A. Ward, T. Weidt, Energy code enforcement for beginners : a tiered approach to energy code in India, in: *ACEEE Summer Study Energy Effic.*, Build 2002 (2012) 313–324.
- [38] R. Gupta, S. Sankhe, N. Unni, M. Divy, Decarbonising India: charting a pathway for sustainable growth, McKinsey Co (2022) 1–244. <https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonising-india-charting-a-pathway-for-sustainable-growth> (accessed December 30, 2023).
- [39] Z. Wang, J.S. Zhang, Characterization and performance evaluation of a full-scale activated carbon-based dynamic botanical air filtration system for improving indoor air quality, *Build. Environ.* 46 (2011) 758–768, <https://doi.org/10.1016/j.buildenv.2010.10.008>.
- [40] A. Nin-Valencia, M. Tomás-Pérez, B. Bartolomé Zavala, Allergic rhinitis due to the ornamental plant sansevieria trifasciata, *J. Investig. Allergol. Clin. Immunol.* 32 (2022) 62–64, <https://doi.org/10.18176/jiaci.0704>.
- [41] J. Cui, Z. Li, W. Zhang, L. Wang, H. Liu, H. Liu, Integrating aromatic plants into indoor biophilic environments: species selection based on psychophysiological effects and bioactive volatile compounds, *Build. Environ.* 267 (2025) 112169, <https://doi.org/10.1016/j.buildenv.2024.112169>.
- [42] Bureau of Indian Standards, National building code of India, New Delhi, 2005.
- [43] S. Kumar, M.K. Singh, A. Mathur, S. Mathur, J. Mathur, Thermal performance and comfort potential estimation in low-rise high thermal mass naturally ventilated office buildings in India: an experimental study, *J. Build. Eng.* 20 (2018) 569–584, <https://doi.org/10.1016/j.jobe.2018.09.003>.
- [44] F. Bano, V. Sehgal, Evaluation of energy-efficient design strategies: comparison of the thermal performance of energy-efficient office buildings in composite climate, *India, Sol. Energy* 176 (2018) 506–519, <https://doi.org/10.1016/j.solener.2018.10.057>.
- [45] K. Han, Effects of indoor plants on self-reported perceptions: a systemic review, *Sustainability* 11 (2019) 4506, <https://doi.org/10.3390/su11164506>.
- [46] S. Sugano, M. Tazaki, H. Arai, K. Matsuo, S.I. Tanabe, Effects of indoor plants on human functions: a systematic review with meta-analyses, *Int. J. Environ. Res. Public Health* 19 (2022) 7454, <https://doi.org/10.3390/ijerph19127454>.
- [47] T. Bringslimark, T. Hartig, G.G. Patil, The psychological benefits of indoor plants: a critical review of the experimental literature, *J. Environ. Psychol.* 29 (2009) 422–433, <https://doi.org/10.1016/j.jenvp.2009.05.001>.
- [48] F. Liu, L. Yan, X. Meng, C. Zhang, A review on indoor green plants employed to improve indoor environment, *J. Build. Eng.* 53 (2022) 104542, <https://doi.org/10.1016/j.jobe.2022.104542>.
- [49] J. Berger, E. Essah, T. Blanus, C.P. Beaman, The appearance of indoor plants and their effect on people's perceptions of indoor air quality and subjective well-being, *Build. Environ.* 219 (2022) 109151, <https://doi.org/10.1016/j.buildenv.2022.109151>.
- [50] B.V. Pennisi, Growing indoor plants with success, *Univ. Georg. Coop. with Fort Val. State Univ. U.S. Dep. Agric. Cties. State.* (2020) 1–27. extension.uga.edu.
- [51] S. Chauhan, B. Bhargava Manisha, K.C. Kandpal, A. Kumar, Analyzing preferred indoor ornamental potted plants for their air pollution tolerance ability, *Polish J. Environ. Stud.* 31 (2022) 2019–2027, <https://doi.org/10.15244/pjoes/140291>.
- [52] D.N. Wagh, B.R. Salvi, K.V. Malshe, R.G. Khandekar, Performance of indoor plants in pots after transplanting, *Pharma Innov. J.* 10 (2021) 25–27.
- [53] T. Thakar, The 8 best indoor plants for homes in India.” good homes India, (2023). <https://www.goodhomes.co.in/lifestyle/wellness/the-8-best-indoor-plants-for-homes-in-india-7339.html> (accessed November 22, 2023).
- [54] J. Gao, P-values - A chronic conundrum, *BMC Med. Res. Methodol.* 20 (2020) 1–8, <https://doi.org/10.1186/s12874-020-01051-6>.
- [55] M. El Maniani, M. Rechchach, A. El Mahfoudi, M. El Moudane, A. Sabbar, G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences, *J. Mater. Environ. Sci.* 7 (2016) 3759–3766.
- [56] T.F. Meijman, de V.A.H. de Vries-Griever, G. The Evaluation of the Groningen Sleep Quality Scale, *Heymans Bulletin*, Groningen, 1988 (HB 88—13—EX).
- [57] A.S.H.R.A.E., Thermal environmental conditions for human occupancy, *ANSI/ASHRAE Stand* 55 (7) (2017) 60.
- [58] R. Thomas, Environmental design: an Introduction For Architects and Engineers, 3rd Ed, Taylor & Francis, 2006, <https://doi.org/10.4324/9780203013663-15>.
- [59] S.T. Mueller, B.J. Piper, The psychology experiment building language (PEBL) and PEBL test battery, *J. Neurosci. Methods* 222 (2014) 250–259, <https://doi.org/10.1016/j.jneumeth.2013.10.024>.
- [60] A.K. Mishra, R.P. Kramer, M.G.L.C. Loomans, H.L. Schellen, Development of the thermal discernment among visitors: results from a field study in the Hermitage Amsterdam, *Build. Environ.* 105 (2016) 40–49, <https://doi.org/10.1016/j.buildenv.2016.05.026>.
- [61] P. Strom-Tejnen, D. Zukowska, P. Wargocki, D.P. Wyon, The effects of bedroom air quality on sleep and next-day performance, *Indoor Air* 26 (2016) 679–686, <https://doi.org/10.1111/ina.12254>.

- [62] S. Lee, C. Mu, B.D. Gonzalez, C.E. Vinci, B.J. Small, Sleep health is associated with next-day mindful attention in healthcare workers, *Sleep Heal* 7 (2021) 105–112, <https://doi.org/10.1016/j.sleh.2020.07.005>.
- [63] M. Alhainen, M. Härmä, J. Pentti, J.M. Ervasti, M. Kivimäki, J. Vahtera, S. Stenholm, Sleep duration and sleep difficulties as predictors of occupational injuries: a cohort study, *Occup. Environ. Med.* 79 (2022) 224–232, <https://doi.org/10.1136/oemed-2021-107516>.
- [64] T.F. Meijman, M.J. Thunnissen, A.G.H. De Vries-Griever, The after-effects of a prolonged period of day-sleep on subjective sleep quality, *Work Stress* 4 (1990) 65–70, <https://doi.org/10.1080/02678379008256965>.
- [65] J.A. Russell, A circumplex model of affect, *J. Pers. Soc. Psychol.* 39 (1980) 1161–1178, <https://doi.org/10.1037/h0077714>.
- [66] N. Unsworth, R.P. Heitz, R.W. Engle, An automated version of the operation span task NASH, *Behav. Res. Methods* 37 (2005) 498–505, <https://doi.org/10.3758/BF03192720>.
- [67] A. Zeileis, K. Hornik, M.A. Wiel, T. Hothorn, Implementing a class of permutation tests: the coin package, *J. Stat. Softw.* 28 (2008).
- [68] A.K. Mishra, M.G.L.C. Loomans, J.L.M. Hensen, Thermal comfort of heterogeneous and dynamic indoor conditions — An overview, *Build. Environ.* 109 (2016) 82–100, <https://doi.org/10.1016/j.buildenv.2016.09.016>.
- [69] G.M. Sullivan, R. Feinn, Using effect size—Or why the P value is not enough, *J. Grad. Med. Educ.* 4 (2012) 279–282, <https://doi.org/10.4300/jgme-D-12-00156.1>.
- [70] S. Mangiafico, Package ‘rcompanion’, *Cran Repos* (2023) 1–71.
- [71] J. Cohen, A. Power Primer, *Psychol. Bull.* 112 (1992) 155–159, <https://doi.org/10.1016/j.jorganchem.2011.01.025>.
- [72] C.J. Ferguson, An effect size primer: a guide for clinicians and researchers, *Prof. Psychol. Res. Pract.* 40 (2009) 532–538, <https://doi.org/10.1037/a0015808>.
- [73] J. Berger, E. Essah, T. Blanus, The impact of plants on the humidity of naturally-ventilated office indoor environments, *J. Build. Eng.* 86 (2024) 108814, <https://doi.org/10.1016/j.job.2024.108814>.
- [74] X. Ma, M. Du, P. Deng, T. Zhou, B. Hong, Effects of green walls on thermal perception and cognitive performance: an indoor study, *Build. Environ.* 250 (2024), <https://doi.org/10.1016/j.buildenv.2024.111180>.
- [75] F. Tartarini, S. Schiavon, T. Cheung, T. Hoyt, CBE thermal comfort tool: online tool for thermal comfort calculations and visualizations, (2020). <https://comfort.cbe.berkeley.edu/>.
- [76] A. Shah, A. Garg, V. Mishra, Quantifying the local cooling effects of urban green spaces: evidence from Bengaluru, India, *Landsc. Urban Plan.* 209 (2021), <https://doi.org/10.1016/j.landurbplan.2021.104043>.
- [77] S.H. Park, R.H. Mattson, Ornamental indoor plants in hospital rooms enhanced health outcomes of patients recovering from surgery, *J. Altern. Complement. Med.* 15 (2009) 975–980, <https://doi.org/10.1089/acm.2009.0075>.
- [78] W.H. Ko, S. Schiavon, L.T. Graham, G. Brager, I. Mauss, The impact of a view from a window on thermal comfort, emotion, cognitive performance, in: 16th Conf. Int. Soc. Indoor Air Qual. Clim. Creat. Smart Solut. Better Built Environ. *Indoor Air* 2020, 2020, p. 175.
- [79] A. Tseng, R. Bansal, J. Liu, A.J. Gerber, S. Goh, J. Posner, T. Colibazzi, M. Algermissen, I.C. Chiang, J.A. Russell, B.S. Peterson, Using the circumplex model of affect to study valence and arousal ratings of emotional faces by children and adults with autism spectrum disorders, *J. Autism Dev. Disord.* 44 (2014) 1332–1346, <https://doi.org/10.1007/s10803-013-1993-6>.
- [80] J. Posner, J.A. Russell, B.S. Peterson, The circumplex model of affect: an integrative approach to affective neuroscience, cognitive development, and psychopathology, *Dev. Psychopathol.* 17 (2005) 715–734, <https://doi.org/10.1017/S0954579405050340>.
- [81] R. Rietveld, W. van Dolen, M. Mazloom, M. Worring, What you feel, is What you like influence of message appeals on customer engagement on Instagram, *J. Interact. Mark.* 49 (2020) 20–53, <https://doi.org/10.1016/j.intmar.2019.06.003>.
- [82] A.E. van den Berg, J.E. Wesselius, J. Maas, K. Tanja-Dijkstra, Green walls for a restorative classroom environment: a controlled evaluation study, *Environ. Behav.* 49 (2017) 791–813, <https://doi.org/10.1177/0013916516667976>.
- [83] C. McGilligan, S. Natarajan, M. Nikolopoulou, Adaptive comfort degree-days: a metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates, *Energy Build.* 43 (2011) 2767–2778, <https://doi.org/10.1016/j.enbuild.2011.06.037>.
- [84] S. Manu, Y. Shukla, R. Rawal, L.E. Thomas, R. de Dear, Field studies of thermal comfort across multiple climate zones for the subcontinent: india model for adaptive comfort (IMAC), *Build. Environ.* 98 (2016) 55–70, <https://doi.org/10.1016/j.buildenv.2015.12.019>.
- [85] EnergyPlus energy simulation software – weather data, U.S. Dep. Energy (2012). https://energyplus.net/weather-region/asia_wmo_region_2/IND.
- [86] Bansal N.K. and Minke G., Climatic zones and rural housing in India, 1988.
- [87] T. Hoyt, E. Arens, H. Zhang, Extending air temperature setpoints: simulated energy savings and design considerations for new and retrofit buildings, *Build. Environ.* 88 (2015) 89–96, <https://doi.org/10.1016/j.buildenv.2014.09.010>.