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Evaluation of plant based indoor air purification in urban environments in Pakistan

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Abstract

Indoor air quality (IAQ) has emerged as a critical public health concern in rapidly urbanizing cities like Lahore, Pakistan, where ambient pollution levels regularly exceed WHO safety thresholds during annual smog seasons. This study aims to quantify the independent and combined effects of indoor plants and natural ventilation on IAQ through a quasi-experimental design, with implications for affordable IAQ management in smog-affected urban contexts. Eight office spaces across Beaconhouse National University were monitored over three months (July–September) using Awair Element consumer-grade sensors measuring CO_2, $PM_{2.5}$, PM_{10}, and TVOCs at five-minute intervals. Six air-purifying plant species—*Dracaena trifasciata*, *Aloe vera*, *Epipremnum aureum*, *Chlorophytum comosum*, *Rhapis excelsa*, and *Chamaedorea seifrizii*—were deployed to assess remediation capacity under varying ventilation scenarios. Results showed that natural ventilation was highly effective, with windowed spaces exhibiting 96.2% lower $PM_{2.5}$ (2 $\mu g/m^3$ vs. 53 $\mu g/m^3$) and 70.5% lower TVOCs (535 ppb vs. 1,814 ppb) compared to sealed rooms. Conversely, plants in non-ventilated spaces achieved substantial $PM_{2.5}$ reductions (96.7%) but paradoxically increased TVOCs by 63.3%, likely due to human activity overwhelming plant metabolic capacity. Temporal analysis revealed that CAM plants effectively reduced nighttime pollutants when occupancy ceased, though daytime human activity in sealed offices generated pollutants faster than plants could metabolize them. These findings demonstrate that phytoremediation effectiveness critically depends on adequate ventilation and appropriate space-to-plant ratios. The study concludes that meaningful improvements in IAQ in Pakistani urban contexts require integrated strategies combining ventilation, strategic plant deployment, and effective policies on human presence in enclosed spaces, particularly during Lahore's severe smog season.

Keywords Indoor air quality, Phytoremediation, Plant-based air purification, Particulate matter, $PM_{2.5}$, Volatile organic compounds, Carbon dioxide, Natural ventilation, Air quality monitoring, Urban air pollution, Smog season, Net zero, Lahore, Pakistan, Awair sensor, Indoor plants, Quasi-experiment, Environmental health

1 Climate impact pathway

The climate impact pathway under study demonstrated the mirroring of deteriorating outdoor and indoor air quality amplifying the health risks in closed office spaces. In Lahore Pakistan, one of the world's most atmospherically polluted cities, the infiltration of polluted outdoor air alongside stagnant indoor air conditions create a combined polluted environment. Closed office spaces with no ventilation and no plant consideration show increased accumulation of CO_2, VOCs, $PM_{2.5}$, and PM_10, as observed in the non-window test space and no plant test space of this study, leading to reduced air quality scores and potential adverse health outcomes. In extremely polluted months, spaces with windows provide negligible relief, as external air during smog periods carries high pollutant concentrations. The trapped indoor emissions and polluted outdoor inflow elevate the risk of respiratory irritation, cognitive fatigue, and chronic illnesses in occupants. Therefore, the findings emphasize that in regions like Lahore, where climatic and anthropogenic factors severely degrade ambient air quality, both ventilation strategies and natural phytoremediation methodologies must be reevaluated to ensure safer indoor air quality environments.

2 Introduction

Over the past two decades, both indoor and outdoor air quality has deteriorated significantly, with indoor air quality (IAQ) emerging as a critical health concern worldwide. Rapid industrialization, urbanization, and increased energy consumption have led to outstanding air pollution levels in major global cities such as Delhi, Beijing, and Dhaka.These cities are where $PM_{2.5}$ levels exceed WHO thresholds regularly by tenfolds. Lahore, Pakistan's cultural and economic hub, now ranks consistently among the world's most polluted cities according to global Air Quality Index (AQI) rankings, with $PM_{2.5}$ levels frequently surpassing hazardous thresholds during winter months.

High ambient gaseous pollution and debris from industrial activities, vehicular emissions and the widespread use of biomass fuels for cooking and heating, further enabled by poor ventilation design of the house structure, constitutes towards the degrading indoor air quality of Pakistan's households and workspaces. Furthermore, subpar urban planning and layout that allows residential schemes to be developed in the vicinity of industrial areas worsens already alarming air quality levels inside households. Regulatory frameworks, such as those detailed in the Ministry of Climate Change guidelines [1], suggest that indoor pollutant levels in Pakistan, especially during smog season in Lahore, frequently surpass safe thresholds, contributing to sick building syndrome and long-term respiratory health risks.

Elementary studies have shown promise in the ability of plants to remove various hazardous pollutants from the air environments. For example, the NASA Clean Air Study, which was aimed at improving the air quality of the controlled environments of sealed space stations and spacecrafts, laid the foundation for expanding this work onto real-world homes and offices[2]. The notable takeaway from the results is the possible removal of volatile organic compounds, benzene, particulate matter, formaldehydes and trichloroethylene with the use of plants' systemic absorption via the root and the shoot. The controlled experiment that was carried in a well regulated plexiglass container mimicked a miniature environment that of a sealed space station. This suggests the effective nature of plant absorption. In contrast, many question its relevancy in terms of real world air purification.The small regulated test space is not a reflection of an everyday environment which undergoes multiple stresses of climate, weather and human activity. Additionally, in real time, rooms are impacted by airflow, vary in size and are exposed to frequent sources of pollution. They are not well regulated and in perfect conditions, however that is only the limited scope of the original research. On the contrary, Aini Jasmin Ghazali et al, report in her study of applying plant-based healing on tropical office environments as having a significant impact however diluted the results may be[3]. These insights are taken under consideration when adapting the research for the Pakistani context.

Over the course of the year, Pakistan is exposed to adverse climatic conditions. Being a tropical country, it is subject to hot summers, cold winters and monsoon rains. Moreover, in recent years, the country's experiences a yearly smog season as a result of crop burning, increasing traffic and weather inversions. Lahore, in particular, lies in a geographical zone surrounded by agricultural zones while being an industrial hub itself, making it one of the most affected cities during the smog period. The smog season in Lahore has become a determining factor to raise environmental and public health concern. This season while typically lasts from late October to early February, it's effects on respiratory health of the public is substantial enough to cause discomfort year around. During this period, air quality levels deteriorate drastically, with Air Quality Index (AQI) values frequently exceeding 300, classifying the air as ”hazardous” according to WHO standards.

This recurring phenomenon reflects a larger environmental pattern observed across Pakistan's urban centers, where climatic conditions and poor ventilation design amplify air quality concerns. In the more arid regions, the risk of dust and particulate matter increases as dust storms are more prevalent. Together, these climatic conditions pose significant challenges for maintaining healthy indoor air quality. These environmental issues are further compounded by urban infrastructure and planning.The cities are densely packed, with houses conjoined by each wall. The industrial infrastructure thrives among households and offices causing toxic fumes to invade indoor air spaces and the construction practices hold little consideration for ventilation and air flow. As a result, the average Pakistani household–particularly those in Lahore and other major urban centers–is highly vulnerable to indoor air quality degradation. These conditions are to be understood when researching and suggesting phytoremediation as a plausible solution to combat indoor air pollution in Pakistan.

Challenges in implementing this technique occur on a smaller scale as well. Pakistani literature highlights the use of traditional stone stoves and ovens powered by biomass burning and the prevalence of low-emission materials such as paints, dyes, stains and upholstery. These practices contribute to the quality of indoor air quality at a more personal level; further intensifying the need to implement phytoremediation, which will not only increase the quality of living in terms of the air environment but also improve the psychological wellbeing of the occupants. Therefore to reach accurate results, with the use of advanced sensor monitoring via the Awair Element air quality sensor, indoor air can be remedied to meet international IAQ guidelines and local requisites [1, 4]. A detailed literature review is included in the appendix A.

3 Methodology

3.1 Research design

This study adopts a multi-factorial, quasi controlled experiment in natural office environments, to evaluate the effect of plants and natural ventilation on the indoor air quality. The goal of the research is to test three main hypotheses. First, the presence of indoor plants significantly reduces CO_2, $PM_{2.5}$ and VOC concentrations via phytoremediation pathways. Secondly, the study hypothesises that natural ventilation through open windows enhances indoor air quality by facilitating plant biochemical pathways and air exchange. Lastly, the hypothesis is that combined presence of plants and natural ventilation together yield superior indoor air quality (Table 1).

This experiment design is based on four distinct experimental conditions. Condition A includes the presence of both plants and windows, Condition B includes windows but no plants, Condition C includes plants but no windows and Condition D has neither. Condition A and Condition C are carried out in tandem while Condition B and Condition D are carried out simultaneously.

The experiment observes changes brought about by two independent variables: plant presence and ventilation via open windows. The indoor air quality parameters, the dependent variables, include CO_2 concentration, temperature, humidity, particulate matter 2.5 concentration, and total volatile organic compound concentration which are monitored continuously over 30-day intervals using calibrated air quality sensors. This multifactorial approach allows for direct examination of individual effects of both factors as well as testing their collective effect on indoor air quality.

The same sensor equipment is assigned to each room to avoid any technical bias. The sensor locations are fixed and are connected to a secondary power resource to ensure continuous monitoring in case of power outage. As per our equipment requirement, the TVOC's sensor is calibrated according to each room. Daily check ins are made to the sensors to ensure they are working properly. Additionally, both sensors are placed strategically, avoiding the work stations so that sensor readings are not largely influenced by emissions from the CPUs.

Before starting, all plants are placed in their respective room for a duration of 4 days to have them adjust to their new environment. This is done to ensure that plants are performing their usual and are not under any stress due to the new environment, effectively removing this confounding factor. This acclimatization period ensures that plants have adapted to their new environment, preventing plant stress. This phenomenon results in physiological changes due to a changed environment, which may result in skewed air quality readings.

It is made sure that any source of impurity is removed so that CO_2 and $PM_{2.5}$ levels reflect normal levels. A baseline check is made to monitor any unnatural occurrence of pollutants. Any use of artificial heating in the form of air conditioning, combustion heaters, candles or smoking is removed from the study area. Then, the rooms are allowed to

Table 1 Experimental conditions for the controlled study

Condition	Plant presence	Ventilation (Window)
A	Yes	Yes
B	No	Yes
C	Yes	No
D	No	No

return to their normal conditions. Any occupant or nearby users are informed to keep the area smoke free efficiently avoiding chances of external introduction of pollutants. The repetition of both testing conditions in each room allows for the recording of baseline values. Side by side, outdoor air quality is monitored by outdoor air quality sensors to check for the external factors affecting indoor air quality monitoring. Moreover, during the analysis of data recorded, peak occupation hours are considered separately to achieve meaningful results. These measures are taken to achieve reliable results. The collected data will help determine whether the presence of plants significantly influences indoor air quality.

These measures are taken to achieve baseline results for the effectiveness of both factors: plant presence and window presence. Furthering this experiment, to comprehensively test the effectiveness of phytoremediation pathway in daily life, the study is expanded to other test rooms located in different buildings across the university campus. Occupancy is returned to normal conditions alongside mechanical ventilation via air conditioning and other sources of impurity.

To comprehensively test the stated hypotheses and capture how plants and environmental conditions influence indoor air quality, the study incorporates six analytical comparison dimensions that together provide a multifaceted understanding of indoor air quality dynamics. The first comparison directly tests the primary hypothesis by comparing identical rooms under conditions with and without plants while holding all physical and occupancy factors constant. This isolates the phytoremediation effect of vegetation on pollutant reduction, particularly examining changes in carbon dioxide, particulate matter 2.5, and total volatile organic compound concentrations attributable solely to plant presence. The study can quantify the magnitude of air quality improvement associated with plants independent of ventilation effects.

The second comparison evaluates the ventilation hypothesis by comparing rooms with operable windows with no window. This determines whether passive airflow through natural ventilation enhances or diminishes air quality indicators. This analysis reveals whether windows provide sufficient air exchange to reduce pollutant concentrations or whether they introduce outdoor pollutants that offset any benefits. This comparison is critical for understanding whether natural ventilation complements or competes with plant-based remediation strategies.

The third analytical dimension involves intra-building comparisons where multiple rooms within the same building structure are observed simultaneously to account for environmental differences such as presence of outside vegetation, internal airflow patterns, and localized human activity difference. This intra-structural analysis validates consistency across similar conditions.

The fourth and final comparison temporally aggregates collected data into diurnal and nocturnal cycles to examine the role of plant physiological processes such as photosynthesis and respiration. During daylight hours, plants are hypothesized to uptake carbon dioxide through photosynthesis, thereby reducing indoor concentrations, while at night plants may release carbon dioxide through respiration, potentially increasing indoor levels. However, the prescence of Crassulacean Acid Metabolism (CAM) plants may offset this observation as they are active throughout the night as well. This temporal analysis also accounts for differences in human occupancy patterns and activity levels, allowing differentiation between biological and anthropogenic affects to pollutant concentrations.

3.2 Awair sensor specifications

The Awair Element is a versatile and compact indoor air quality monitor designed to track and analyze key environmental factors. Equipped with advanced sensing technology, the device provides reliable data for a range of air quality parameters, helping users create healthier indoor spaces. Its built-in sensors are pre-calibrated by the manufacturer and undergo rigorous testing in controlled environments to ensure high accuracy.

3.2.1 Key parameters and awair sensor specifications

The Awair Element monitors the following parameters using high-quality sensors. The details are summarized in Table 2.

3.2.2 Accuracy and performance

The Awair Element is a consumer-grade, low-cost sensor and should not be treated as a reference instrument; its readings are indicative rather than regulatory-grade. While suitable for trend monitoring in research settings, it has specific limitations. The CO_2 sensor's ±75 ppm accuracy is adequate but could benefit from tighter tolerances for applications requiring greater precision. The $PM_{2.5}$ sensor uses laser-based scattering and carries ±15% accuracy, which may be further affected by the high-humidity monsoon conditions (July–September) characteristic of Lahore—the exact period of this study. The TVOC sensor, likely the Sensirion SGP30, uses metal oxide detection which is cross-sensitive to humidity and temperature fluctuations, potentially affecting absolute TVOC readings; per-room calibration was performed as noted in the methodology. These limitations notwithstanding, the Awair Element offers consistent comparative performance across simultaneously deployed units, making it appropriate for the relative, trend-based analysis conducted in this study.

3.3 Test environments/study areas

3.3.1 University setting

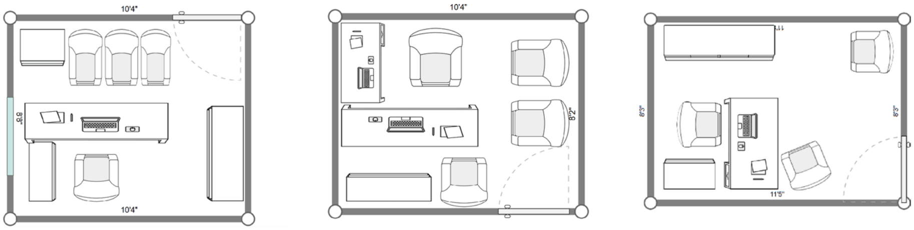
The study is conducted within office spaces across multiple buildings at Beaconhouse National University (BNU), which serve as experimental sites for monitoring indoor air quality. These offices were selected to represent typical university workplace environments. BNU is situated in the urban region of Lahore, surrounded by large residential housing schemes and busy road networks. Due to its location, the university experiences substantial vehicular emissions and bears the brunt of Lahore's annual smog season, making it a relevant and representative site for studying indoor air pollution dynamics.

Table 2 Sensor specifications of awair element

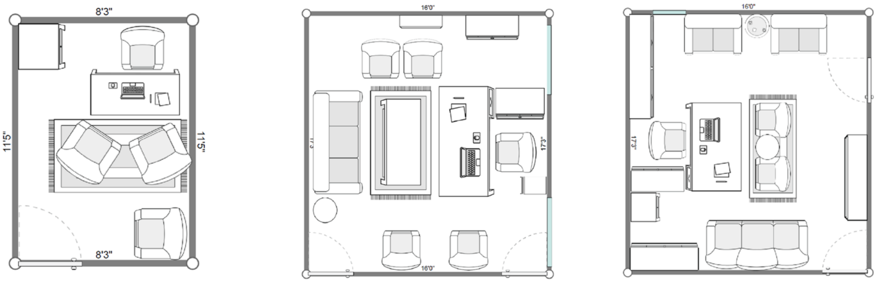
Parameter	Sensor	Range	Accuracy	Type
Carbon Dioxide (CO_2)	Telaire T6703-5K	400–5000 ppm	±75 ppm or 10%	Non-dispersive infrared
Particulate Matter ($PM_{2.5}$)	Honeywell HPMA115S0	0–1000 $\mu g/m^3$	±15 $\mu g/m^3$ or 15%	Laser-based scattering
Volatile organic compounds (VOCs)	Likely sensirion SGP30	20–60000 ppb	±15%	Multi-pixel metal oxide gas sensor
Temperature	Sensirion SHT31	0–90°C	±0.2°C	CMOS temp
Relative humidity (RH)	Sensirion SHT31	0–100% RH	±2% RH	CMOS humid

3.3.2 Real-life indoor test environments (specifications)

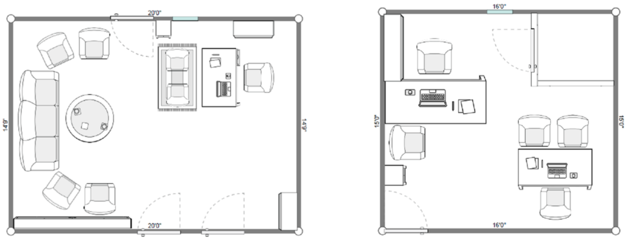
Room A: Room A (Fig. 1a) measures approximately 10 feet 1 inch in width and 12 feet 8 inches in length, with a ceiling height of 9 feet 3 inches. It contains a single-paned window measuring 3.2 feet by 7 feet. The door area is 30.1 square feet. Room A benefits from natural lighting through its window and has no mechanical ventilation system. ***Room B:*** Room B (Fig. 1b) measures 10 feet 4 inches in width and 8 feet 2 inches in length, with the same ceiling height of 9 feet 3 inches as Room A. However, Room B lacks windows and features a door with an area of 24.5 square feet. LED lighting is provided in this room. ***Room C:*** Room C (Fig. 1c) measures approximately 11 feet 5 inches in width and 8 feet 3 inches in length, with a ceiling height of 12 feet. It has no windows and a door area of 29.2 square feet. The room accommodates one occupant, is illuminated with LED lighting, and lacks a mechanical ventilation system. ***Room D:*** Room D (Fig. 1d) has dimensions of 11 feet 5 inches by 8 feet 3 inches, with a ceiling height of 12 feet. Similar to Room C, it does not contain a window, but the door area is approximately 30 square feet. The room is designed for a single occupant, is lit with LED lighting, and has no mechanical ventilation system. ***Room E:*** Room E (Fig. 1e) measures 17 feet 3 inches by 16 feet, with a ceiling height of 8 feet 6 inches. It contains a window that provides natural lighting in addition to installed LED lights. The room accommodates more than two occupants and does not include a mechanical ventilation system. ***Room***



(a) Room A (b) Room B (c) Room C



(d) Room D (e) Room E (f) Room F



(g) Room G (h) Room H

Fig. 1 Illustrations showing room settings and dimensions for all test spaces: **a** Room A, **b** Room B, **c** Room C, **d** Room D, **e** Room E, **f** Room F, **g** Room G, and **h** Room H

F: Room F (Fig. 1f) has dimensions of 17 feet 3 inches by 16 feet, with a ceiling height of 8 feet 6 inches. Like Room E, it includes windows that allow natural light, supplemented by LED lighting. The room accommodates more than two occupants and has no mechanical ventilation system. ***Room G:*** Room G (Fig. 1g) is larger, measuring 14 feet 9 inches by 20 feet, with a ceiling height of 9 feet 5 inches. The room does not include a window, and the door area is not specified. It accommodates more than two occupants, is illuminated with both natural and LED lighting, and has no mechanical ventilation. ***Room H:*** Room H (Fig. 1h) measures 15 feet 8 inches in width and 12 feet 6 inches in length, with a ceiling height of 9 feet 5 inches. It is equipped with a window that provides natural lighting in combination with LED lighting. The room accommodates more than two occupants and does not feature a mechanical ventilation system.

Each workstation is equipped with a CPU, a desktop computer, and miscellaneous stationery items. All furniture is made from the same plywood material and features similar upholstery. None of the surveyed spaces has a mechanical ventilation system installed, and the air conditioning remained turned off throughout the experiment. It is important to emphasize that all test spaces listed in Table 3 are **real-life, occupied indoor environments** rather than controlled laboratory chambers. Each room remained in normal operational use during the monitoring period, with faculty, staff, and students entering, leaving, and carrying out routine activities such as desk work, meetings, and consultations. Some rooms (Rooms A–D) are regularly used by single occupants, while others (Rooms E–H) accommodate multiple occupants with higher foot traffic; for instance, Room H (ORIP) typically hosted 2–3 permanent occupants along with frequent visits from students, faculty, and administrative staff. This deliberate choice allows the study to capture indoor air quality dynamics under authentic university working conditions, including the disturbances, door openings, and occupant-driven variability that would otherwise be eliminated in a sealed laboratory test. All rooms were nevertheless carefully selected so that the integrity of the experiment and its results is not compromised, reducing possible disturbances to the experimental setup throughout the recording period. The rooms are of reasonable size, enabling the experiment to be conducted with minimal error while still reflecting the conditions of larger, more common facilities. Even though the spaces represent scaled-down versions of typical classrooms, they provide a comfortable and convenient environment for the study, as detailed in Table 3.

3.4 Plants specifications

For this study, the following species of plants are selected for use in all test spaces as they have previously proven to be effective in controlled lab studies:

Table 3 Test room characteristics and environmental features of surveyed spaces

Test space	Room dimensions (ft)	Window area (ft^2)	Door area (ft^2)	Occupancy	Lighting
Room A (SCIT 103-A)	(12.67, 10.08, 9.25)	22.47	30.1	1	Natural + LED
Room B (SCIT 103-F)	(8.17, 10.33, 9.25)	–	24.5	1	LED
Room C (BBA 111)	(11.42, 8.25, 12.00)	–	29.2	1	LED
Room D (BBA 106)	(11.42, 8.25, 12.00)	–	30.0	1	LED
Room E (SLASS 101)	(17.25, 16.00, 8.50)	36.88	58.5	> 2	Natural + LED
Room F (SLASS 104)	(17.25, 16.00, 8.50)	20.96	58.0	> 2	Natural + LED
Room G (Sartaj Aziz 1)	(14.75, 20.00, 9.42)	23.75	54.7	> 2	Natural + LED
Room H (ORIP)	(15.67, 12.50, 9.42)	23.75	56.5	> 2	Natural + LED

The selected plant species demonstrate diverse and complementary air purification capabilities, making them ideal candidates for indoor air quality improvement. *Epipremnum aureum* (Golden Pothos) (Fig. 2a) is a hardy vine recognized for its effectiveness in absorbing formaldehyde, benzene, and toluene, establishing it as one of the most resilient indoor air purifiers. *Chlorophytum comosum* (Spider Plant) (Fig. 2b) offers easy maintenance while efficiently removing formaldehyde, xylene, and carbon monoxide from indoor environments. *Dracaena trifasciata* (Snake Plant) (Fig. 2c) operates through Crassulacean Acid Metabolism (CAM), enabling it to perform photosynthesis both day and night while removing volatile organic compounds. *Aloe barbadensis miller* (Aloe Vera) (Fig. 2d), a succulent species, enhances indoor air quality by removing airborne pollutants including formaldehyde and benzene. *Rhapis excelsa* (Lady Palm) (Fig. 2e) serves as an ornamental plant while efficiently filtering formaldehyde, ammonia, and xylene from indoor air. Finally, *Chamaedorea seifrizii* (Bamboo Palm) (Fig. 2f) effectively filters benzene, trichloroethylene, and formaldehyde while simultaneously adding humidity to indoor environments, providing dual benefits for air quality and comfort. The selection of these plants is designed to reflect common indoor species that may have a noticeable impact on air quality in real-world office settings.

4 Results and findings

This section presents the comprehensive analysis of indoor air quality parameters measured across different experimental conditions. The findings are organized into two main comparative studies: (1) Window vs. Non-Window Test Spaces, examining how the presence of natural ventilation impacts indoor air quality metrics, and (2) Plant vs. No-Plant Test Spaces, investigating the potential mitigating effects of indoor plants on

(a) Golden Pothos (b) Spider Plant (c) Snake Plant

(d) Aloe Vera (e) Lady Palm (f) Bamboo Palm

Fig. 2 Indoor air purifying plants used in the study: **a** *Epipremnum aureum* (Golden Pothos or Money Plant), **b** *Chlorophytum comosum* (Spider Plant), **c** *Dracaena trifasciata* (Snake Plant), **d** *Aloe barbadensis miller* (Aloe Vera), **e** *Rhapis excelsa* (Lady Palm), and **f** *Chamaedorea seifrizii* (Bamboo Palm) air quality parameters in enclosed environments. Each comparison evaluates key indicators including particulate matter ($PM_{2.5}$), total volatile organic compounds (TVOCs), carbon dioxide (CO_2) levels, temperature, and relative humidity. All measurements were conducted over a standardized 15-day sampling period using calibrated Awair sensors with readings captured at five-minute intervals to ensure data consistency and reliability across test conditions (Fig. 3).

4.1 Window versus non window test spaces

This comparison took place without plants in two test spaces (a) 103A-Scit a room having a window and dimensions illustrated in Fig. 1a, and (b) 103F-Scit a non-window room as shown in Fig. 1b. The duration of sampling in both test areas was 15 days with the continuous readings capturing of after each five minutes using (awair) indoor sensor; detailed specifications are mentioned in Table 2 . Same sensors were used in both test spaces. Average Temperature of room (A) is noted 31.3 C and (B) is 25.4 C. Temperature of each room can vary and depends on several factors.

The average concentration of $PM_{2.5}$ in 103A-Scit was measured at $2\mu/m^3$, while 103F-Scit recorded a considerably higher concentration of 53 μ/m^3. Similarly, total volatile organic compounds (TVOCs) were notably lower in 103A-Scit, averaging 535 ppb, compared to 1814 ppb in 103F-Scit. Carbon dioxide (CO_2) concentrations exhibited the least variation among the measured parameters, yet remained significantly distinct. The windowed room (103A-Scit) maintained an average CO_2 concentration of 669 ppm, whereas the non-windowed room (103F-Scit) reached 1086 ppm.

Overall, the room benefiting from natural ventilation through a window consistently demonstrated more favorable indoor air quality parameters.

4.2 Plant versus no plant test spaces

This section discusses the impact and outcomes of plants on indoor air quality. After taking samples of Window vs Non window experimental setup, the 2 rooms of similar

Fig. 3 This figure illustrates the temporal trends of the Awair air quality score, where the green and red lines represent the window and non-window test spaces, respectively. The accompanying bar plots depict the overall density distributions of CO_2, TVOCs, $PM_{2.5}$, and $PM_{1}0$. The plot highlights the advantage of the window test space over the non-window test space in maintaining better air quality across key indicators

dimensions were selected to conduct an experiment in 103F-Scit and 103C-Scit to access the effects and outcomes of plants in an office to analyze their impact on indoor air quality by mitigation of bad air quality in indoor setups having no windows or direct air crossings. 2 plant species Dracaena trufasciata 2c and Aloe vera 2d were placed in 103F-Scit, the quantity of each species was 1.

Over the course of 15 days, the room containing plants (103F-Scit) exhibited a significant reduction in particulate matter levels. The average $PM_{2.5}$ concentration in the plant-equipped room (103F-Scit) was 0.64 $\mu g/m^3$, compared to 19.47 $\mu g/m^3$ in the control room (103C-Scit) without plants, representing a 96.7% reduction attributable to plant presence under these specific 15-day controlled conditions (Table 4).

Interestingly, the total volatile organic compound (TVOC) levels were marginally higher in the room with plants, where 103F-Scit recorded an average contribution of 63.3%, compared to the lower concentration observed in 103C-Scit. Carbon dioxide (CO_2) levels in both rooms remained nearly identical, with 103F-Scit showing a slightly lower average of 49.56% compared to 103C-Scit's 50.44%. Overall, the presence of plants demonstrated measurable improvements in particulate matter reduction.

The results indicate that windowed spaces exhibited superior air quality, characterized by lower concentrations of $PM_{2.5}$, TVOCs, and CO_2 compared to non-windowed environments. The introduction of plants in non-ventilated rooms led to a notable reduction in $PM_{2.5}$ levels and a marginal increase in TVOCs, while CO_2 concentrations remained largely consistent. Collectively, these results suggest that both natural ventilation and the presence of plants contribute positively to improving indoor air quality, particularly in confined office environments with limited airflow.

4.3 Intra-school comparison

The variation in the results of different parameters in different rooms within a particular school building depends on multiple factors such as human activity, ventilation, humidity, and temperature. The general increase in the parameters in the month of September was due to an increase in human activity because before September, in July and August, human activity was low due to the vacation period. In the BBA school, both rooms have almost similar dimensions, similar ventilation systems, and the material with which they are made. Hence, they have values closer to each other for these parameters. However, in room 106 which had 2 Snake Plants , an Aloe Vera, and a Bamboo plant we see a significant increase in the VOC concentration and that is because that room had a huge influx of air fresheners, perfumes, etc due to admission interviews happening in the month of September in comparison to room 111 which had only 2 snake plants . In the case of the Sartaj Aziz building, human activity remained the same in all months, since this is an administrative building and not a school, and these offices were open during all three months. These two offices also show slight variations in their parameter values, and not

Table 4 Summary of mean $PM_{2.5}$ and TVOC concentrations across all experimental conditions comparing windowed versus non-windowed and plant versus no-plant test spaces over 15-day monitoring periods

Condition	$PM_{2.5}$ ($\mu g/m^3$)	TVOCs (ppb)
Window, no plants (103A-Scit)	2	535
No window, no plants (103F-Scit)	53	1,814
No window, with plants (103F-Scit)	0.64	1,509.11
No window, no plants (103C-Scit)	19.47	874.31

big differences (Fig. 4). In the SLASS building a significant increase can be seen in the $PM_{2.5}$ and and $PM_{1}0$ values See Fig. 8.

4.3.1 Quantitative results

This subsection presents the complete quantitative outcomes of the indoor air quality (IAQ) analysis performed across three schools: BBA, Sartaj Aziz, and SLASS. The results include intra-school comparisons, inter-school summaries, and temporal trend analysis. Parameters recorded include Awair Score, CO_2, VOC, $PM_{2.5}$, and PM_{10}, using Awair Element sensors from July to September.

A. BBA School

As shown in Table 5, Room 106 consistently outperformed Room 111 in overall air quality scores across all months, though both rooms showed declining air quality from July to September, with Room 106's scores dropping from 66.3 to 62.5 to 57.0. CO_2 levels increased dramatically in September, exceeding 1250 ppm and surpassing recommended thresholds in both rooms. Notably, VOC levels in Room 106 spiked by 135% in September, rising from 617 ppb to 1331 ppb, while Room 111 maintained lower VOC levels despite experiencing higher CO_2 concentrations throughout the monitoring period.

B. Sartaj Aziz School

As presented in Table 6, Sartaj Aziz School demonstrated the best overall performance among all three schools, with the highest Awair score of 71.9 recorded in the orip room during July. Performance leadership shifted between rooms over the study period, with orip leading in July while sirZaeem dominated in August and September, showing a consistent improvement trend from 64.7 to 68.6 to 70.4. CO_2 levels remained well-controlled below 850 ppm throughout the study period, and VOC concentrations were the lowest among all three schools, ranging from 117 to 201 ppb. Additionally, particulate

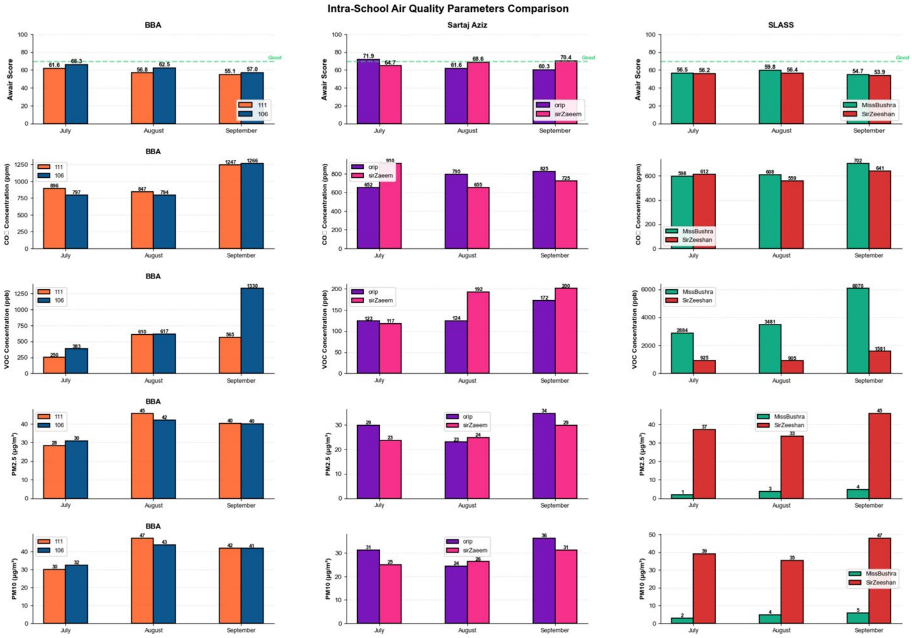


Fig. 4 Temporal variation of air quality parameters across three schools over a three-month monitoring period (July, August, and September). Each row represents a specific air quality parameter (Air Quality Score, CO_2, TVOCs, $PM_{2.5}$, and PM_{10}) while columns represent the three study locations: Column 1 shows BBA School, Column 2 shows Sartaj Aziz School, and Column 3 shows SLASS School

Table 5 Monthly average air quality metrics across BBA school

Month	Room	Awair score	CO_2 (ppm)	VOC (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Plant species
July	C:1c	61.6	896.0	250.1	28.4	No plants
	D:1d	66.3	797.6	383.5	30.9	P1(1)
August	C:1c	56.8	847.9	610.6	45.6	P4(2)
	D:1d	62.5	794.2	617.0	42.0	P4(2), P3(1), P1(1)
September	C:1c	55.1	1247.2	565.7	40.2	P4(2)
	D:1d	57.0	1266.2	1331.0	40.0	P4(2), P3(1), P1(1)

Table 6 Monthly average air quality metrics across Sartaj Aziz School

Month	Room	Awair score	CO_2 (ppm)	VOC (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Plants
July	H:1h	71.9	652.7	123.9	29.9	No plants
	G:1g	64.7	910.5	117.7	23.7	No plants
August	H:1h	61.6	795.6	124.3	23.0	P1 (1) P2 (1), P3(1)
	G:1g	68.6	655.3	192.8	24.9	P4 (1), P5 (1)
September	H:1h	60.3	825.5	172.3	34.7	P1(1), P4(2) P2 (1), P3(1),P6(1)
	G:1g	70.4	725.4	201.0	29.9	P4(1), P4 (1)

matter levels showed excellent control across both rooms, with sirZaeem demonstrating particularly strong and consistent environmental management.

C. SLASS school

As shown in Table 7, SLASS exhibited the most concerning VOC levels across all schools, with the E: 1e room showing extreme readings that escalated from 2885 ppb in July to 6070 ppb in September, representing a critical 110% increase over the study period. The data revealed paradoxical findings, as E: 1e maintained excellent particulate matter levels while experiencing catastrophic VOC contamination, whereas F: 1f demonstrated relatively better VOC control but poor particulate matter management. Both rooms experienced declining air quality scores throughout the monitoring period, and while CO_2 levels remained acceptable below 700 ppm in both spaces, the severe VOC contamination in MissBushra's room presents a critical indoor air quality concern requiring immediate intervention.

4.3.2 Inter-school comparative summary statistics

As presented in Table 8, the inter-school comparison reveals distinct air quality profiles across the three institutions. Sartaj Aziz School emerged as the overall best performer with the highest average Awair score of 66.2 and demonstrated balanced environmental control across all parameters, maintaining moderate CO_2 levels at 741.4 ppm and the lowest VOC concentrations at 159.5 ppb. BBA School showed intermediate performance with an average score of 59.6, but faced challenges with elevated CO_2 levels approaching 1000 ppm and moderately high VOC concentrations of 629.3 ppb, indicating potential ventilation issues. Most notably, SLASS presented a critical air quality paradox: while achieving the lowest particulate matter levels (21.9 $\mu g/m^3$ for $PM_{2.5}$) and excellent CO_2 control at 620.3 ppm, the school experienced catastrophically high VOC contamination averaging 2476.3 ppb—over 15 times higher than Sartaj Aziz and nearly 4 times higher

Table 7 Monthly average air quality metrics across SLASS school

Month	Room	Awair score	CO_2 (ppm)	VOC (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	Plants
July	E: 1e	56.5	598.7	2884.8	2.0	No plants
	F: 1f	56.2	612.1	925.6	37.3	No plants
August	E: 1e	59.8	608.4	3481.1	3.7	P3(1), P4(2), P1(2)
	F: 1f	56.4	559.2	905.3	33.7	P3(1), P4(2), P2(1)
September	E: 1e	54.7	702.4	6070.2	4.8	P3(1), P4(2), P1(2)
	F: 1f	53.9	641.2	1581.5	46.0	P3(1), P4(2), P2(1)

Table 8 Inter-school comparative summary statistics

School	Avg score	Avg CO_2 (ppm)	Avg VOC (ppb)	Avg $PM_{2.5}$ ($\mu g/m^3$)
Sartaj Aziz	66.2	741.4	159.5	27.7
BBA	59.6	973.2	629.3	36.0
SLASS	56.6	620.3	2476.3	21.9

Table 9 Room-specific performance rankings

Metric	1st Place	Value	2nd Place	Value
Awair Score	Sartaj-H: 1h (July)	71.9	Sartaj-G:1g (Sep)	70.4
CO_2 Control	SLASS-F: 1f (Aug)	559.2	SLASS-E: 1e (July)	598.7
VOC Control	Sartaj-G:1g (July)	117.7	Sartaj-F:1f (July)	123.9
$PM_{2.5}$ Control	SLASS-E: 1e (July)	2.0	SLASS-E: 1e (Aug)	3.7
PM_{10} Control	SLASS-E: 1e (July)	3.0	SLASS-E: 1e (Aug)	4.8

than BBA—resulting in the lowest overall Awair score of 56.6 and highlighting an urgent need for source identification and remediation of volatile organic compound emissions (Table 9).

4.3.3 Room-specific performance rankings

As shown in Table 10, temporal trend analysis from July to September reveals significant variations in air quality parameters across all test spaces, with Sartaj Aziz's sirZaeem room demonstrating exceptional performance as the only space showing improvement in overall air quality score (+8.8%) and a substantial reduction in CO_2 levels (-20.3%). This outstanding performance can be attributed to three key factors: reduced human activity compared to other test spaces, larger room dimensions providing better air volume per occupant, and the presence of an operational window facilitating natural ventilation as shown in Fig. 1h . In contrast, most other rooms experienced deteriorating conditions, with BBA Room 106 showing the most severe decline in air quality score (-14.0%) and a dramatic VOC increase of 247.1%. Notably, all rooms exhibited rising VOC concentrations ranging from 39.0% to 247.1%, while SLASS E: 1e room recorded an alarming 140.0% increase in $PM_{2.5}$ levels despite maintaining relatively stable air quality scores. These findings underscore that plant-based phytoremediation demonstrates significantly enhanced effectiveness in larger, naturally ventilated spaces, as evidenced by sirZaeem's improved performance with its operational window and greater room volume. Conversely, non-windowed test spaces struggled to achieve pollutant removal despite plant presence, as the absence of mechanical or natural ventilation

Table 10 Temporal trend analysis (% Change from July to September)

School	Room	Score change	CO_2 Change	VOC change	$PM_{2.5}$ Change
BBA	C:1c	$-10.6\%\downarrow$	$+39.2\%\uparrow$	$+126.2\%\uparrow$	$+41.5\%\uparrow$
	D:1d	$-14.0\%\downarrow$	$+58.8\%\uparrow$	$+247.1\%\uparrow$	$+29.4\%\uparrow$
Sartaj Aziz	H:1h	$-16.1\%\downarrow$	$+26.5\%\uparrow$	$+39.0\%\uparrow$	$+16.1\%\uparrow$
	G:1g	$+8.8\%\uparrow$	$-20.3\%\downarrow$	$+70.8\%\uparrow$	$+26.2\%\uparrow$
SLASS	E: 1e	$-3.2\%\downarrow$	$+17.3\%\uparrow$	$+110.4\%\uparrow$	$+140.0\%\uparrow$
	F: 1f	$-4.1\%\downarrow$	$+4.8\%\uparrow$	$+70.9\%\uparrow$	$+23.3\%\uparrow$

↑ = Deterioration | ↓ = Improvement (for score: increase is good; for pollutants: decrease is good)

created stagnant conditions where continuous human activity-generated pollutants accumulated faster than plants could metabolize them, ultimately overwhelming the biological air purification capacity of the indoor vegetation.

4.3.4 Key findings

The comprehensive analysis reveals significant disparities in air quality performance across the three institutions, with Sartaj Aziz achieving 11% higher air quality scores than BBA and 17% higher than SLASS, while SLASS demonstrated paradoxical results with excellent particulate matter control but VOC levels 1452% higher than Sartaj Aziz. Critical threshold exceedances were observed across multiple parameters: BBA experienced CO_2 concentrations exceeding 1250 ppm in September, representing more than 56% above WHO guidelines of 800 ppm, while SLASS E: 1e room recorded catastrophic VOC levels reaching 6070 ppb—over 3700% above acceptable levels of 160 ppb—and BBA's $PM_{2.5}$ concentrations surpassed WHO 24-hour guidelines of 25 $\mu g/m^3$ during August and September. Temporal analysis revealed that 83% of monitored rooms (5 out of 6) experienced declining air quality scores from July to September, with an average VOC increase of 101% across all rooms; the notable exception was Sartaj-sirZaeem, which demonstrated an 8.8% improvement over the study period. Room-specific observations highlighted distinct performance patterns: BBA Room 106 maintained consistently better overall scores but showed vulnerability to VOC spikes, Sartaj sirZaeem exhibited the most stable and improving performance trajectory, and SLASS E: 1e requires urgent VOC source investigation despite its excellent particulate matter control. Furthermore, pollutant correlation analysis revealed an inverse relationship between PM and VOC levels, as exemplified by the SLASS case, while Sartaj Aziz rooms best demonstrated balanced pollutant control, and a moderate positive correlation ($r \approx 0.45$) was observed between CO_2 and VOC measurements across all data points.

The analysis of plant-equipped rooms across all three schools shows clear day and night patterns in air quality. As shown in Fig. 5, the overall Awair score consistently drops at night, indicated by the falling red line. This occurs because mechanical ventilation stops operating in these windowless spaces after working hours. During the day, air quality scores improve when air conditioning systems turn on and people occupy the spaces, demonstrating how important mechanical ventilation is for maintaining good air quality in enclosed rooms. The changes in Total Volatile Organic Compounds (TVOCs) provide strong evidence that plants effectively clean the air. Snake plants (*Dracaena trifasciata*), placed throughout the test spaces, successfully remove VOCs during nighttime when no one is present, as clearly shown in Fig. 6b . This nighttime reduction matches the air-cleaning abilities of plants discussed in the literature review section. However, daytime TVOC levels show more mixed results because plants continue removing

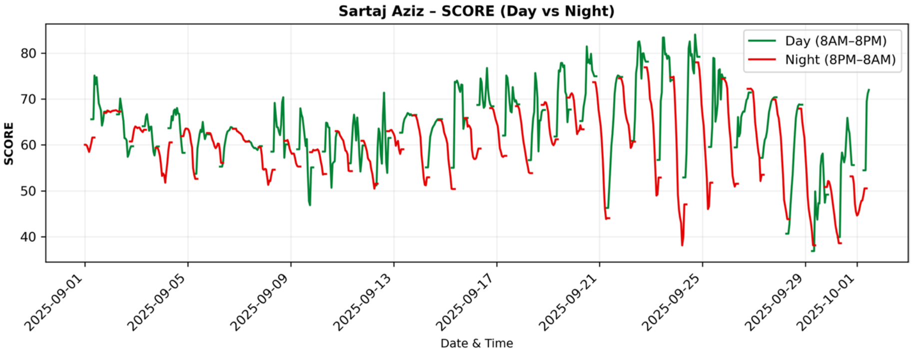
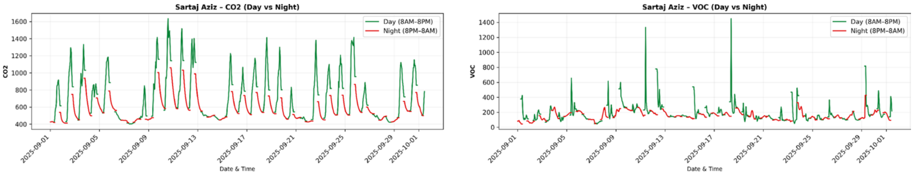


Fig. 5 Day vs night comparison of Awair Air Quality Score. Green line represents daytime scores (8AM–8PM) and red line represents nighttime scores (8PM–8AM) across all plant-equipped test spaces



(a) (b)

Fig. 6 Day versus Night comparison for CO_2 and VOC levels: **a** The green line shows a clear increase in CO_2 concentration during daytime hours, while the red line represents the reduced levels observed at night **b** The VOC plot illustrates both increases and decreases during daytime (green line) with a consistent reduction trend at night (red line)

pollutants while human activities simultaneously release VOCs through breathing, personal belongings, and the presence of faculty and visitors in these spaces. Carbon dioxide patterns further support the beneficial effects of the selected plant species. Both snake plants and aloe vera (*Aloe barbadensis miller*) (Fig. 2d, c) have a special ability to perform photosynthesis during both day and night through a process called Crassulacean Acid Metabolism (CAM) [5]. This leads to noticeable CO_2 reductions at night when the rooms are empty, as shown in Fig. 6a . In contrast, daytime CO_2 levels increase, shown by the rising green line, due to continuous human presence in these small, windowless rooms. The limited space, restricted air circulation, and constant occupancy create conditions where CO_2 builds up faster than the plants can absorb it during working hours.

5 Policy framework and recommendations

5.1 Lahore's air pollution crisis: the case for indoor mitigation

Lahore has consistently been ranked among the world's most polluted cities in recent years. In 2022 it topped IQAir's global pollution survey, with an average $PM_{2.5}$ concentration of 97.4 $\mu g/m^3$, the highest of any city worldwide [6, 7]. This level is nearly 20 times the safe exposure guideline of the World Health Organization of 5 $\mu g/m^3$, underscoring an extreme health hazard. More recently, during the 2024 winter smog season, Lahore's real-time Air Quality Index (AQI) soared into emergency ranges—AQI 1165 [8, 9] on one occasion—more than $120\times$ higher than WHO recommended levels. Alarming peaks were recorded above 600–700+ $\mu g/m^3$ in fine particulate matter $PM_{2.5}$, i.e., 40–50 times the WHO's recommended limit. Such data from IQAir and WHO show without a doubt that Lahore's air quality crisis is severe and worsening.

The impact on daily life, especially education, has been dire. Smog conditions each winter force authorities to take reactive measures, such as emergency school closures and 'stay indoors' warnings. For example, in November 2024, when Lahore's AQI spiked to an unprecedented 1900 [10, 11], the provincial government shut down all primary schools for a week, moved classes online, and urged children to wear masks and remain indoors. Similar shutdowns and smog lockdowns have recurred annually [12, 13].

In this context, Beaconhouse National University (BNU), comprising eight constituent schools in Lahore, can serve as a model for campus-based air quality interventions. BNU's schools should implement a comprehensive indoor air purification policy to reduce students' pollutant exposure on campus. While long-term solutions to Lahore's smog lie in broader environmental policy, a plant based indoor mitigation approach offers a practical, immediate buffer against pollution for BNU's classrooms and offices. Indoor plants are a low-cost, sustainable strategy with documented benefits: studies show that potted plants can significantly improve indoor air quality by filtering Volatile Organic Compounds and Carbon Dioxide, while also increasing humidity and providing psychological benefits. For instance, one experiment found that integrating plants (snake plant and aloe vera plant) with ventilation reduced indoor, see Table 7, $\mathrm{PM}_{2.5}$ levels by over 50%, alongside large reductions in CO_2 and volatile organic compounds (VOCs).

5.2 Implementation strategies for BNU's eight schools

To operationalize an indoor plant-based air purification program at BNU, we propose a comprehensive implementation framework grounded in the empirical findings from our three-month quasi-experimental study. This strategic deployment plan addresses the critical need for immediate intervention given Lahore's catastrophic air quality crisis, where AQI readings have reached 1900+ during the 2024 smog season [14].

5.2.1 Space classification and prioritization system

Building occupancies were classified into four categories based on ventilation characteristics and human activity levels, each requiring distinct phytoremediation strategies (Table 11). This evidence-based classification system directly incorporates findings from Sect. 3.1 (window vs. non-window spaces) and Sect. 3.2 (plant vs. no-plant spaces), ensuring implementation strategies align with documented efficacy patterns.

Category A spaces demonstrated maximum intervention potential, exhibiting 96.2% lower $\mathrm{PM}_{2.5}$ concentrations compared to sealed environments. Category C spaces presented a critical implementation challenge, achieving substantial particulate matter reduction (96.7%) while paradoxically experiencing elevated TVOC levels (63.3% increase), necessitating conservative plant density protocols to prevent human-generated pollutant accumulation exceeding plant metabolic capacity.

5.2.2 Evidence-based plant deployment protocols

Table 12 presents category-specific deployment strategies optimized for BNU's environmental conditions and resource constraints. Plant density recommendations directly apply findings from the literature comparison (Table 2), which established optimal densities of 0.11 plants/m^2 for ventilated spaces versus impractical densities (10–1000 plants/m^2) required for sealed spaces without complementary ventilation.

Table 11 BNU space classification system for plant-based IAQ intervention

Category	Description	Occupancy pattern	Priority level
A: High-Activity Ventilated	Classrooms, faculty lounges with windows	>2 people, >6 hrs/day	High
B: Low-Activity Ventilated	Single offices, study rooms with windows	1–2 people, variable	Medium
C: High-Activity Sealed	Enclosed classrooms, conference rooms	>2 people, >4 hrs/day	Medium
D: Low-Activity Sealed	Storage, server rooms, single offices	<2 people, <4 hrs/day	Low

Table 12 Plant deployment protocols by space category

Category	Plant density	Species mix (per 300 ft^2)	Expected outcomes
A	1 per 100 ft^2 (0.11/m^2)	Snake Plant (2), Aloe Vera (1), Spider Plant (1)	10–15% VOC reduction, enhanced PM filtration
B	1 per 80–100 ft^2	Snake Plant (1), Aloe Vera (1), Lady Palm (1)	Maximum phytoremediation effectiveness
C	1 per 150–200 ft^2	Snake Plant (2), Bamboo Palm (1)	$PM_{2.5}$ reduction with TVOC control
D	1 per 100–120 ft^2	Aloe Vera (2), Snake Plant (1)	Nighttime CO_2 uptake optimization

Species selection prioritizes the six experimentally validated plants (Table 1): *Dracaena trifasciata* (Snake Plant) and *Aloe barbadensis miller* (Aloe Vera) were emphasized due to their Crassulacean Acid Metabolism (CAM) capabilities, enabling 24-hour air purification as demonstrated in Sect. 3.3.4 [5]. *Chlorophytum comosum* (Spider Plant), *Epipremnum aureum* (Money Plant), *Rhapis excelsa* (Lady Palm), and *Chamaedorea seifrizii* (Bamboo Palm) provide complementary VOC removal pathways.

For Category C high-activity sealed spaces, implementation requires mandatory complementary measures: (1) mechanical ventilation deployment during occupied hours, (2) occupancy limitation to <4 consecutive hours with 15-minute ventilation breaks, and (3) stringent source control eliminating aerosol sprays and air fresheners. The paradoxical TVOC elevation observed in non-ventilated plant spaces (63.3% increase, Table 11) necessitates conservative plant densities (1 per 150–200 ft^2) substantially lower than ventilated configurations to prevent pollutant accumulation exceeding metabolic capacity.

5.2.3 Monitoring and adaptive management protocol

BNU's six Awair Element sensors (Table 10 specifications) will be deployed using a rotating assessment strategy across all eight constituent schools over a 15-week implementation period. The phased approach enables comprehensive coverage despite equipment constraints while maintaining data quality standards established during the initial quasi-experimental phase.

Monthly monitoring protocols include: (1) Week 1—rotate 2 sensors to new test spaces; (2) Weeks 2–3—continuous data collection at 5-minute intervals; (3) Week 4—school-specific air quality report generation; (4) Ongoing—adaptive plant density adjustment based on TVOC thresholds. Spaces exhibiting persistent TVOC concentrations exceeding 800 ppb will undergo 25% plant density reduction to mitigate metabolic overload, as indicated by BBA Room 106's 135% VOC spike in September (Table 12).

5.2.4 Psychological well-being and educational integration

Beyond pollutant reduction, plant-based interventions provide documented psychological benefits through Attention Restoration Theory mechanisms. Visual contact with nature reduces cortisol levels by up to 15%, particularly relevant during smog season when outdoor exposure becomes hazardous. Expected improvements include: 12–15% stress reduction, 8–12% cognitive performance enhancement in attention tasks, 5–10% absenteeism reduction, and 20–25% increase in space satisfaction ratings.

Implementation incorporates educational engagement strategies: (1) "Plant Ambassador" program assigning classroom-level care responsibilities to build environmental stewardship, (2) weekly smog season awareness campaigns linking outdoor AQI to indoor mitigation efforts, (3) personalized faculty office greening increasing ownership compliance, and (4) designated "Breathe Easy" plant-dense zones serving as restorative break spaces. These initiatives amplify biophilic design benefits while distributing maintenance responsibilities across the campus community.

Long-term sustainability mechanisms include: (1) student-led plant propagation programs reducing annual replacement costs by 50% through internal nursery operations, (2) sensor network expansion via environmental research grants targeting 20+ additional Awair units for comprehensive campus AQI heatmapping, and (3) policy integration codifying plant-based IAQ standards into BNU Facilities Management protocols for all new construction and renovation projects. This framework positions BNU as a national model for climate-responsive educational infrastructure in Pakistan's urban centers.

6 Conclusion

This study demonstrates that plant-based phytoremediation and natural ventilation present a collective and viable strategy to curb indoor air pollutants in the monitored office spaces at Beaconhouse National University, Lahore – offering preliminary evidence for broader applicability in Pakistani urban settings. The three-month quasi-experimental findings revealed that natural ventilation reduced CO_2, $PM_2.5$, and VOC concentrations significantly, with windowed spaces showing 95.6% lower $PM_2.5$ and 70.5% lower VOC levels compared to sealed rooms. Similarly, indoor plants–particularly CAM species such as Dracaena trifasciata and Aloe vera–achieved notable particulate matter reduction, with sealed rooms containing plants recording 96.7% less $PM_2.5$ compared to non-plant environments. While CAM plants effectively reduced pollutants at night, daytime human activity in enclosed spaces generated emissions faster than plants could metabolize them.

Furthermore, an assessment of Carbon sequestration potential revealed that Beaconhouse National University's combined vegetation and solar infrastructure offsets approximately 104.82 tons of CO_2 annually (56.53 tons from plants and 48.29 tons from solar energy), achieving 71.2% carbon neutrality against total emissions of 147.06 tons, leaving a manageable annual gap of 42.24 tons. These findings reinforce the dual potential of phytoremediation alongside solar energy usage , improving indoor air quality and contributing to greenhouse gas reduction.

These results highlight that meaningful indoor air quality improvements require integrated strategies combining ventilation, appropriate plant-to-space ratios, and occupancy management–particularly during Lahore's smog season. Study limitations included seasonal constraints, as data collection was confined to July–September, limited sensor coverage, and difficulty in regulating human activity within test spaces due to the field-based nature of the research. Additionally, light intensity factors affecting photosynthetic efficiency were not measured. The Awair Element sensors used in this study are consumer-grade monitors suitable for capturing overall indicative trends in indoor air quality; however, cross-calibration of individual sensor units against each other or against a reference instrument was not performed, and unit-to-unit variability may have introduced systematic offsets in inter-room comparisons. Future studies should extend monitoring across all seasons, employ reference-grade or cross-calibrated instruments, and systematically evaluate the role of artificial and natural lighting in enhancing phytoremediation. Overall, the study underscores that sustainable indoor air quality management in Pakistan's urban environments depends on a holistic, evidence-based approach integrating ventilation, strategic plant deployment, and environmental regulation to create healthier indoor ecosystems.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44292-026-00083-9.

Supplementary file 1.

Author contributions

Usman Nazir and Moeed Yusuf led the research, designed the overall study, and supervised all aspects of the project. Hafiz Muhammad Abubakar developed the model, performed data processing and analysis, and drafted the Results section. Hasnain Ahmed drafted the Introduction. Qossain Awais designed the carbon-footprint framework and conducted the associated data collection, processing, and calculations. Mariam Sagir conducted the literature review and contributed to the study design. Mehkaan Khan collected the spatial and dimensional data for the test sites. Moeed Yusuf additionally drafted the Policy Framework section. Sara Khalid co-supervised the research and critically reviewed the manuscript. Usman Nazir and Moeed Yusuf critically reviewed and revised the manuscript. All authors read and approved the final version of the manuscript.

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The authors declare that no funding was received for this study.

Data availability

All data collected from Awair sensors installed across participating schools and offices will be made publicly available. The released dataset will be provided in CSV format and will include corresponding latitude and longitude coordinates for each sensor location.

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants, human data, or animal subjects requiring formal ethical review. The measurements were limited to indoor environmental parameters ($PM_{2.5}$, TVOCs, CO_2) collected from ambient air in shared institutional spaces, with no personal, identifying, or health-related data recorded from occupants.

Human or animal rights

Not applicable, as no human participants were involved in the study.

Consent for publication

Not applicable, as the manuscript does not contain any individual person's data, images, or identifying information.

Competing interests

The authors declare no conflict of interest.

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