scientific reports

Check for updates

OPEN

Sustainable modular biofiltration system with rainshower technology for AQI reform

Vivek Jaiswal[1]✉, Shubham Singh[2], Arpit Mangal[2] & Pushpendra P. Singh[3]

India is the tenth most polluted nation in the world, according to the World Health Organization (WHO) 2022 assessment. Approximately 1.67 million deaths are caused by lung, cardiovascular, stroke, and chronic pulmonary obstruction worldwide (WHO 2024). In 2019, 1.36% of GDP was reported to be lost because of air pollution and related issues. The results presented in this article demonstrate the efficacy of UBREATHE RAIN. Ambient (outside), untested enclosure (reception), and tested enclosure (breathing lounge with 3 Ubreathe Rain) were the 3 test venues that were found based on proximity and interaction to the stubble burning site. The Air Quality Index (AQI) was recorded as the highest sub-index of pollutants involved (CO, PM, SO_2, NO_2, and O_3) through grab sampling. Throughout the studies, the AQI in the tested enclosure was ~ 35% lower than that in the ambient environment and ~ 30% lower in the untested enclosure. Statistical analysis also supported this finding, as the p-value remains < 5% throughout (p-value ≈ 2%). Additionally, temperature and relative humidity changes were examined and demonstrated to represent significantly less of a challenge to the effectiveness of the proposed technology. The experiment's duration and demographics may have limited the given results and their importance.

Keywords Air pollution, Nature-based solutions, Rain showers, Phytoremediation

Recently, several research groups have focused on air pollution, which is the leading cause of respiratory and pulmonary diseases worldwide. Sustainable Development Goal 3 (SDG 3) is directly related to health and well-being. Additionally, the challenge of coping with natural solutions is limited. Lee and Kim (2018) reported that the mortality rate due to air pollution was more than 4.5 million worldwide in 2015[1]. The WHO 2024 report also states that household air pollution is responsible for 3.2 million deaths per year, including 0.2 million child deaths. The criteria for estimating the mortality rate due to air pollution were attributed to the burden of diseases caused by PM2.5, PM10, and nitrogen dioxide (NO_2)[2]. The magnitude will worsen in 2025, as predicted. The study also discussed the segregation and conjugate effects of indoor and outdoor air pollution. Odo et al. (2022) reported a link between acute respiratory disease and air pollution among children younger than 5 years old in 35 developing countries[3]. This finding replicates the adverse effects of air pollution on younger and future generations. Goldstein et al. (2020) reported and discussed the effects of the indoor environment on exposure to air pollution[4]. They followed a narrative of questions and answers to determine the entangled relationship between the indoor environment, air pollution, and exposure. They linked the concentration of PM2.5 indoors to outside air pollution and presented the challenge of exposure to more organic compounds due to enclosed spaces.

A review on harnessing plant phytoremediation capabilities to prevent air pollution in indoor spaces. Phytoremediation is a remedial process that uses various plants to remove, stabilize, and destroy contaminants in soil, air, and groundwater[5]. In this case, we are leveraging phytoremediation to clean air pollutants. Kumar et al. (2023) also presented a review highlighting the need for natural solutions to the air pollution problem. In addition, they discuss the different mechanisms for phytoremediation to explore the molecular-level settlement of pollutants through root penetration techniques[6]. A few studies have been related to predictive measures to quantify AQI depending on multifactorial functions, including AI and machine learning algorithms[7,8]. The prediction algorithm focuses on finding the weight of the dominant parameter on the AQI but still focuses on finding worthy solutions. A few studies have focused on finding nature-based solutions to address air pollution, but they have focused on managing the outdoor environment or spatial arrangement[9–11]. Additionally, most of the work in AQI management needs to integrate preventive and curative changes with technological/nature-

[1]Pandit Deendayal Energy University, Gandhinagar, Gujarat, India. [2]Urban Air Labs, Gurugram, Haryana, India. [3]iHub-AWaDH, Indian Institute of Technology, Ropar, Rupnagar, Punjab, India. ✉email: vivek.jaiswal@sot.pdpu.ac.in

based changes applied for improvement. All the cited works have shaped the current research in this field. This study aims to bridge the gap between using plant-based natural solutions to address air pollution indoor air quality (IAQI) and the environment. We propose a novel technology based on the Breathing Roots Technology, "Ubreathe Rain."

Ubreathe Rain is an innovative, nature-inspired air purification system designed for large semi-open regions experiencing heavy population influx. The semi-open regions are different from the indoor regions because they also include openings towards the outside for intentional ventilation. The system developed by Urban Air Labs, uses a modular, wall-mounted design and introduces pioneering technologies to overcome the limitations associated with existing air purification methods. Standard air purification technologies, such as HEPA-based mechanical filtration and charcoal filtration, rely on fan-driven suction systems, leading to issues such as high-power consumption, frequent filter replacements, environmental impact, increased noise, and inefficiency outdoors. Urban Air Labs addresses these challenges with a modular system incorporating "Breathing Roots Technology" and "Rain Shower Technology." These technologies leverage phytoremediation capabilities and simulate wet deposition during rainfall to efficiently purify air in semi-open spaces.

The first layer of filtration involves "Breathing Roots Technology," inspired by the process of phytoremediation, and builds upon research findings from those by[12–14], which support NASA's findings[15–17] on the ability of plants to clean pollutants. 'Breathing Roots Technology optimizes the breathability of the soil-root zone, enhancing the phytoremediation process and improving overall pollution mitigation efficacy. In conventional wall planters, the soil root zone remains enclosed, limiting its exposure to ambient air and reducing its effectiveness in air purification. In contrast, Ubreathe Rain incorporates an innovative planter design with strategically placed open slits, allowing for direct interaction between the soil-root zone and the surrounding air. To prevent soil loss through these slits, the planters are internally lined with a mesh-like cellulose material, which serves as both a structural support and a functional filtration medium. This technology also increases oxygen and controls carbon dioxide levels through photosynthesis. In the implementation of the "Breathing Roots Technology", a carefully chosen selection of plants establishes a layer comprising plant leaves and exposed root zones. The implementation of "Breathing Roots Technology" involves a reasonable selection of plant species, strategically composing a stratum characterized by the symbiosis of foliar structures and exposed root systems. The curated assemblage, distinguished for its exceptional phytoremediation ability, encompasses *Dieffenbachia compacta*, *Epipremnum aureum*, and *Hedera helix*[18], as well as *Ficus elastica*, *Pachira aquatica*, *Syngonium podophyllum*[19], *Ficus benjamina*, *Gerbera jamesonii*, various *Philodendron* species, *Sansevieria laurentii*, *and Spathiphyllum* '*Mauna Loa*'[20]. The second filtration layer mimics the cleaning effect of rainfall through "Rain Shower Technology.' Wet deposition, a natural process in which atmospheric pollutants are removed by precipitation, is scientifically explained by parameters such as droplet size and charges present in the droplets[21]. Accordingly, rain optimizes the droplet size and charge balance to maximize wet deposition ability. This technology effectively absorbs gases and breaks them down into simpler, non-harmful forms.

The rain shower system consists of strategically placed holes in a pipe fed with water through a submersible pump. Nozzles with optimized diameters facilitate the formation of droplets, thereby ensuring maximum effectiveness. The ion-splasher inside the module strategically emits positive and negative ions, which charge the droplets that interact with the suspended particles and harmful gases, thus increasing the coagulation capacity of the droplets. In natural ecosystems, wet deposition is critical in reducing airborne pollutants by leveraging ions to enhance particulate aggregation and removal. Ions, whether from rainwater, humidity, or artificial sources like ionizers, help neutralize charged airborne particles, causing them to cluster together and settle out of the air more efficiently. This mechanism significantly improves gravitational settling and deposition, making air purification systems more effective. Without ions, pollutant removal relies solely on passive filtration and microbial breakdown, which can be slower and less efficient in capturing fine particulate matter. Figure 1 shows a schematic of Ubreathe Rain shows a cross-sectional view. Ubreathe Rain, provides a novel solution for controlling air quality in large, semi-open spaces with unpredictable pollutant loads. The modular design allows for scalability, and the energy requirement per unit module is significantly lower than that of conventional air purifiers with similar specifications and coverage areas. This innovative air purification system offers a sustainable and effective solution for improving air quality in densely populated areas. Throughout the fabrication and testing, the space was very selective due to the focus on the vicinity of stubble burning. In addition, the timing and duration were chosen, especially to target the stubble burning. These specific choices may pose limitations with variations in demographic conditions adding to fluctuations in the efficacy of the products deployed. However, the efficacy of the proposed technology is limited in highly ventilated spaces due to the large air change rate, timely sunlight, which rejuvenates plants follicles, and dependency on water splashing.

Experimental methodology

The objectives of conducting the experiments are:

a. Benchmarking with audits to record the base data.
b. Discussion on preventive and corrective measures and their capability to reduce the air quality parameters in general.
c. Investigation of the efficacy of Ubreathe Rain in a particular environment by recording air quality parameters (with increased air pollution due to specific activity in the vicinity of the location).
d. Establish standards for the measuring different air quality parameters to state possible future works.

The investigation location was the ground floor of the guest house of the Indian Institute of Technology Ropar, Punjab (Fig. 2G.I.S. image). The lounge area has 600 squares feet with a total floor area of 2500 square feet. The location methodical suits to conducting and addressing pertinent variables inherent in semi-open environments

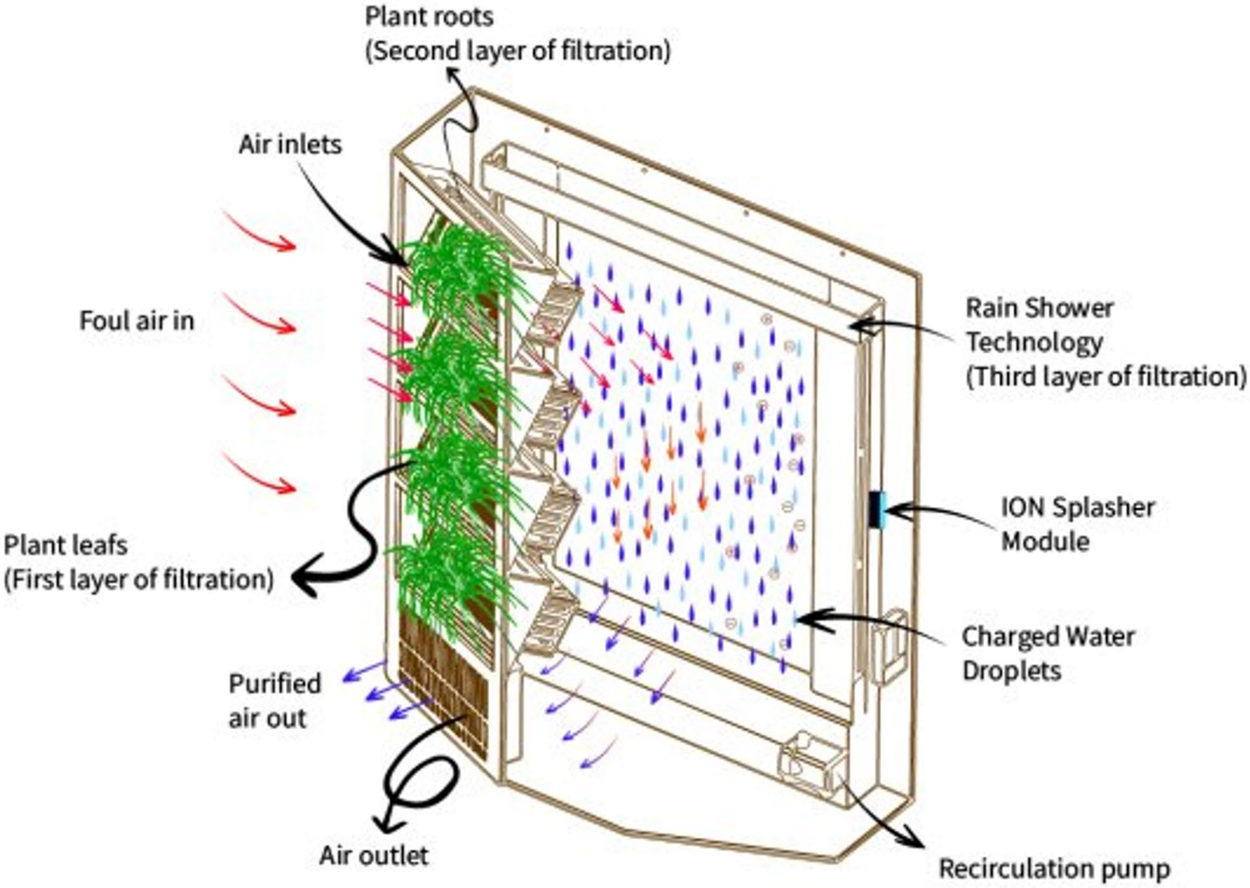

Fig. 1. Schematic of Ubreathe Rain Technology.

and mitigating heightened indoor air pollution. The objectives of selecting a lounge area are to choose a space that includes diverse activities, such as mass gatherings, cooking in adjacent kitchens, and intermittent door opening, and acknowledge their potential impact on indoor air quality. The lounge space is generally open from 7 A.M. to 10 P.M. in general. Within the regional context of Ropar, Punjab, a notable surge in air pollution during the winter months was attributed to stubble-burning practices[22], highlighting the significance of this study in the lounge space. Scientific assessments underscore the consistent exceedance of permissible PM2.5 and PM10 levels by 7–10 times. The tests were performed over 15 days during the stubble-burning season.

The deployed product is 3.1 ×2.7 ×1.1 feet, and it consumes 40 Watts of power during operation, costing approximately 1 unit/day for 24 h of continuous usage. To address the air quality concerns comprehensively, a three-step strategy was implemented. First, a precise air quality audit was conducted from October 31, 2023, to November 16, 2023, employing AQI monitoring stations. The duration was selected to reflect the general presence of smog due to stubble burning. This audit quantified vital parameters, including PM2.5, PM10, total volatile organic compounds (T.V.O.C.s), and overall AQI. The audit revealed that PM2.5 was the primary concern at the site, largely due to its proximity to agricultural farms and significant exposure to stubble burning during the winter season when the study was conducted. Additionally, the initial assessment and root cause analysis indicated that concentrations of total volatile organic compounds (TVOCs) and other gaseous pollutants remained within safe limits, which can be attributed to the presence of adequate ventilation in the observed area. The audit outcomes, which indicated that the concentrations of PM2.5 and PM10 surpassed the recommended levels, aligned with findings from similar studies in regions affected by stubble burning[23]. Studies have highlighted the susceptibility of indoor spaces to outdoor pollution ingress, especially in the winter, with higher outdoor to indoor gradients. It aids in constant air filtration, substantiating the unique challenge of maintaining air quality as stubble burning occurs in the lounge area, which is connected to the outdoors through an adjacent reception area[24].

Second, preventive measures were implemented following established indoor air quality management protocols. This included applying sealing stripes on windows and doors to prevent outdoor air leakage, installing hydraulic door closers to limit air exchange, performing comprehensive site cleaning to remove deposited dust pollutants, and enforcing partial space closure via curtains in the lounge area. Additionally, 3 Ubreathe rain modules were introduced into the lounge at the centre of 3 different walls, facing each other to cover the lounge space effectively within their zone of influence. The Ubreathe Rain system is an innovative air purification technology that addresses high-air-volume interactions and mitigates air pollutants within the designated

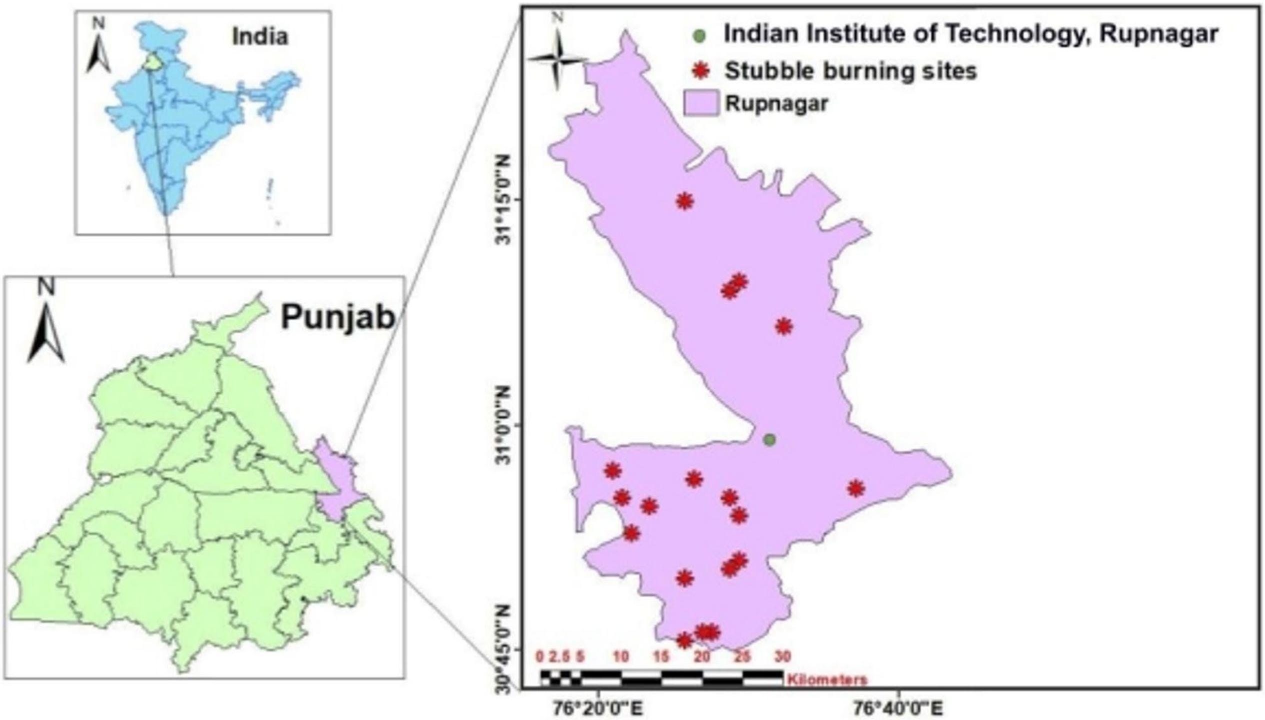

Fig. 2. The location of the test site was determined on a map using a geographic information system (GIS).

space. Lastly, strategically positioned air quality monitoring stations have facilitated continuous and real-time assessments, in line with recommendations from the environmental engineering literature (TAD Report US 2018[2]). These stations were strategically located to capture nuanced variations in air quality, providing a comprehensive understanding of the dynamics within the lounge space.

The combination of real-time monitoring, preventive measures and technological interventions reflects a holistic to record the assessment of air quality in the specified lounge space. The collected data is initially reviewed for any patterned aberrations or anomalies, if present. After assessing of possible causes, a few modifications were incorporated in one of the three steps discussed. The statistical tools are applied to search for deductions in a pile of information. The hourly and daily averages, standard deviations, upper to lower bounds of variation, and distribution patterns of the entire dataset were thoroughly examined. Hypothesis testing is also carried out to test the validity of the collected data and to bring confidence into the methodology applied. The design of the experimentation was carried out to fulfil the designated four aims enlisted above. In line with the aim of the work, the experiments recorded the effect of stubble burning and focussed on primary indicators to navigate the cause-and-effect paradigm. The audit data set up the benchmark and recorded data is compared to represent the effect of the Ubreathe Rain for air purification and air quality management.

Results and discussion

The results and discussion section are subdivided into investigations and representations of AQI and PM2.5. The measurements of AQI and PM2.5 were chosen as two performance parameters to represent the effectiveness of the aforementioned technology mentioned above. Additionally, variations in temperature and relative humidity were tested to determine the break-even point for the technology to be applicable and effective. The Air Quality Index (AQI) is a standardized metric used to assess and communicate the quality of air in specific location. One of the primary pollutants influencing AQI is fine particulate matter (PM2.5), which consists of airborne particles with a diameter of 2.5 microns or smaller. By using AQI as a standardized measure, authorities can effectively communicate air quality conditions while ensuring that the scientific nuances of particulate pollution are accounted for. The distinction between the ambient, untested enclosure, and tested enclosure is clearly illustrated in Fig. 3 as per the actual experimental location.

Air Quality Index (AQI)

As shown in Fig. 4, the ambient environment represents the status of the AQI outside the tested enclosure. The AQI is directly affected by all general movements, agricultural practices (stubble burning), and demographic locations. The untested enclosure data are collected upon guest reception, Except for the Ubreathe Rain technology, everything remains the same. The spikes on dates 04/11 and 12/11 were reported in all cases due to the burning of stubble in the nearby areas of the tested enclosure, as shown in Fig. 2. The AQI of the tested enclosure was ~ 35% lower than that of the ambient enclosure and ~ 30% lower than that of the untested enclosure when Ubreathe Rain was used. This ensures that the arena in which the technology is implemented is

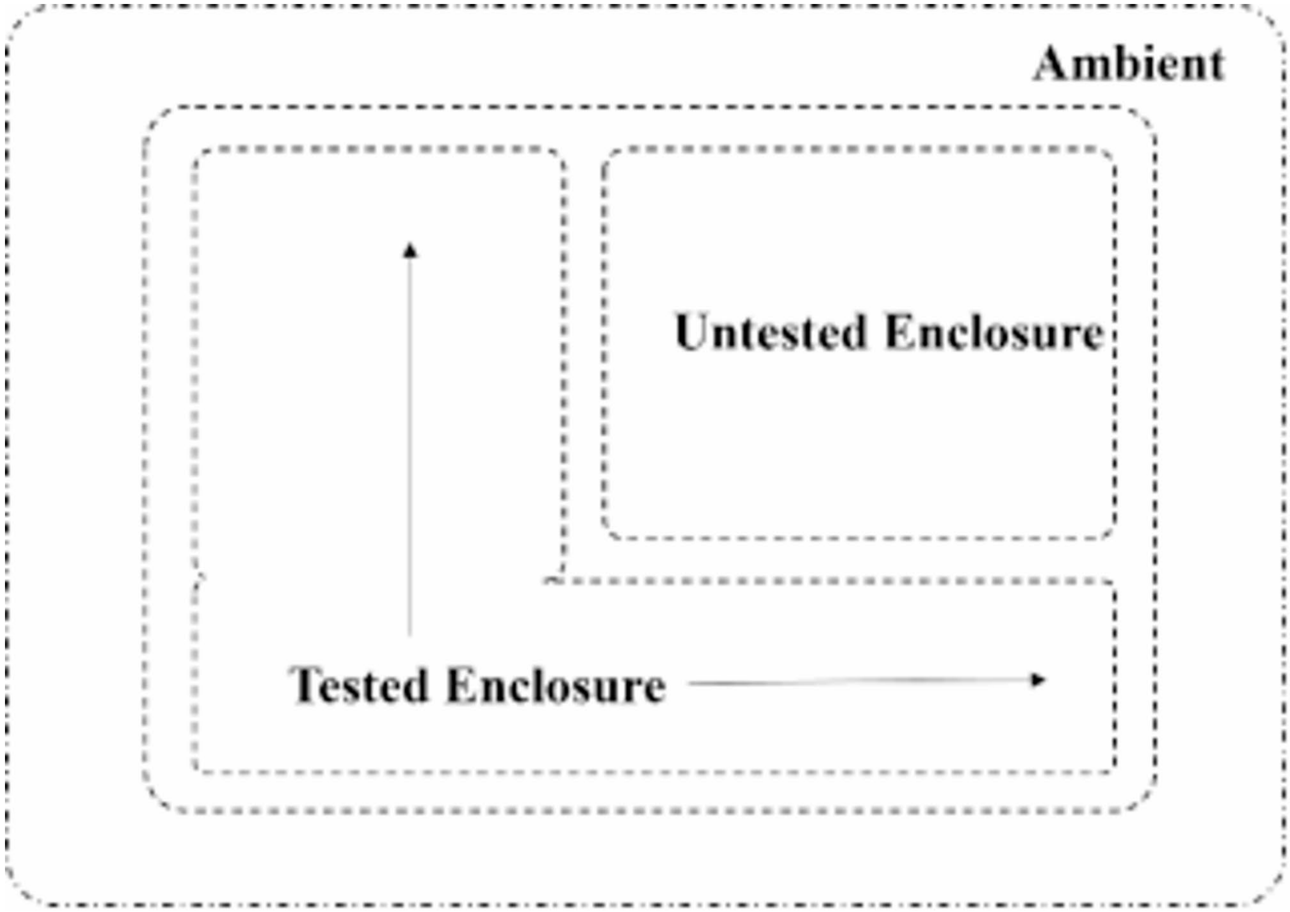

Fig. 3. Schematic of the test site and its surroundings.

less polluted and can be tracked down to breathable AQIs with continuous effort. A z-test was conducted on the gathered data, and it was found that the p-values of ambient to the tested enclosure and tested to the untested enclosure were 0.0002 and 0.0004, respectively, confirming the unlikely possibility of the null hypothesis. The results are presented as 95% confidence intervals.

The integration of Rain Shower Technology, which incorporates a water curtain, facilitates direct air-water interaction, leading to measurable thermodynamic effects. Due to evaporative cooling, the air passing through the water curtain exhibits a temperature reduction of approximately 1.5–2 °C, whereas the ambient relative humidity increases by 5–10%. The modulation of the thermal comfort and hygrometric parameters was further optimized by regulating the air velocity, which enabled the system to achieve and maintain conditions conducive to thermal comfort. The experimental conditions included a temperature variation of 20 ± 2 °C. Previous studies have suggested that a decrease in temperature leads to a higher AQI. Nevertheless, the tested enclosure was found to vary little in the vicinity of the breathable regime (Fig. 5). The regime below the line of AQI = 150 represents breathable and above as unhealthy and beyond. This means that temperature changes do not drastically affect the performance of Ubreathe Rain over a given temperature range. Additionally, the test enclosure records a ~ 38% lower AQI than the ambient AQI. The ambient AQI increased with increasing temperature due to occasional stubble burning and poor particle sedimentation due to high transportation. The p-values of all possible combinations (ambient-tested, tested-untested, and untested-ambient) were less than 1%. Hence, the null hypothesis is not satisfied.

Figure 6 establishes the relationship between the relative humidity and the AQI. The experimental conditions for relative humidity were 68 ± 5%. For most experimental data, the AQI lies in an unhealthy and beyond regime. Only a few points in the tested enclosure belong to the breathable regime. In addition, in contrast to previous research, the AQI was not consistent with the increase in relative humidity.

Particulate Matter 2.5 (PM2.5)

The PM2.5 concentration is the other performance parameter. Figure 7 shows the variation in the model over different testing durations. Although the runs at the testing enclosure are also unhealthy and regime beyond, compared with the ambient environment, 50% less are conducted on average. The PM2.5 concentration and AQI data are interrelated, as both respond similarly to the technology and strategies used to purify the air in the tested space. The demographic and environmental conditions also play pivotal roles in determining air quality. The

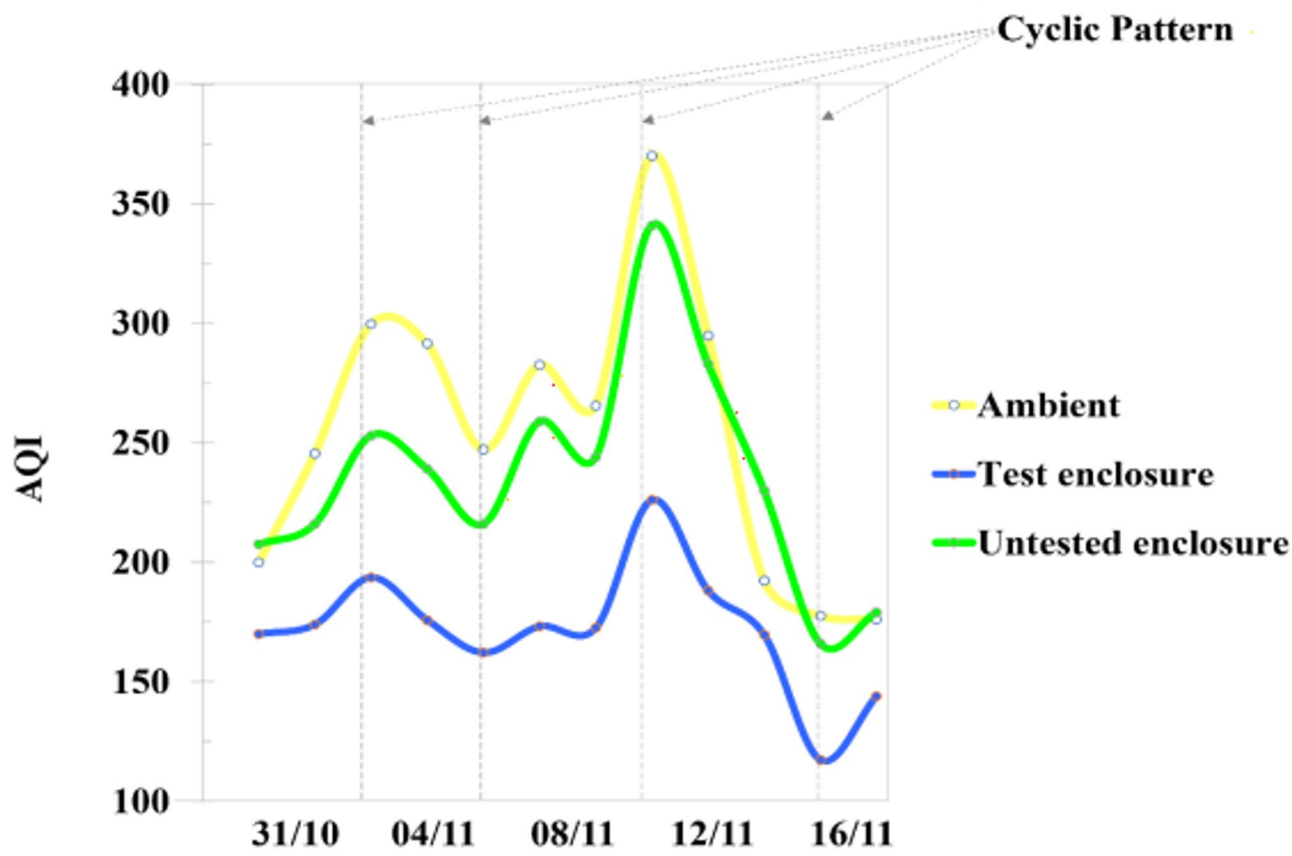

Fig. 4. Variations in AQI during the test.

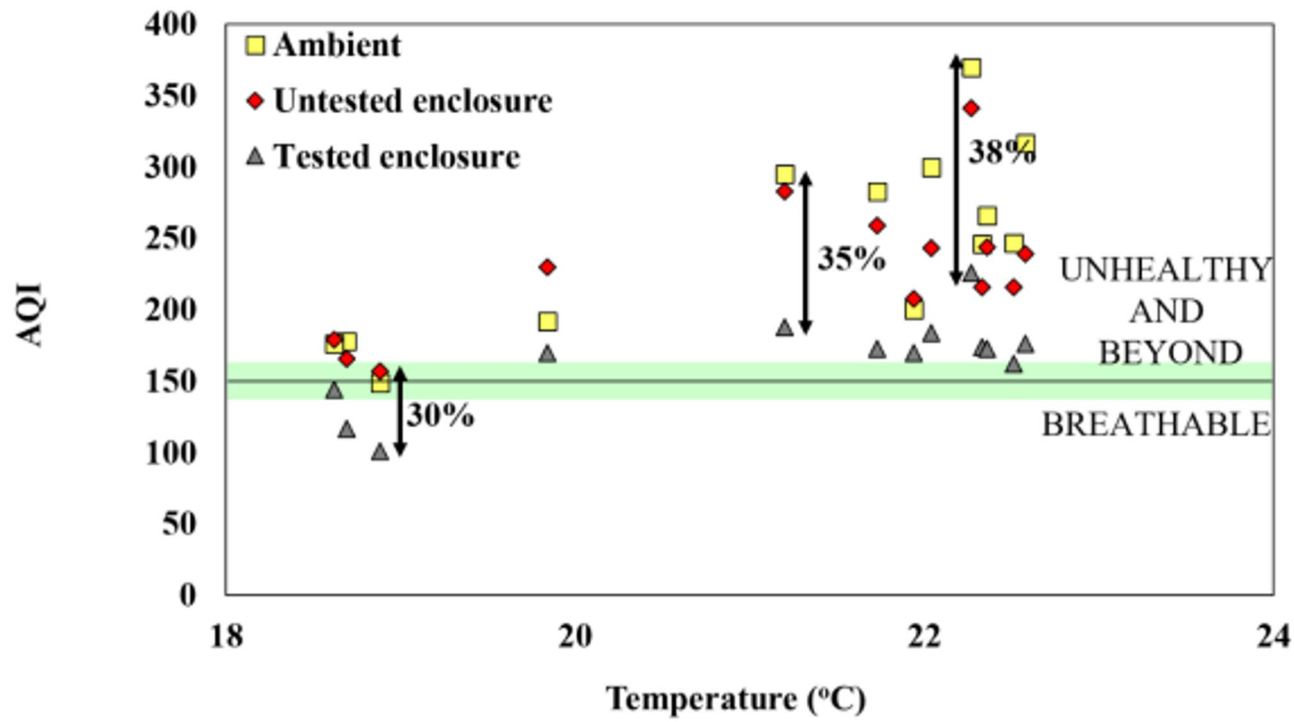

Fig. 5. The air quality index variation to temperature change.

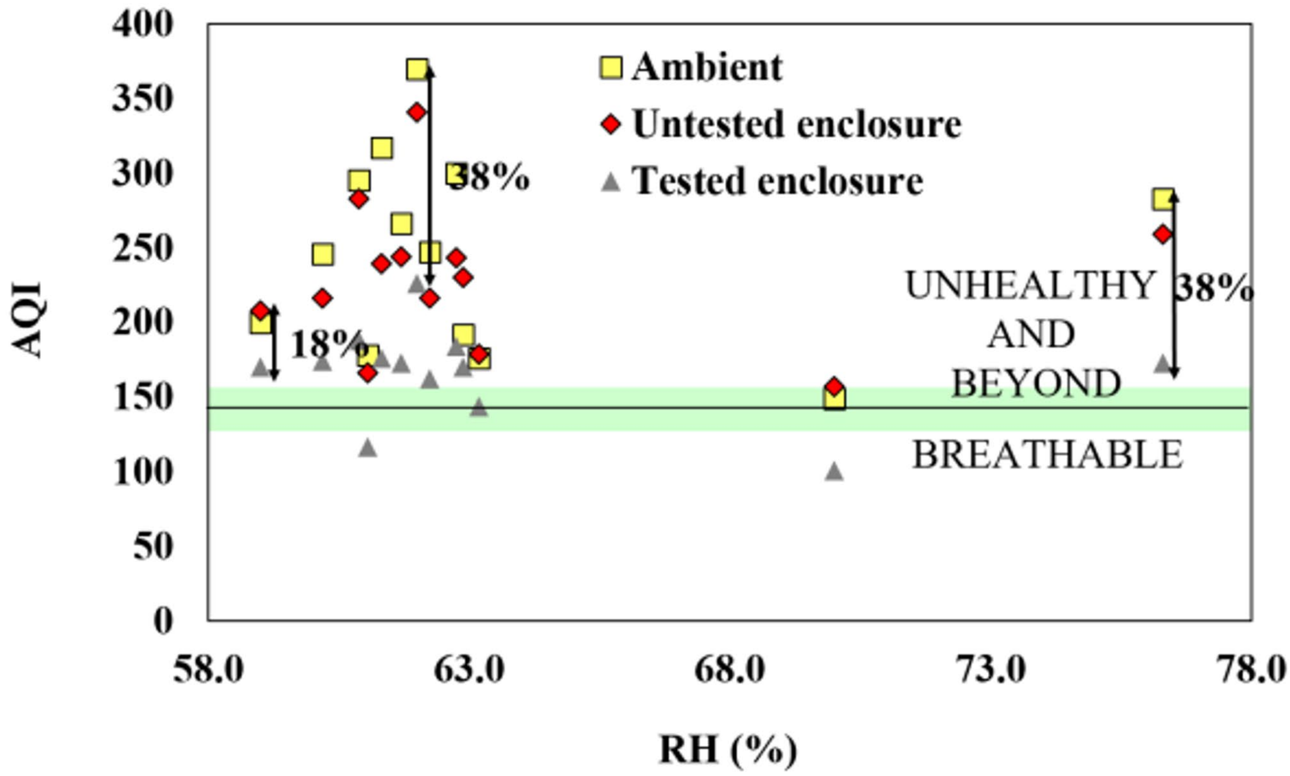

Fig. 6. Variation in AQI with relative humidity (%).

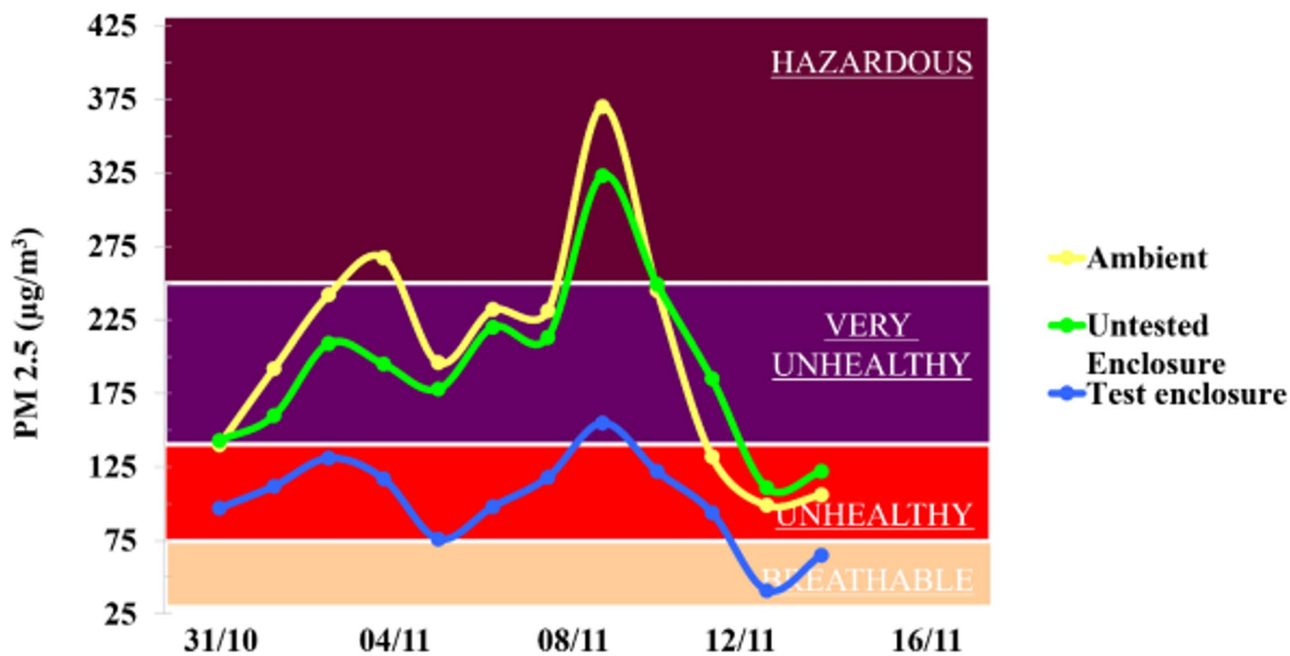

Fig. 7. Variation in the PM2.5 concentration over the test duration.

p-value for the PM2.5 concentration in the ambient environment compared to the tested enclosure lies below 2% (~ 0.00017), which satisfies the null hypothesis and proves the efficacy of Ubreathe rain technology.

Similar to the AQI, observations and supporting arguments also been reported for PM2.5 (Fig. 8). The regime below the PM2.5 = 75 lie in the breathable range. The reduction in the PM 2.5 concentration relative to the ambient concentration was approximately 50%. The concentration of PM2.5 remains just above the

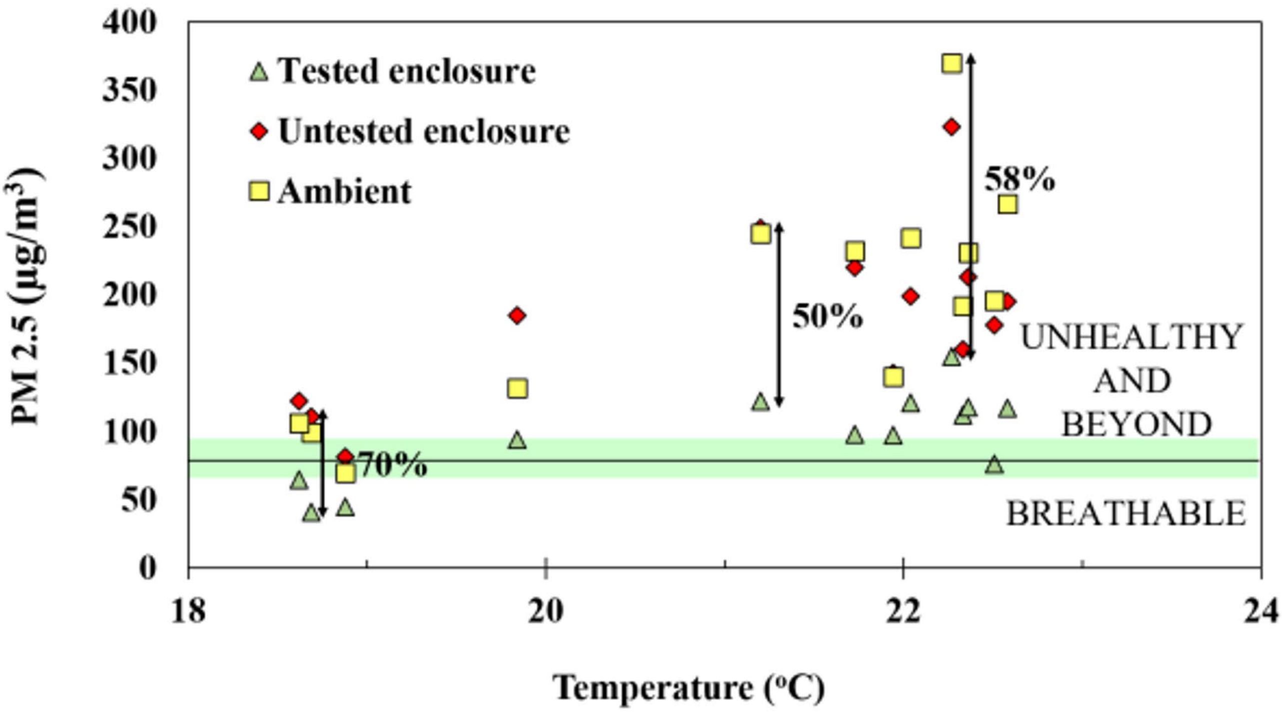

Fig. 8. PM2.5 concentration versus temperature variation.

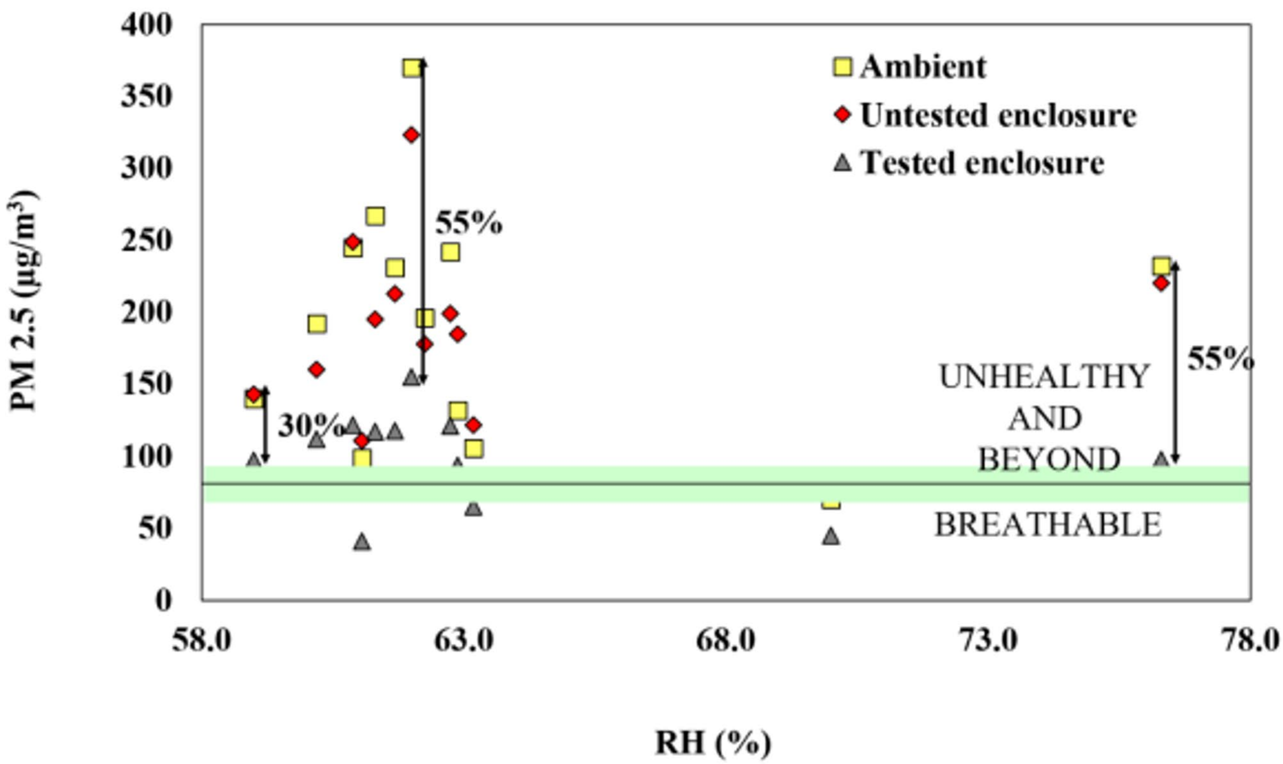

Fig. 9. Effect of relative humidity (%) on PM2.5 concentration.

breathable regime with the implementation of the Ubreathe rain shower technology compared with the ambient and untested enclosures.

Figure 9 shows variations in the PM2.5 concentration and relative humidity. The PM2.5 concentration in the tested enclosure hovered around the breathable regime with a few points on both sides of the healthy range.

The concentration of PM2.5 can be drained to the region under investigation with more curative and preventive measures. As suggested in the literature, particle deposition and removal enhance at increased relative humidity. As humidity (moisture content) in air increases, particles tend to grow more rapidly and sediment. The investigation and discussion of AQI and PM2.5 concentrations with time intervals (including stubble burning time), temperature, and relative humidity variation presents information specific to demography and is suited to a particular statement of purpose (S.O.P.) for operations. The relationships among the AQI, PM2.5 concentration, temperature, and relative humidity are nonlinear, which indicates that air quality cannot be predicted using only two- or three-parameter information. These constraints set the boundary of the effectiveness Ubreathe rain shower technology.

Conclusion

A novel technology, Ubreathe Rain, is being tested to explore its ability to improve air quality within enclosed space under the effect of stubble burning in the vicinity. The results revealed a reduction in the AQI in the tested enclosure, ~ 35% from the ambient environment and ~ 30% from the untested enclosure throughout the experiments. The statistical analysis also supported the deduction effectiveness of the Ubreathe product in the deployed area (p-values < 2%). The testing was conducted by controlling air passage rate, specific surface area, and demographic location (to capture the effect of stubble burning). With increasing temperature, the changes in AQI and PM2.5 concentration occur ~ 35% and ~ 50% less, respectively, than under ambient conditions. Similarly, the effects of increasing relative humidity on the AQI and PM2.5 concentrations were also tested, resulting in reductions of approximately 38% and 55%, respectively. Therefore, variations in temperature and relative humidity were investigated and found to be less challenging to the performance of the proposed technology. This study establishes that the proposed technology can fulfill this task. Proper preventive measures may reduce an enclosure's AQI and PM2.5 concentration to healthy and breathable limits. Ubreathe rain has widespread reach at different locations and has been proven to be effective in reducing air pollution. The quantitative analysis compares the proposed technology to the benchmark technology. The results also indicate the effectiveness of Ubreathe rain shower technology, which is again commendable as the variety of test site applications were investigated.

Future scope

The device is not intended for testing conditions alone; therefore, qualitative and quantitative analyses are required at different locations. Some elaborative features, such as TVOC measurement, AI integration, and IoT, will also help in market penetration and reach the public. In the future, the ionizer can be used with more stabilization, and the dependency on water for maintenance can be improved.

Data availability

The data used in this paper are available from VJ (vivek.jaiswal@sot.pdpu.ac.in) and SS (shubham.singh@urbanairlabs.com).

Received: 6 September 2024; Accepted: 6 May 2025
Published online: 18 May 2025

References

1. Lee, J. Y. & Kim, H. Ambient air pollution-induced health risk for children worldwide. *Lancet Planet. Health.* **2** (7), e285 (2018). e286.
2. Technical Assistance Document for Reporting Daily Air Quality – the Air Quality Index (AQI) by U.S. Environmental Protection Agency. Accessed 26 January 2024. (2018).
3. Odo, D. B. et al. Ambient air pollution and acute respiratory infection in children under 5 years living in 35 developing countries. *Environ. Int.* **159**, 107019 (2022).
4. Goldstein, A. H., Nazaroff, W. W., Weschler, C. J. & Williams, J. How do indoor environments affect air pollution exposure? *Environ. Sci. Technol.* **55** (1), 100–108 (2020).
5. Jhanji, S. & Dhatt, U. K. Phytoremediation of indoor air pollutants: Harnessing the potential of plants beyond aesthetics. *J. Hortic. Sci.* **16** (2), 131–143 (2021).
6. Kumar, R., Verma, V., Thakur, M., Singh, G. & Bhargava, B. *A Systematic Review on Mitigation of Common Indoor Air Pollutants Using plant-based Methods: a Phytoremediation Approach*pp. 1–27 (Air Quality, Atmosphere & Health, 2023).
7. Rani, S., Kumari, P. & Singh, S. K. Machine Learning-based Multiclass Classification Model for Effective Air Quality Prediction. In 2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET) 1–7. (2023).
8. Kumar, S., Mishra, S. & Singh, S. K. A machine learning-based model to estimate PM2. 5 concentration levels in Delhi's atmosphere. *Heliyon* **6** (11), e05618 (2020).
9. Gopalakrishnan, V., Ziv, G., Hirabayashi, S. & Bakshi, B. R. Nature-based solutions can compete with technology for mitigating air emissions across the united States. *Environ. Sci. Technol.* **53** (22), 13228–13237 (2019).
10. Marando, F., Salvatori, E., Fusaro, L. & Manes, F. Removal of PM10 by forests as a nature-based solution for air quality improvement in the metropolitan City of Rome. *Forests* **7** (7), 150 (2016).
11. Menon, J. S. & Sharma, R. Nature-based solutions for co-mitigation of air pollution and urban heat in Indian cities. *Front. Sustainable Cities.* **3**, 705185 (2021).
12. Clemens, S., Palmgren, M. G. & Krämer, U. A long way ahead: Understanding and engineering plant metal accumulation. *Trends Plant Sci.* **7** (7), 309–315 (2002).
13. Gupta, D. K., Huang, H. G. & Corpas, F. J. Lead tolerance in plants: strategies for phytoremediation. *Environ. Sci. Pollut. Res.* **20** (4), 2150–2161 (2013).
14. Wood, R. A., Orwell, R. L., Tarran, J., Torpy, F. & Burchett, M. Potted-plant/growth media interactions and capacities for removal of volatiles from indoor air. *J. Hortic. Sci. Biotechnol.* **77** (1), 120–129 (2002).
15. Aydogan, A. & Montoya, L. D. Formaldehyde removal by common indoor plant species and various growing media. *Atmos. Environ.* **45** (16), 2675–2682 (2011).

16. Chun, S. C. et al. Effect of bacterial population from the rhizosphere of various foliage plants on the removal of indoor volatile organic compounds. *Hortic. Sci. Technol.* **28** (3), 476–483 (2010).
17. Wolverton, B. C., Johnson, A. & Bounds, K. *Interior Landscape Plants for Indoor Air Pollution Reduction, NASA/ALCA Final Report* (Plants for Clean Air Council, Mitchellville, 1989).
18. Wolverton, B. C., Johnson, A. & Bounds, K. Interior landscape plants for indoor air pollution abatement (No. NASA-TM-101766). (1989).
19. Wolverton, B. C., McDonald, R. C. & Watkins, E. A. Jr. Foliage plants for removing indoor air pollutants from energy-efficient homes. *Econ. Bot.* **38** (2), 224–228 (1984).
20. Wolverton, B. C., McDonald, R. C. & Mesick, H. H. Foliage plants for the indoor removal of the primary combustion gases carbon monoxide and nitrogen oxides. *J. MS Acad. Sci.* **30**, 1–8 (1985).
21. Ardon-Dryer, K., Huang, Y. W. & Cziczo, D. J. Laboratory studies of collection efficiency of sub-micrometer aerosol particles by cloud droplets on a single-droplet basis. *Atmos. Chem. Phys.* **15** (16), 9159–9171 (2015).
22. Jethva, H. et al. Connecting crop productivity, residue fires, and air quality over Northern India. *Sci. Rep.* **9** (1), 16594 (2019).
23. Singh, D. et al. Crop residue burning and its relationship between health, agriculture value addition, and regional finance. *Atmosphere* **13** (9), 1405 (2022).
24. Mendoza, D. L., Benney, T. M. & Boll, S. Long-term analysis of the relationships between indoor and outdoor fine particulate pollution: A case study using research-grade sensors. *Sci. Total Environ.* **776**, (2021).

Author contributions

VJ, SS, and PPS contributed to the study conception and design. SS, AM, and VJ performed material preparation, data collection, and analysis. VJ wrote the first draft of the manuscript, and all the authors commented on previous versions. All the authors read and approved the final manuscript.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to V.J.