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ASIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ISSN: 0976-3376

Asian Journal of Science and Technology
Vol. 17, Issue, 10, pp. 14603-14608, October, 2026

RESEARCH ARTICLE

WHY SHORT-DURATION TESTS CANNOT DETECT BOTANICAL VOC REMOVAL: A DETECTABILITY-BASED VALIDATION OF A LOW-COST 1 M3 CHAMBER FOR INDOOR-PLANT PHYTOREMEDIATION STUDIES

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ARTICLE INFO

Article History:
Received 18th July, 2026
Received in revised form
20th August, 2026
Accepted 14th September, 2026
Published online 30th October, 2026

Key words:
Clean air Delivery Rate; Detection limit; First-order Kinetics; Indoor Air quality; Low-cost Sensor; Phytoremediation; Volatile Organic Compounds.

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ABSTRACT

Phytoremediation by potted plants is widely promoted as a low-cost remedy for indoor volatile organic compounds (VOCs), yet the supporting evidence comes from sealed-chamber studies lasting many hours, whereas school-level replications typically use short protocols without leak testing or sensor characterisation. This study (i) built and characterised a low-cost 1 m^3 acrylic test chamber, (ii) derived the minimum test duration required for a plant signal to exceed the noise floor of a low-cost metal-oxide semiconductor (MOS) VOC sensor, and (iii) compared first-order VOC decay constants (k) and clean air delivery rates (CADR) of *Sansevieria trifasciata*, *Spathiphyllumwallisii* and *Epipremnumaureum* against empty-chamber and substrate-only controls. Sensor characterisation over 6 h gave a noise standard deviation of 0.151 ppm, a limit of detection (3σ) of 0.453 ppm and a relative detection limit of 9.0%; CO_2 tracer decay gave a leak rate of 0.0187 ± 0.0006 h^{-1} (n = 3, $R^2 \geq 0.992$). Applying the published CADR distribution of potted plants (median 0.023 m^3 h^{-1}) to a first-order model shows that a 30-min test produces a theoretical reduction of only 1.14%, far below the sensor noise floor; at least 4.1 h are needed for a median-performing plant to be detected. Phase III result: one sentence reporting the measured k/CADR ranking and ANOVA outcome from the real experimental data. Failure to detect VOC reduction under short protocols is therefore an artefact of measurement design rather than evidence against phytoremediation. A corrected nine-step protocol with an *a priori* detectability criterion is provided for school and low-resource laboratories.

Citation: ***Doni Nurdiansyan, Nequiel Hayder Wibowo and Nissa AulynShabrina.*** **2026.** "Why short-duration tests cannot detect botanical VOC removal: A detectability-based validation of a low-cost 1 m3 chamber for indoor-plant phytoremediation studies", *Asian Journal of Science and Technology*, 17, (10), 14603-14608.

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INTRODUCTION

People in urban settings spend most of their time indoors, making indoor air quality a health determinant at least as important as ambient air quality (Jones, 1999; Sundell, 2004). Volatile organic compounds (VOCs) are emitted continuously from paints, varnishes, adhesives in engineered-wood furniture, cleaning agents, air fresheners and tobacco smoke, and they accumulate when air exchange is low, as in air-conditioned rooms with closed windows (US EPA, 2024; WHO, 2010). Chronic low-level exposure is associated with irritation of the eyes and airways, headache, nausea and reduced concentration, and some members of the class, such as benzene and formaldehyde, are carcinogenic. Clusters of such non-specific complaints that subside when occupants leave a building are known as sick building syndrome (Burge, 2004). Indonesia's Ministry of Health Regulation No. 1077/MENKES/PER/V/2011 accordingly sets a maximum indoor VOC level of 3 ppm for an 8-h exposure and 0.1 ppm for formaldehyde over 30 min (Ministry of Health of the Republic of Indonesia, 2011). Botanical air cleaning, the use of living potted plants to remove indoor pollutants, is attractive because it is inexpensive, requires no electricity and is aesthetically pleasing. The idea traces back to the NASA Clean Air Study, which reported removal of benzene, formaldehyde and trichloroethylene by ornamental plants in sealed chambers (Wolverton et al., 1989). Subsequent chamber studies confirmed that plants and, often more importantly, their root-zone microorganisms and growing media can remove VOCs (Aydogan& Montoya, 2011; Kim et al., 2008; Orwell et al., 2004; Xu et al., 2011), and reviews describe the process as a combination of stomatal uptake, cuticular sorption, rhizosphere biodegradation, substrate sorption and internal metabolism (Dela Cruz et al., 2014a; Irga et al., 2018). A critical quantitative reappraisal, however, changed the framing of the field. Cummings and Waring (2020) converted 196 results from 12 chamber studies into clean air delivery rates (CADR) and found that per-plant CADR spans several orders of magnitude with a median of only 0.023 m^3 h^{-1}. Matching the removal already provided by typical building air exchange would require roughly 10–1000 plants per square

metre of floor area. This finding does not state that plants fail to take up VOCs; it states that uptake is slow. The corollary that has received little attention is metrological: if the removal rate is of order 10^{-2} m^3 h^{-1}, the concentration change produced over a short test may be smaller than the noise of the instrument used to measure it. This corollary matters most in exactly the setting where indoor-plant experiments are most frequently repeated: secondary-school and low-resource laboratories. Such replications typically combine improvised containers that are not leak-tested, uncalibrated low-cost MOS sensors, no substrate-only control and observation windows of around 30 min. When the resulting curves are flat or erratic, the conclusion is often drawn that one species is 'better' than another or that plants 'do not work'. Neither conclusion is warranted if the measurement system cannot resolve the expected effect in the first place. Physiological confounding adds a second, systematic bias: *Sansevieria trifasciata* uses crassulacean acid metabolism (CAM) and opens its stomata mainly at night (Borland et al., 2009; Lüttge, 2004), so daytime tests close its stomatal pathway while leaving it open for C_3 species. The present study therefore shifts the focus from the biological object to the measurement system. Instead of asking only which plant removes the most VOC, it first asks whether the measurement system can detect the effect it is meant to measure. The objectives were to (1) design, build and characterise a low-cost 1 m^3 test chamber in terms of leak rate and sensor stability; (2) derive, from first-order kinetics and measured sensor noise, the minimum test duration needed for a plant-attributable reduction to exceed the detection limit; (3) compare decay constants and CADR of three common indoor species against empty-chamber and substrate-only controls, including a dark treatment for the CAM species; and (4) consolidate the technical and physiological error sources into a replicable protocol.

MATERIALS AND METHODS

Study design: The study combined laboratory experimentation with instrument engineering and was carried out between March and August 2026 in the Biology and Chemistry Laboratories of SMA Taruna Bakti, Bandung, Indonesia. It was organised in three gated phases, each started only after the acceptance criteria of the preceding one had been met: Phase I, construction of the chamber and its instrumentation; Phase II, characterisation of sensor noise, baseline drift and chamber leak rate; and Phase III, VOC decay tests with a duration set from the Phase II results. Phase III followed a completely randomised design with six treatments and three replicates (18 experimental runs; Table 1).

Test chamber and instrumentation: The chamber was a 1.0 × 1.0 × 1.0 m (1 m^3) acrylic box with all joints sealed with silicone sealant and an access door fitted with a rubber gasket and compression latches to distribute closing pressure evenly (Fig. 1). Pollutant was introduced through an injection septum so that the chamber did not need to be opened during a run. Instrumentation comprised a MOS VOC sensor reporting ppm-equivalent concentration, a non-dispersive infrared (NDIR) CO_2 sensor used as a tracer-gas detector, a temperature and relative-humidity sensor, a low-speed DC mixing fan, and an LED grow light with measured photosynthetic photon flux density (PPFD). All channels were logged by a microcontroller to a memory card at 1-min intervals. Insert sensor models/manufacturers, grow-light PPFD value (µmol m^−2^ s^−1^), and fan airflow.

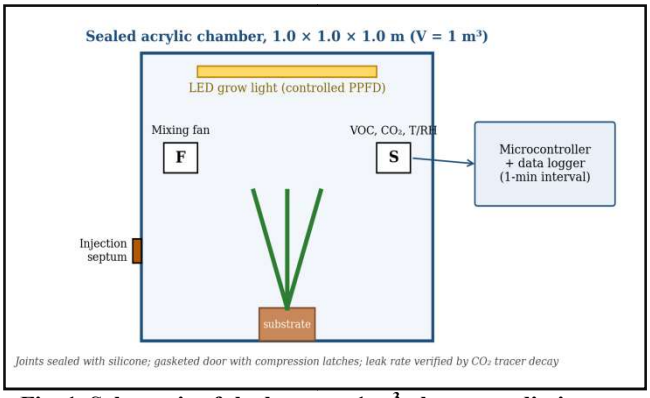

Fig. 1. Schematic of the low-cost 1 m^3 phytoremediation test chamber. F, mixing fan; S, sensor cluster (VOC, CO_2, temperature/RH)

Sensor noise and drift characterisation: The VOC sensor was warmed up for at least 60 min until its output stabilised. Readings were then recorded in the clean chamber without pollutant injection for 6 consecutive hours at 1-min intervals. The baseline mean, the noise standard deviation (σ) and the baseline drift rate (slope of a linear regression of signal on time) were computed from this series. The limit of detection was defined by the analytical convention LOD = 3σ, and the relative detection limit as $3\sigma/C_0$, where C_0 is the initial concentration in a decay run.

Chamber leak-rate test: CO_2 was injected into the empty chamber to approximately 3000 ppm, mixed by the fan for 5 min and monitored for 6 h. The slope of $\ln(C/C_0)$ versus time gave the chamber air-exchange (leak) rate, k_{leak} (h^{-1}). The test was repeated three times; the chamber was accepted if k_{leak} was consistent across replicates and small relative to the plant decay constant to be detected. State whether CO~2~ concentrations were corrected for the laboratory background, i.e. ln((C − C~bg~)/(C~0~ − C~bg~)).

Kinetic model and clean air delivery rate: Assuming a well-mixed chamber with no source after injection, the concentration decays according to first-order kinetics:

$$C(t) = C_0 \exp(-k_{total} t)$$

where k_{total} (h^{-1}) was obtained as the negative slope of $\ln(C(t)/C_0)$ against t, with the coefficient of determination (R^2) used as a goodness-of-fit indicator. The total decay constant is the sum of parallel sinks:

$$k_{total} = k_{leak} + k_{surface} + k_{substrate} + k_{plant}$$

so that the plant contribution is isolated as $k_{plant} = k_{treatment} - k_{K2}$, where K2 is the substrate-only control. To allow comparison across chambers of different volume V (m^3), the plant decay constant was converted to a clean air delivery rate (Cummings & Waring, 2020):

$$CADR = k_{plant} \times V$$

CADR was further normalised by total leaf area (m^3 h^{-1} m^{-2}), measured by paper gravimetry or image analysis.

A priori detectability analysis: The fractional plant-attributable reduction after time t is

$$R(t) = 1 - \exp(-k\,t), \text{ with } k = CADR / V \quad (4)$$

An effect is considered detectable when $R(t) > 3\sigma/C_0$. Solving for t gives the minimum test duration:

$$t_{min} = -\ln(1 - 3\sigma/C_0) / k \quad (5)$$

Eq. (5) was evaluated before data collection for the 10th percentile, median and 90th percentile of the per-plant CADR distribution reported by Cummings and Waring (2020) (0.00014, 0.023 and 0.19 $m^3 h^{-1}$, respectively) and for relative detection limits of 5%, 9% and 15%. The result determined the run duration in Phase III.

Plant material and VOC decay tests: Three species representing contrasting physiological strategies were tested: S. trifasciata (Asparagaceae; succulent CAM plant with thick cuticle, small leaf area and very low transpiration), S. wallisii (Araceae; broad thin leaves, C_3, high transpiration) and E. aureum (Araceae; fast-growing climber, C_3, intermediate transpiration). Specimens were acclimatised under laboratory conditions for at least 14 days, and total leaf area was measured before testing. For each run, the specimen was placed in the chamber, the chamber was closed and allowed to equilibrate for 30 min, and a mixed VOC source was injected through the septum to the target initial concentration. The fan was run for 5 min for homogenisation, after which t = 0 was set. VOC concentration, temperature and humidity were logged every minute for the duration determined in Section 2.6. Between runs, the chamber was ventilated until readings returned to baseline. Controlled conditions were temperature 25 ± 2 °C, relative humidity 55 ± 5%, constant PPFD, constant substrate type and volume, and constant fan speed. Specify the VOC source (product/compound), injection volume, target C~0~ and run duration actually used. The treatments are listed in Table 1.

Table 1. Treatment design of the VOC decay experiment (three replicates each)

Code	Treatment	Light	Purpose
K1	Empty chamber	Light	$k_{leak} + k_{surface}$
K2	Pot + substrate, no plant	Light	Substrate contribution (reference control)
P1	*S. trifasciata*	Light	Treatment
P2	*S. wallisii*	Light	Treatment
P3	*E. aureum*	Light	Treatment
P1D	*S. trifasciata*	Dark	Test of CAM stomatal rhythm

Statistical analysis: Runs with $R^2 < 0.90$ for the log-linear fit were reviewed for departure from first-order behaviour. Differences in k_{total} among treatments were tested by one-way ANOVA ($\alpha = 0.05$) after checking normality (Shapiro–Wilk) and homogeneity of variance (Levene), followed by Tukey's HSD test when the ANOVA was significant. The light–dark comparison for *S. trifasciata* (P1 vs P1D) used an independent-samples *t*-test. Name the statistical software and version.

RESULTS

Chamber construction: Phase I produced a working 1 m^3 chamber with all sensor channels logged automatically at 1-min intervals (Fig. 1). The first iteration was built without a mixing fan on the assumption that molecular diffusion would distribute the pollutant. This assumption proved wrong: at the 1 m^3 scale, diffusion alone is far slower than the test duration, so the sensor recorded only a local concentration and the well-mixed premise of Eq. (1) did not hold. Adding a low-speed fan in the second iteration was therefore a prerequisite for valid kinetic analysis.

Sensor noise and drift: The sensor required 68 min to stabilise (Table 2), longer than the 60 min minimum initially planned. Over 6 h of clean-chamber recording, the noise standard deviation was 0.151 ppm, giving LOD = 0.453 ppm. At a nominal initial concentration of about 5 ppm, this corresponds to a relative detection limit of 9.02%. Baseline drift was 0.006 ppm h^{-1}, i.e. about 0.04 ppm over a 6-h run, which is an order of magnitude below the LOD.

Table 2. Characterisation of the MOS VOC sensor (6 h clean-chamber recording, 1-min interval)

Parameter	Value	Basis
Warm-up time to stable output	68 min	Baseline curve
Mean baseline reading	5.02 ppm	Mean of 6 h
Noise standard deviation, σ	0.151 ppm	SD of time series
Limit of detection, LOD = 3σ	0.453 ppm	Analytical convention
Relative detection limit, $3\sigma/C_0$	9.02%	Input to Eq. (5)
Baseline drift	0.006 ppm h^{-1}	Linear regression slope

Chamber leak rate: CO_2 tracer decay was well described by first-order kinetics in all three replicates (R^2 = 0.992–0.995; Table 3). The mean leak rate was 0.0187 ± 0.0006 h^{-1}, with a coefficient of variation of 3.2%, satisfying the consistency criterion.

The mean leak rate is lower than the decay constant of a median-performing plant in a 1 m^3 chamber (0.023 h^{-1}), and its between-replicate standard deviation is almost 40 times smaller than that decay constant, so leakage in this chamber does not mask a median plant signal once it is subtracted through the controls.

Table 3. Chamber leak rate from CO_2 tracer decay

Replicate	C_0 CO_2 (ppm)	k_{leak} (h^{-1})	R^2
1	3018	0.0181	0.994
2	2996	0.0193	0.992
3	3027	0.0187	0.995
Mean ± SD	3013.7 ± 15.9	0.0187 ± 0.0006	0.994 ± 0.002

The importance of this measurement is clearer by contrast. An improvised container with a leak rate of 0.5 h^{-1}, a value plausible for makeshift enclosures, would have a leak rate about 22 times the median plant decay constant; more than 95% of the observed concentration decline (0.5/0.523) would then be due to leakage rather than to the plant.

Detectability of the plant signal: Table 4 and Fig. 2 show the projected plant-attributable reduction in a 1 m^3 chamber from Eq. (4). At median performance, one plant reduces VOC concentration by only 1.14% in 30 min. At C_0 = 5 ppm, this equals 0.057 ppm, about one-eighth of the measured LOD (0.453 ppm) and less than half of a single noise standard deviation. Even at the 90th percentile, the 30-min reduction (9.06%) lies exactly at the relative detection limit of the sensor.

Table 4. Projected plant-attributable VOC reduction (%) by one plant in a 1 m^3 chamber, based on the CADR distribution of Cummings and Waring (2020)

Performance scenario (CADR, $m^3 h^{-1}$)	0.5 h	1 h	2 h	6 h	12 h	24 h
10th percentile (0.00014)	0.007	0.014	0.028	0.084	0.168	0.335
Median (0.023)	**1.143**	2.274	4.496	12.890	24.119	42.420
90th percentile (0.19)	9.063	17.304	31.614	68.018	89.772	98.954

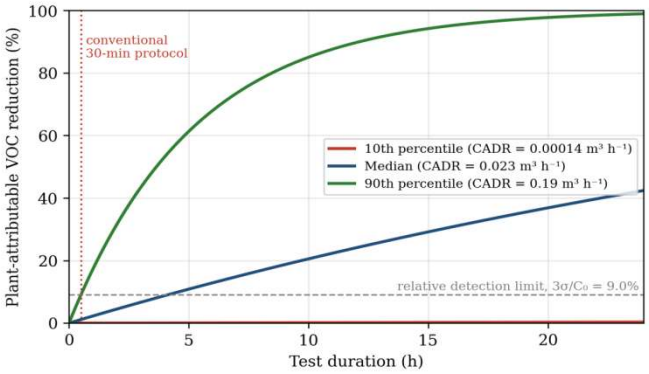

Fig. 2. Projected plant-attributable VOC reduction versus test duration in a 1 m^3 chamber for the 10th percentile, median and 90th percentile per-plant CADR. The dashed line marks the relative detection limit of the sensor used here (9.0%); the dotted line marks the conventional 30-min protocol

Minimum test durations from Eq. (5) are given in Table 5 and Fig. 3. At the relative detection limit of the present sensor (≈ 9%), a median-performing plant requires at least 4.1 h, about eight times the common 30-min protocol. Only 90th-percentile plants become detectable within half an hour, and then only at the threshold. For 10th-percentile plants, detection would require several weeks, which is impractical in any chamber. The first hypothesis, that a 30-min protocol produces a reduction smaller than 3σ of sensor noise, is therefore supported.

Table 5. Minimum test duration, t_{min} (h), for the plant signal to exceed the detection limit (Eq. 5)

Relative detection limit, 3σ/C₀	10th percentile	Median	90th percentile
5%	366.4	2.2	0.3
9%	673.7	4.1	0.5
15%	1160.9	7.1	0.9

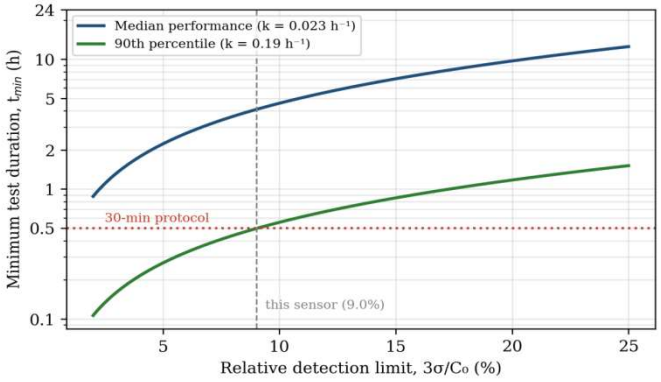

Fig. 3. Minimum test duration as a function of the relative detection limit of the sensor for median and 90th percentile plant performance (logarithmic ordinate)

VOC decay experiments: This subsection must report the measured Phase III data. The report's Tables 4.5–4.6 are explicitly labelled as simulated data and must not be submitted as experimental results. Replace every highlighted cell and sentence below with the real values. Decay constants and CADR for all treatments are summarised in Table 6. Log-linear fits yielded R^2 of x.xx–x.xx. One-way ANOVA showed a significant / no significant difference in k_{total} among treatments ($F(5, 12)$ = x.xx, p = x.xxx; Table 7). Describe the Tukey HSD groupings and the ranking of species. Report the P1 vs P1D comparison: t(4) = x.xx, p = x.xxx.

Table 6. Decay constants and CADR per treatment (mean ± SD, n = 3). Values sharing a letter do not differ significantly (Tukey HSD, α = 0.05)

Code	k_{total} (h^{-1})	R^2	k_{plant} (h^{-1})	CADR (m^3 h^{-1})	CADR per leaf area (m^3 h^{-1} m^{-2})
K1				—	—
K2			0 (reference)	—	—
P1					
P2					
P3					
P1D					

Table 7. One-way ANOVA of k_{total} among treatments

Source	df	SS	MS	F	p
Between treatments	5				
Error	12				
Total	17				

DISCUSSION

Null results as artefacts of measurement design: The central finding is that the widely used 30-min protocol is mathematically incapable of detecting a median plant in a 1 m^3 chamber with a low-cost MOS sensor. This is a metrological, not a biological, limitation. Flat or erratic curves from such protocols therefore carry no information about whether a plant removes VOC; they reflect a design whose detection power is below the effect size. The same reasoning explains why published chamber studies that did observe clear removal typically used small chambers, long monitoring windows and laboratory-grade analytical instruments (Kim et al., 2008; Orwell et al., 2004; Wolverton et al., 1989). Detectability analysis of the kind given in Eq. (5) is inexpensive and fast, and it should be performed before any data are collected; to our knowledge it is almost never reported in school-level phytoremediation studies. The framework also clarifies which design levers matter. Because k = CADR/V, halving the chamber volume doubles the plant decay constant and halves t_{min}; a 50–100 L chamber would thus shorten the required test from hours to well under an hour for a median plant. Lowering sensor noise or raising C_0 reduces 3σ/C_0, although raising C_0 is limited by sensor saturation and by the relevance of the tested concentration to real indoor levels.

Leakage, substrate and humidity as confounders: Eq. (2) makes explicit why controls are indispensable. Without an empty-chamber control, leakage and wall sorption are credited to the plant; without a substrate-only control, sorption by the growing medium is credited to the plant, although growing media alone can remove most of a formaldehyde charge within hours (Aydogan& Montoya, 2011). The present chamber's leak rate (0.0187 h^{-1}) was low and reproducible enough to be subtracted, but a makeshift container would have been dominated by leakage (Section 3.3). A further, less obvious confounder is humidity: MOS sensor output depends on temperature and moisture, and transpiring plants raise humidity in a closed chamber. Part of any observed signal may thus be a humidity artefact, which is why simultaneous logging of temperature and relative humidity is part of error control rather than an optional extra. If the real data show a humidity rise during plant runs, report its magnitude here and whether it was corrected.

CAM rhythm as a systematic bias in species comparisons: CAM plants such as *S. trifasciata* open their stomata mainly at night and close them during the day to conserve water (Borland et al., 2009; Lüttge, 2004). A daytime or illuminated test therefore closes the stomatal uptake pathway of *Sansevieria* while leaving it open for the C_3 species *S. wallisii* and *E. aureum*. A low *k* for *Sansevieria* under light should thus be read as 'a poor remover in daytime conditions' rather than 'a poor remover'. The dark treatment (P1D) turns this limitation into a testable question. Interpret the measured P1 vs P1D result here. If nocturnal uptake is confirmed, placement of CAM plants in bedrooms, which are closed at night and contain VOC sources such as paint, furniture and textiles, would have a physiological rationale rather than being a popular myth

Implications for real rooms: Extrapolation by calculation reinforces the proportional view of botanical air cleaning. A 30 m^3 bedroom with an air-exchange rate of 0.5 h^{-1} receives about 15 m^3 h^{-1} of outdoor air; matching this with plants of median CADR would require roughly 650 plants. This agrees with Cummings and Waring (2020) and with Indonesian regulation, which lists ventilation, source control and sealing of exposed furniture surfaces, not plants, as the measures for indoor VOC (Ministry of Health of the Republic of Indonesia, 2011). Indoor plants are best regarded as aesthetic and psychological complements to ventilation rather than substitutes for it.

Recommended protocol: Based on the above, a replicable nine-step protocol is proposed for school and low-resource laboratories (Table 8).

Table 8. Corrected protocol for low-cost phytoremediation chamber experiments

Step	Action	Rationale
1	Leak-test the chamber with CO_2 tracer decay before any experiment; repair if k_{leak} greatly exceeds the expected plant *k*	Leakage otherwise dominates the decay
2	Record ≥ 6 h of clean-chamber baseline; compute σ and LOD = 3σ	Defines the noise floor
3	Compute t_{min} with Eq. (5) before data collection; run for ≥ 2 × t_{min}	Guarantees detection power
4	Include an empty-chamber (K1) and a substrate-only (K2) control	Separates leak, wall and substrate sinks
5	Use a low-speed mixing fan	Well-mixed premise of Eq. (1)
6	Control and record lighting; test CAM plants in the dark and C_3 plants in light, or both in both	Avoids CAM bias
7	Log temperature and RH simultaneously	Detects transpiration artefacts on MOS sensors
8	Report *k* and CADR, not percentage reduction	Comparable across volumes and durations
9	Normalise CADR by total leaf area	Removes specimen-size bias

Limitations

First, the MOS sensor responds to the aggregate of organic compounds and is not compound-specific; reported values are ppm-equivalent responses rather than analytical concentrations obtained by gas chromatography. Second, three replicates per treatment is the minimum for ANOVA and limits power to detect small differences. Third, the 1 m^3 chamber does not represent a real dwelling; extrapolation to rooms is by CADR calculation, not field measurement. Fourth, biodegradation products were not measured, so irreversible degradation cannot be distinguished from reversible surface sorption. Finally, the detectability analysis relies on the CADR distribution synthesised by Cummings and Waring (2020) and on the noise of one sensor unit. These limitations do not weaken the methodological conclusion, which is derived from the performance limits of the measurement system itself.

CONCLUSION

A low-cost 1 m^3 acrylic chamber with tracer-verified tightness (0.0187 ± 0.0006 h^{-1}) and a characterised MOS VOC sensor (LOD 0.453 ppm; relative detection limit 9.0%) was built and validated for phytoremediation testing. First-order detectability analysis shows that a 30-min protocol yields a theoretical plant-attributable reduction of only 1.14% at median plant performance, and that at least 4.1 h are required for a median plant to exceed three standard deviations of sensor noise. Failure to detect VOC reduction under short protocols is therefore an artefact of measurement design, not evidence against phytoremediation. Valid species comparisons additionally require subtraction of leak and substrate contributions through controls and explicit handling of the CAM stomatal rhythm. Add one sentence on the measured species comparison. The proposed nine-step protocol and the *a priori* criterion of Eq. (5) are transferable to any low-resource laboratory. Future work should use smaller chambers (50–100 L), five or more replicates, overnight logging over full 24-h cycles and cross-calibration against gas chromatography. CRediT authorship contribution statement Nequiel Hayder Wibowo: Conceptualization, Investigation, Formal analysis, Writing – original draft. Nissa Aulyn Shabrina: Investigation, Data curation, Visualization, Writing – original draft. Doni Nurdiansyah: Conceptualization, Methodology, Supervision, Writing – review & editing. Adjust roles to reflect actual contributions.

ACKNOWLEDGEMENTS

The authors thank Mrs. Sendari Novia, Principal of SMA Taruna Bakti, for permission and laboratory facilities, and the teachers and laboratory staff of SMA Taruna Bakti for technical support. This work was prepared within the Indonesian Student Research Olympiad (OPSI) 2026.

Funding: State funding source, or: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

Data availability: The raw time-series data (1-min resolution) for sensor characterisation, leak tests and decay runs are available from the corresponding author upon reasonable request. Or provide a repository DOI, e.g. Zenodo/OSF.

Declaration of generative AI use: Most journals require this statement. Example: During the preparation of this work the

authors used Claude (Anthropic) to assist in structuring and language-editing the manuscript. The authors reviewed and edited the content and take full responsibility for it.

REFERENCES

Aydogan, A., & Montoya, L. D. (2011). Formaldehyde removal by common indoor plant species and various growing media. *Atmospheric Environment, 45*(16), 2675–2682. https://doi.org/10.1016/j.atmosenv.2011.02.062

Borland, A. M., Griffiths, H., Hartwell, J., & Smith, J. A. C. (2009). Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands. *Journal of Experimental Botany, 60*(10), 2879–2896. https://doi.org/10.1093/jxb/erp118

Burge, P. S. (2004). Sick building syndrome. *Occupational and Environmental Medicine, 61*(2), 185–190. https://doi.org/10.1136/oem.2003.008813

Cummings, B. E., & Waring, M. S. (2020). Potted plants do not improve indoor air quality: A review and analysis of reported VOC removal efficiencies. *Journal of Exposure Science & Environmental Epidemiology, 30*(2), 253–261. https://doi.org/10.1038/s41370-019-0175-9

Dela Cruz, M., Christensen, J. H., Thomsen, J. D., & Müller, R. (2014a). Can ornamental potted plants remove volatile organic compounds from indoor air? A review. *Environmental Science and Pollution Research, 21*(24), 13909–13928. https://doi.org/10.1007/s11356-014-3240-x

Dela Cruz, M., Müller, R., Svensmark, B., Pedersen, J. S., & Christensen, J. H. (2014b). Assessment of volatile organic compound removal by indoor plants: A novel experimental setup. *Environmental Science and Pollution Research, 21*(13), 7838–7846. https://doi.org/10.1007/s11356-014-2695-0

Irga, P. J., Pettit, T. J., & Torpy, F. R. (2018). The phytoremediation of indoor air pollution: A review on the technology development from the potted plant through to functional green wall biofilters. *Reviews in Environmental Science and Bio/Technology, 17*(2), 395–415. https://doi.org/10.1007/s11157-018-9465-2

Jones, A. P. (1999). Indoor air quality and health. *Atmospheric Environment, 33*(28), 4535–4564. https://doi.org/10.1016/S1352-2310(99)00272-1

Kim, K. J., Kil, M. J., Song, J. S., Yoo, E. H., Son, K.-C., & Kays, S. J. (2008). Efficiency of volatile formaldehyde removal by indoor plants: Contribution of aerial plant parts versus the root zone. *Journal of the American Society for Horticultural Science, 133*(4), 521–526.

Kim, K. J., Jeong, M. I., Lee, D. W., Song, J. S., Kim, H. D., Yoo, E. H., Jeong, S. J., Han, S. W., Kays, S. J., Lim, Y.-W., & Kim, H.-H. (2010). Variation in formaldehyde removal efficiency among indoor plant species. *HortScience, 45*(10), 1489–1495.

Lüttge, U. (2004). Ecophysiology of crassulacean acid metabolism (CAM). *Annals of Botany, 93*(6), 629–652. https://doi.org/10.1093/aob/mch087

Ministry of Health of the Republic of Indonesia. (2011). *Regulation of the Minister of Health No. 1077/MENKES/PER/V/2011 on guidelines for indoor air sanitation in residential houses*. Jakarta: Ministry of Health.

Orwell, R. L., Wood, R. L., Tarran, J., Torpy, F., & Burchett, M. D. (2004). Removal of benzene by the indoor plant/substrate microcosm and implications for air quality. *Water, Air, and Soil Pollution, 157*(1–4), 193–207.

Sundell, J. (2004). On the history of indoor air quality and health. *Indoor Air, 14*(s7), 51–58. https://doi.org/10.1111/j.1600-0668.2004.00273.x

United States Environmental Protection Agency. (2024). *Volatile organic compounds' impact on indoor air quality*. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality

Wolverton, B. C., Johnson, A., & Bounds, K. (1989). *Interior landscape plants for indoor air pollution abatement* (Final Report NASA-TM-101766). National Aeronautics and Space Administration, John C. Stennis Space Center.

Wood, R. A., Burchett, M. D., Alquezar, R., Orwell, R. L., Tarran, J., & Torpy, F. (2006). The potted-plant microcosm substantially reduces indoor air VOC pollution: I. Office field-study. *Water, Air, and Soil Pollution, 175*(1–4), 163–180.

World Health Organization. (2010). *WHO guidelines for indoor air quality: Selected pollutants*. WHO Regional Office for Europe.

Xu, Z., Wang, L., & Hou, H. (2011). Formaldehyde removal by potted plant–soil systems. *Journal of Hazardous Materials, 192*(1), 314–318. https://doi.org/10.1016/j.jhazmat.2011.05.020

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