Supplementary Information

for

Ten Questions on Indoor Greening and Environmental Quality

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S1. IEQ benefits for the classified individual typologies

Passive planting: In particular, potted plants (typically floor-standing) are the most common iGI. They can typically reduce specific VOCs and modestly increase relative humidity, with small temperature effects. In addition, controlled condition experiments (test chamber) identified that indoor light intensity has a considerable influence on the amount of CO_2 small-scale potted plants remove. Recent studies also report the influence of passive indoor plantings on task performance, health, and stress, supporting their deployment for wellbeing alongside IEQ [1]. However, the in situ efficacy is variable and highly sensitive to plant species, substrate microbiota, density and ventilation/airflow [2,3].

Vertical greenery systems (VGS): These structures typically provide larger active leaf area and boundary-layer exchange that enables stronger pollutant and microclimate benefits than isolated passive planting. The most common approach for VGS is implementing vascular plants, which contain functional xylem and phloem tissues to transport fluid and nutrients; [4]. Ghazalli et al. (2018) have demonstrated its effectiveness for reductions in PM, especially for coarse particles [5]. Additionally, a large green wall that covers a significant amount of surfaces can act as passive acoustic insulation for buildings, while recent research [6,7] has already proven its significant potential for noise reduction. Conversely, non-vascular plants are an alternative low-maintenance approach (compared to a green wall planted with vascular plants), but require a shady and humid environment. Among these typologies, the moss systems (living or preserved) are popular for their low-maintenance characteristics. Evidence for PM capture by moss is mixed at the species level, but laboratory studies suggest a substantial deposition potential on moss surfaces [8,9]. Acoustic absorption is often strong due to the porous microstructure and thickness of moss composites [9,10].

Aquatic systems: The understanding of IEQ benefits associated with aquatic systems remains underexplored in both modelling and real-world experiments. To our best knowledge, there are no current empirical studies focused on evaluating the nexus between aquatic systems and IEQ.

Hydroponic system (vertical farming): This type of vertical farming is a type of indoor agriculture that cultivates stacked greenery and often uses soil-free techniques such as hydroponics and aeroponics [11], to allow tight control of water, nutrients or lighting, to greater the total size of the leaves to optimise photosynthesis and growth. Field deployment of hydroculture facilities has shown greater indoor plant ability to remove CO_2 [12], and consequently, reduce ventilation energy consumption for up to 50% [13]. Their IAQ benefits are typically heightened when configured to active biofilters that force air through the planted media. However, similar to aquatic systems, the understanding of hydroponic systems is scarce, and research has primarily focused on outdoor/semi-outdoor environments. For instance, outdoor hydroponic and aeroponic planting was found to be an efficient way to reduce CO_2, VOCs, PM and noise [14,15]

Hybrid interventions (active botanical biofilters): Active systems draw room air through plant foliage and microbially active substrates, enhancing contact and mass transfer [16]. These botanical filters are effective biotechnology for IAQ filtration, especially VOCs [17]. Single-pass removal tests show high VOC abatement efficiencies [18,19]. Field deployment of active biofilters further justifies their effectiveness, reporting CO_2 reductions (5–50%), sensible indoor thermal cooling (net 3–5 °C), and consequently saving energy consumption from HVAC load [20,21]. For instance, Wang et al. (2022) discovered that long-term deployment of an active biofilter system would result in an energy savings of 1 % for HVAC load, including 2 % for cooling, 26 % for heating, and an overall of 10–15 % annual energy saving [22]. Recent work has also provided evidence that effective filtration of NOx is possible with active botanical biofilter technology [23]. Refer to Q3 (Section 2.3) for further details.

Space-scale planting: Large planters in balconies and other semi-exterior niches function as a façade-level "green buffer" that can indirectly enhance indoor conditions. Planting on balconies and other semi-exterior niches functions as a façade-level "green buffer". For instance, window boxes, planters, trellised climbers, etc, can provide shading and evapotranspirative cooling that mitigates heat to the indoor environment (balcony greening can lowered indoor air and surface temperatures by ~3 °C; [24]), moreover these continuous planter liners/hedge-like structure can altering the incoming airflow to filter/intercept pollutants at the air inlets. Although there are no studies directly conducting acoustic evaluations on semi-indoor balconies with scale plantings, similar studies on vertical greening systems have proven an effective noise attenuation on traffic noise [25,26].

S2. Expert assessment and data availability scoring for iGI performance matrix

All data used to construct the iGI performance matrix were obtained through a structured expert assessment survey completed by the authorship team. For each of the ten analytical questions in the paper, the designated Question Lead and Co-Lead, together with additional co-authors possessing relevant subject-matter expertise, were invited to provide ratings for the iGI typologies and indicators associated with their domain. This ensured that the evaluation reflected the multidisciplinary expertise of the team, covering plant sciences, indoor air quality, environmental psychology, building physics, HVAC engineering, and microbiology.

The survey instrument asked contributors to provide two linked ratings for each typology–indicator pair within their area of expertise: an Impact score (0–5) reflecting the expected magnitude of influence of a given iGI typology on a specific parameter (e.g., particulate removal, thermal comfort, microbial diversity, stress reduction), and a corresponding Confidence score (0–5) expressing the assessor's certainty in that judgement. To ensure consistent interpretation, contributors were provided with explicit definitions for each scale: Impact scale: 0 = No impact; 1 = Modest impact; 2 = Low impact; 3 = Medium impact; 4 =

High impact; 5 = Very high impact. Confidence scale: 0 = No confidence; 1 = Modest confidence; 2 = Low confidence; 3 = Medium confidence; 4 = High confidence; 5 = Very high confidence. Impact and Confidence ratings were collected within the same survey form and displayed together for each typology–indicator pair. Contributors were asked to assign the Impact score first, followed immediately by the Confidence score positioned directly below it. This side-by-side arrangement ensured that paired judgements were made in a consistent and contextually informed manner, while minimising the risk of scoring mismatches across typologies.

Where multiple experts rated the same typology indicator pair, all available Impact and Confidence scores were retained. To incorporate uncertainty into the synthesis, Weighted Impact values were calculated using a confidence-weighted average across all expert inputs:

$$Weighted\ Impact = \frac{\sum_{i=1}^{n} I_i \times C_i}{\sum_{i=1}^{n} C_i}$$

where I_i is the Impact score and C_i the Confidence score from expert i. To ensure consistent interpretation across categories, all weighted values were rounded to the nearest decimal using standard rounding procedures.

Ratings provided with higher confidence contribute proportionally more to the final value, while still retaining lower-confidence inputs without over-amplifying them. If all contributors skipped a given cell (i.e., no non-zero Confidence scores were available), the matrix entry was left blank. For cases where contributors provided Impact scores but assigned a Confidence score of zero, these entries were excluded from weighting to avoid numerical instability.

Another survey was conducted to evaluate the maturity and depth of the evidence base supporting each of the ten analytical questions. Contributors assigned a single Data Availability score ranging from 0 to 5, reflecting the number of relevant peer-reviewed publications identified in their literature search: 0 indicated an absence of evidence, 1 corresponded to very sparse literature (<5 publications), 2 indicated lightly researched areas (⩾5 and <10 publications), 3 reflected modest evidence (⩾10 and <20 publications), 4 represented well-established topics (⩾20 and <30 publications), and 5 indicated very well researched domains (⩾30 publications). Authors were instructed to provide scores only for the questions within their domain expertise, ensuring that the assessment reflected expert judgement rather than speculation, while questions outside their knowledge scope were left blank. When multiple contributors rated the same question, all responses were retained to capture variation in disciplinary perspectives. The resulting scores provide a semi-quantitative overview of the unevenness of the current evidence base and complement the Impact–confidence matrix by identifying questions where empirical knowledge is abundant, emerging, or notably lacking.

iGI type	Categories	VOC removal	CO₂ modulation	RH moderation	Noise absorption	PM removal	Irrigation demand	Light demand	Sensitivity to high AER	HVAC/energy synergy	Thermal comfort	IoT/control readiness	Bioaerosol risk severity	Mould risk severity	Microbial diversity contribution	Stress/wellbeing benefit	Productivity/attention benefit	Equity/access potential	Maturity/field evidence	Maintainability ease	Integration difficulty severity
Active biofilter	Active green wall	4	4	3	2	3	3	3	4	3	3	3	4	4	3	2	2	3	5	5	5
	Active green wall: across-leaf airflow	3	3	3	2	3	3	3	4	3	3	3	4	3	2	2	2	3	4	4	4
	Desktop active planter (mini biofilter)	2	2	2	2	2	4	3	4	2	1	3	3	2	2	1	2	2	2	4	3
	Duct-integrated biofilter module	2	3	2	2	2	3	3	4	3	1	3	4	2	2	2	1	2	2	2	3
	Return-air plenum planted module	2	2	2	2	2	4	3	4	3	1	3	3	2	2	2	1	2	2	2	4
	Standalone planter-box biofilter	2	2	3	2	2	3	3	4	3	1	3	3	3	2	2	2	2	2	4	4
Aquatic systems	Aquaponic edible wall	1	1	1	1	1	3	2	2	1	1	3	2	2	1	2	1	2	1	2	2
	Paludarium / indoor water garden	1	1	1	1	1	2	2	2	1	1	2	3	3	1	2	1	2	1	2	2
Hydroponics/ vertical farming	Aeroponic tower	2	2	2	2	2	4	4	4	2	1	4	3	2	2	2	2	3	3	3	4
	Hydroponic rack: leafy greens	2	2	2	2	2	4	4	4	3	1	3	3	3	2	2	2	2	3	3	4
	Kitchen herb wall (hydroponic)	2	1	2	2	1	4	3	4	2	1	3	3	2	2	2	2	2	4	2	2
	Microgreens shelf	2	2	2	2	2	4	4	4	3	1	4	3	3	2	2	2	3	3	2	3
Passive green wall	Green wall: felt/soil (no forced airflow)	3	3	3	3	4	3	3	3	3	2	2	4	4	2	3	3	3	4	5	4
	Green wall: modular pocket system	2	3	3	3	3	2	3	3	3	2	2	4	4	2	2	2	2	3	4	4
	Living moss/ bryophyte panel	1	2	1	2	2	2	2	3	1	1	2	2	3	1	2	2	2	3	2	3
	Preserved moss panel (non-living)	1	1	1	1	2	2	1	3	1	1	2	1	2	1	2	1	1	2	2	2
Passive planting	Desktop planters / small pots	2	3	2	2	2	3	3	3	2	3	2	3	4	3	4	4	3	4	4	3
	Floor-standing medium plants	2	3	3	2	3	3	4	3	3	3	2	4	4	3	4	4	3	5	5	3
	Hanging planters / trailing vines	2	2	3	2	2	3	4	3	3	2	2	3	3	2	3	3	3	2	3	3
	Large indoor trees/palms	2	2	2	2	2	3	3	3	2	2	2	3	4	2	2	2	2	3	2	3
	Passive plant tower/column	1	2	2	2	2	2	3	3	2	1	3	2	3	2	2	3	2	2	3	3
	Windowsill herb planters (soil)	2	2	2	3	2	3	3	3	2	1	3	3	3	2	3	3	3	3	3	4
Space-scale planting	Balcony/loggia planters (semi-indoor)	1	1	1	1	2	2	2	3	1	2	2	2	3	1	4	3	3	3	3	3
	Indoor atrium planter bed / indoor garden	1	1	1	1	2	2	2	3	1	2	2	3	4	2	4	3	3	3	3	3
	Overhead trellis / green ceiling	1	1	1	1	1	2	2	3	1	1	2	1	2	1	3	3	3	2	2	3
	Winter garden / sunspace	1	1	1	1	1	2	2	3	1	2	2	3	3	2	4	3	3	2	3	3

0	Not researched (no information found)
1	Negligibly researched (<5 publications)
2	Lightly researched (≥5 & <10 publications)
3	Somewhat researched (≥10 & <20 publications)
4	Well researched (≥20 & <30 publications)
5	Very well researched (≥30 publications)

Figure S1. Data availability matrix summarising the level of published evidence (0–5) for each iGI typology across twenty performance indicators.

Table S1. Summary of thematic clusters (TC), including their overarching research questions (OQ) and constituent specific research questions (Q).

Thematic clusters	**Research questions**
TC1. Biophysical and technical performance *OQ1: How does the building environment affect the plant, and how does the plant, in turn, affect the building environment?*	*Key topic areas covered: Impact on IEQ parameters, HVAC integration, energy efficiency, and seasonal performance.* **Q1.** How does iGI impact IEQ? (Fundamental mechanisms) **Q2.** What is the impact of indoor environmental conditions on the ability of plants to deliver IEQ improvements? (plant performance) **Q3.** How does iGI integrated with building heating, ventilation and air conditioning (HVAC) systems affect IEQ? (system integration) **Q4.** How does iGI affect thermal sensation and comfort? (specific performance metrics) **Q5.** How can advanced technologies integrated with iGI predict and maintain IEQ while reducing dampness and health risks of exposure to bioaerosols? (managing microbiological consequences). **Q9.** What types of iGI physical interventions currently exist for IEQ, and for what specific purposes are they implemented? (Current state of-the-art on iGI interventions)
TC2. Ecological and microbiological dynamics *OQ2: How does iGI change the indoor microbiome and contribute to creating a more natural (rewilded) indoor ecological system?*	*Key topic areas covered: Rewilding indoor microbial communities, and managing mould/bioaerosol risks.* **Q6.** Can iGI contribute to rewilding the indoor microbial ecosystems and thereby promote human health? (core ecological hypothesis). **Q5**. How can advanced technologies integrated with iGI predict and maintain IEQ while reducing dampness and health risks of exposure to bioaerosols? (managing microbiological consequences).
TC3. Human health and wellbeing *OQ3: How does iGI directly influence the health, well-being, and performance of people indoors?*	*Key topic areas covered: Effects on cognition, emotion, physiology, mental health, thermal sensation, and behavioural change.* **Q7.** How does iGI affect building user/resident cognition, emotion, physiology, and overall health and wellbeing? (direct human outcomes) **Q6.** Can iGI contribute to rewilding the indoor microbial ecosystems and thereby promote human health? (core ecological hypothesis). **Q4.** How does iGI affect thermal sensation and comfort? (subjective comfort, also fits to TC1).
TC4. Equity, access, and socio-economic impact	*Key topic areas covered: Benefits across social vulnerability factors (income, housing quality).*

OQ4: What evidence exists for using iGI to improve IEQ among socially vulnerable groups?	**Q8**. How might iGI improve IEQ for socially vulnerable groups facing disadvantages (low income, poor quality of housing, crowding)? (core equity related question)
TC5. Implementation and systems integration *OQ5: What are the real-world barriers and solutions for implementing iGI at scale?*	*Key topic areas covered: Existing interventions, engineering barriers, and real-world effectiveness.* **Q9.** What types of iGI physical interventions currently exist for IEQ, and for what specific purposes are they implemented? (Current state of-the-art on iGI interventions) **Q10.** What are the major engineering barriers to deploying iGI? (technical hurdles) **Q3.** How does iGI integrated with building heating, ventilation and air conditioning (HVAC) systems affect IEQ? (integration challenge)

Table S2. Summary of studies investigating the impact of indoor plants on the various parameters of IEQ.

References	Plant species	iGI setting	Sample duration	Parameters measured	Controlled environment volume	Extent of greening considered	Key outcomes	Limitations
Faharani et al. [27]	Aglaonema (‘Black’ cultivar), Dracaena deremensis	Sealed 1 m³ chamber (20 °C, varied RH)	12 h benzene (0.125 ppm)	Benzene concentration (% removed)	1 m³	1 potted plant per 1 m³ chamber; n = 3 per species; plant size/age similar; leaf area not reported (NA)	A. black removed ~92% of benzene (0.125→0.01 ppm) in 12 h; D. deremensis removed ~61% under optimal RH	Lab conditions; single VOC; small chamber
Katoch & Kulshrestha [28]	Ficus elastica	Real indoor (Delhi homes; industrial vs residential)	Dust sampling (cross-sectional)	Dust chemical composition (SO_4^{2-}, NO_3^-); leaf biochemistry	NA	*Potted Ficus elastica placed at each sampling site; number of plants and leaf area not reported (NA).*	Greater sulfate+nitrate flux on leaves in industrial home; higher anion deposition corresponded to stress (lower chlorophyll/sugars)	Only two sites (industrial vs home); one plant species
Katoch & Kulshrestha [29]	Ficus elastica, F. lyrata, Schefflera arboricola	Real indoor (Delhi homes; industrial vs residential)	Seasonal monitoring (1 yr)	Dust deposition flux; leaf biochemistry	NA	Three potted indoor plants per site/household (one each of *Ficus elastica*, *Ficus lyrata*, and *Schefflera arboricola*)	Higher dust deposition flux in industrial site & winter; F. elastica/lyrata showed higher pollution-tolerance (APTI)	Observational (Delhi only); correlation of deposition with leaf chemistry

Gubb et al. [30]	Spathiphyllum wallisii, Dracaena fragrans, Zamioculcas zamiifolia	150 L test chamber; light (0/500 lx), wet/dry soil	1 h with 100 ppb NO_2	NO_2 concentration	150 L (0.15 m^3)	One whole potted plant–growing medium system per chamber run (3 L pot; 227 cm^2 exposed substrate surface area), tested with n = 5 plants per species. Mean leaf area per plant: *Dracaena fragrans* 3081 cm^2, *Spathiphyllum wallisii* 5013 cm^2, *Zamioculcas zamiifolia* 2147 cm^2.	• All tested plants removed indoor NO_2; D. fragrans had highest uptake (~3 ppb·m^{-2}·h^{-1} at 500 lx)	• Short-term, controlled chamber; scale-up uncertain
Dockx et al. [31]	Residential green space (proxy)	Field study (176 households)	Settled dust sampling	Indoor dust microbial diversity (16S/ITS)	NA	Number of indoor plants in the living room (categorised as 0, 1–3, and >3 plants) and indoor plant density expressed as plants per m^2 of living-room floor area (tertiles: low = 0, middle = 0.02–0.06, high	Higher nearby green cover was positively correlated with indoor bacterial/fungal diversity (Shannon index)	Association only; no specific plant tested; indirect measure of iGI effect

						= >0.06 plants/m²)		
Cummings & Waring [32]	Various (meta-analysis of 12 studies, mixed species)	Literature review of chamber studies	Various (from 12 studies)	VOC removal CADR	NA	NA	Median CADR ≈0.023 m³/h per plant	Passive VOC removal very low; ~10–1000 plants/m² needed to equal ventilation
Ryu et al. [33]	Epipremnum aureum (pothos)	Closed plant chamber (0.25 m³)	Smoke $PM_{2.5}$ pulses	$PM_{2.5}$ concentration decay	0.25 m³	One potted *Epipremnum aureum* seedling per chamber run (leaf area 421 cm²; pot Ø 0.10 m; plant height ~0.25 m)	Active leaf transpiration (higher RH) greatly enhanced $PM_{2.5}$ removal; RH increase was "crucial" to $PM_{2.5}$ reduction	One species, simulated smoke; chamber test
Yin et al. [34]	Tree leaves (various species)	Smog chamber (closed system)	$PM_{2.5}$ (NaCl) introduction & decay	$PM_{2.5}$ decay curve (attenuation)	0.402 m³	Leaf area (LA) of suspended leaves in the chamber (e.g., 30 leaves per test; total LA ≈ 0.0995 m² for *Cinnamomum camphora*)	Introduced an "indirect method" to calculate leaf deposition velocity (Vd) from $PM_{2.5}$ decay in a closed chamber	Assumes uniform mixing; requires calibration with known conditions

Irga et al. [35]	Chlorophytum comosum (spider plant) in modular wall	Indoor active biofilter (0.25 m ^{2} panel)	Recirculating air (flow 11.25 L/s)	$PM_{2.5}$, PM_{10} concentration	0.216 m³ (fully sealed Perspex test chamber, 0.6 × 0.6 × 0.6 m internal)	One modular botanical biofilter per test (0.25 m² module; each module holds 16 *Chlorophytum comosum* plants)	In-room biofilter (~0.25 m² panel) achieved ~50% single-pass removal of particulate matter (53.3% PM_{10}, 48.2% $PM_{2.5}$)	Small-scale prototype; performance depends on airflow rate & recirculation
D'Alessandro et al. [36]	Green wall modules (potted plants on soil panels)	Reverberation chamber (ISO 354)	Varied plant coverage	Diffuse-field absorption coefficient	53.36 m³	Plant panels with substrate in a 100-mm-diameter sample holder; coverage varied (25/50/90 plants) on a 1.06 × 1.06 m frame	Dense living-wall panels modestly increased mid-frequency sound absorption (~10–12% over bare soil)	Panel-scale experiment; limited species and configurations
Asdrubali et al. [37]	Understory plants (fern, Soleirolia ("baby-tears"), begonia, maidenhair fern, ivy)	Impedance tube + small reverberant chamber	Soil plant panels	Sound absorption coefficient (250–5000 Hz)	NA	1.06 m × 1.06 m planted panel (12.5 cm thick); greenery density varied as 25 / 50 / 90 plants per panel (plus a mixed setup: 45 baby tears + 45 fern)	Fern panels absorbed up to ~98% of sound energy; baby-tears ~90%. Overall, plants on soil increased absorption by ~11% at 800–1600 Hz	Laboratory tests (small samples); specific plant types and frequencies only

NASA [38]	Various houseplants (e.g., Gerbera, Dracaena)	Sealed 0.44 m^3 chamber + carbon filter	24 h VOC exposure	Benzene, formaldehyde, Trichloroethylene (TCE) concentrations	0.44 m^3	One potted plant per chamber per test; greening extent quantified by total plant leaf surface area (cm^2) per plant	Significant removal of benzene, formaldehyde, TCE	Laboratory chamber; requires ~10–1000 plants/m^2 to match typical ventilation

Table S3. Summary of studies on iGI integration with HVAC systems.

References	iGI	Settings/ Context	Energy efficiency & IEQ metrics assessed	Sample / Duration	Climate/ Season	Key outcomes	Note/ Limitations
Abedi et al. [21]	Activated biological filter	Lab scale experiment; integrated with ventilation inlets	Operative temp, RH	6h at 5-minute intervals	None/ controlled	Higher air flows increased temp reductions and RH	Static seasonal/ climate or diurnal variations not considered; short static run; no real time power measurements; controlled room
Liu et al. [39]	Active Plant Wall	Controlled room ventilation with & without iGI	Indoor temp, RH, CO_2	1 week (summer), 2 weeks (autumn), 1 week (winter) at 5-minute intervals	Humid subtropical; winter, summer, autumn	Temperature reduction, RH increase and CO_2 reduction	Controlled environment with no people; no energy analysis of ACW and HVAC
Vivekanandan et al. [40]	Azolla BioFilters	Numerical model of a room	PM & CO_2	300 seconds	None	High PM and CO_2 removal	iGI modelled as a layer with specified removal rate; isothermal only, no HVAC cycling; steady state
Zhang et al. [41]	Living walls	Experimental room: Guangzhou Simulation: Harbin, Beijing,	CO_2	2h testing period	Experimental: humid subtropical; winter & summer	Fresh air demand and energy consumption reduced by up to ~ 40% and	Controlled office environment; requires a field study in an office;

		Shanghai, Guangzhou, Kunming, Lhasa, Urumqi			simulation: humid continental, humid subtropical, cool semi-arid, subtropical highland	~30%, respectively	Energy plus model
Yungstein & Helman [20]	Living walls (6 species)	Live working laboratory with 2-8 students	Indoor temp, RH, CO_2	30 mins with 30 second intervals with 6 measurement periods	Mediterranean; February to November	Net cooling effect was higher with ventilation on; CO_2 reduction of 5-50% and 20% energy savings	Energy savings not modelled or measured but based on assumptions; no aerosols/bioaerosols measured; data compared across different seasons with and without iGI
Torpy & Zavattorro [42]	Potted plants	Sealed test chamber	PM and VOCs	40-minute test period for PM 3 h test period for VOCs	None; chamber test at 23.5°C ±3.5°C RH68%±15%	PM reduced; VOC removal rates decreased with increasing ventilation	Sealed chamber; no energy analysis; single VOC tested; no field test
Shao et al. [13]	Indoor hydroponic rack	Office, Nanjing	CO_2	Experimental: CO_2 sampled 24h at 1-minute intervals Simulation: 24h at 1-	Humid subtropical; winter & summer	CO_2 reduced indoors; lower fresh air demand; HVAC energy consumption reduced up to ~60%	No full year analysis; limited number of occupants; single iGI type used; single day modelling

				minute intervals			
Fleck et al. [43]	60 m^2 Indoor green walls with/without active airflow	Commercial office, Sydney	Bioaerosols	3 months/3 hrs per day at 2-4 min cycles	Warm temperate climate; Late summer to early autumn	No harmful emissions of fungal propagules or risk from aerosolised Legionella species	New build that might not be replicable to existing structures and higher background contamination
Pettit et al., [23]	9 m^2 AGW in a	Classroom, Beijing	VOC and PM	20 minute test	humid continental ; season not stated	CO_2 reduced by 42.6% and VOC reduced by 28% compared to HVAC system	Fans used to disperse PM and VOC; assumed to replicate movement; HVAC system would replicate these flow conditions
Ibrahim et al. [44]	Botanical indoor air biofilter	Sealed lab scale experiment	Total suspended particle (TSP), $PM_{2.5}$ and PM_{10}	10-minute test	None/ controlled	PM filtration between 71.9-85%	Short duration; field study; power, thermal performance & ventilation flow rates not assessed; sealed room
Torpy et al. [42]	Potted plants (7 species)	Sealed room	CO_2	40-minute test period	None; chamber test at 23.7°C ±3.6°C RH68.1%± 16%	CO_2 removed but rate dependent on light intensity	Sealed room; no climate or seasonal variations; no energy analysis

Tudiwer & Korjenic [45]	Living wall	Classroom, Vienna	RH, temp and CO_2, mould spores	5 minute measurements, 24 students	Temperate continental; February to December (excluding July & August)	RH higher, small CO_2 decrease and no impact on mould spore concentrations	Mould only examined in summer; no energy analysis
Rodgers et al. [46]	Biofilter	Residential buildings, USA	Indoor temp, RH, CO_2 and VOCs	Nine days	Climate not stated; autumn	Temp, VOC and CO_2 reduction; RH increase	Short period; no energy analysis; no seasonal analysis

Table S4. Layered classification of advanced technologies integrated with iGI for predictive IEQ management and microbial-risk mitigation, showing representative studies with annotated evidence types.

Layer	**Main components**	**Key functions for iGI**	**Relation to Dampness / Bioaerosol Risk**	**Evidence base**	**References**
1. Smart Sensing & IoT-Based Monitoring	• Multi-parameter IEQ sensors (T, RH, CO_2, PM, VOCs) • Microbial/bioaerosol sensors (optical, UV-fluorescence, DNA-based) • IoT networks (LoRaWAN, NB-IoT, Wi-Fi) • Edge/fog gateways for local processing	• Continuous, high-resolution IEQ and plant-microclimate monitoring • Early detection of RH > 70 % and condensation • Real-time alerts for ventilation or irrigation adjustment	• Enables early warning of excess humidity and microbial proliferation • Supports rapid corrective action before mould or bioaerosol build-up	• Office; fan-assisted green wall with IoT monitoring; sustained IAQ improvement • Smart office; IoT plants lowered CO_2 peaks. • Chamber; CO_2 uptake 5-15 μmol m^{-2} s^{-1}, RH modulation • IoT-monitored VOC removal correlated with airflow and moisture levels	[47–49]

2. AI, Digital Twins & Predictive Analytics	• ML/DL models (LSTM, RF, ANN) • Reinforcement-learning controllers • Digital twins integrating plant physiology + building physics • Cloud/edge analytics platforms	• Forecasts RH, CO_2, VOCs under dynamic occupancy/weather • Optimises HVAC-irrigation set-points • Simulates scenarios for microbial-risk prevention	• Provides predictive maintenance for dampness/mould risk • Identifies bioaerosol hotspots via AI-based correlation	• DT + ML predicted mould risk trajectories • Hydroponic DT; optimised RH-energy balance. • Aquaponic wall DT; stabilised RH/temp. • AI/IoT analytics improved humidity regulation • Smart building; ML control reduced IAQ excursions	[50–53]
3. Intelligent & Hybrid Environmental Control Systems	• Smart HVAC/demand-controlled ventilation • Active green walls/biofilters with fans • Automated irrigation & moisture-feedback systems • UV-GI/photocatalytic	• Real-time actuation maintaining RH 40-60 % & CO_2 levels • Adaptive irrigation to prevent over-watering • Combined air-cleaning/dehumidification for	• Directly mitigates dampness via adaptive irrigation/dehumidification • Suppresses microbial load via UV-GI/photocatalysis/filtration	• Smart IAQ control; automated RH thresholds prevented mould • Energy-recovery ventilation; 15-25 % HVAC energy savings. • Demand-controlled	[48,54–56]

	filtration units • Energy-recovery & hybrid dehumidifiers	hygiene control using BAS and BMS		ventilation; reduced dampness risk. • Hybrid UV-C + TiO_2 biofilters; > 90 % microbial reduction. • Active biofilters; pollutant removal with moisture control	

Acronyms: RH = Relative Humidity; VOC = Volatile Organic Compounds; CO_2 = Carbon Dioxide; PM = Particulate Matter; BMS = Building Management System; BAS = Building Automation System; IoT = Internet of Things; ML = Machine Learning; AI = Artificial Intelligence; DT = Digital Twin; IEQ = Indoor Environmental Quality.

Table S5. Studies on the microbial effects of iGIs on indoor environments (enclosed environments, ranging from real-life indoor spaces to lab spaces).

References	**Setting / Building**	**iGI type**	**Evidence type**	**Key parameters monitored**	**Control / Integration**	**Analysis**	**Reported IEQ outcomes**
Toyoda et al [57]	Indoor experimental room (no subjects)	Floor-integrated planting	Experimental (3 rooms, 3 different plantings)	Indoor microbiome (air samples)	Microbiome of plants (leaf surfaces), soil, wood chips, water, and blank filters	Sequencing of the 16S rRNA gene amplicon	Indoor planting substantially altered airborne microbiome diversity and composition; room-specific profiles remained stable over months.
Dockx et al [31]	Residential (living rooms)	Potted plants (multiple species)	Field (cohort study, 101 houses)	Indoor microbiome (settled dust on Pds) Indoor plant density	Open kitchen to living area, pet ownership, ventilation system, pollution, urban greenery within 50m	16S and ITS amplicon sequencing and qPCR measurements	More indoor plants associated with fewer human-derived bacteria and modest increases in microbial richness, with little change in total biomass.
Soinien et al [58]	Office spaces in two cities	Air-circulating green wall (size 2 m × 1	Field, randomised control trial	Bacterial abundance and diversity on human skin; blood cytokine	Control office, baseline samples,	16S rRNA sequencing, plasma (Milliplex MAP), TGF-β1 concentrati	Green wall exposure increased skin Lactobacillus spp., enhanced

		m × 0.3 m, 3 species)		(immune response)		on (ELISA)	microbial diversity, and reduced some proinflammatory cytokines.
Adi Wicaksono et al [59]	6 indoor environments (1 botanical garden; 3 residential, 2 commercial)	Not reported (supposedly potted and floor-integrated)	Field	Composition of bacterial and fungal communities; functional characterisation of communities; inhibition of model pathogens, biofilm quantification; screening of biosurfactant producing bacteria; antibiotic resistance profiling	Plants grown under controlled conditions (i.e. temperature and humidity)	16S and ITS amplicon sequencing, shotgun metagenomics; cultured isolates	Plant species strongly shaped indoor phyllosphere microbiomes; plants harboured a core microbiome with isolates active against opportunistic pathogens.
Berg et al [60]	Indoor spaces, hospitals	Not reported	Opinion article	Not reported	Not reported	Not reported	Plants can contribute to indoor microflora and facilitate microbial exchange via pollen and seeds.

Wolverton and Wolverton [61]	Residential (all rooms)	Supposedly potted plants (15 species)	Field (1 private house)	Indoor microbiome (settled dust on Pds)	Temperature, relative humidity, hot season (3 months) vs cool season (3 months), rooms with plants / no plants	Culture of airborne microbes, recording of cfu (colony forming units), colony morphology used to distinguish between bacteria, actinomycetes, and fungi	Rooms with plants had fewer airborne microbial colonies; effects may relate partly to light and humidity.
Burge et al [62]	Residential, greenhouse	N.a. supposedly potted, hanging or windowsill	Field (10 homes, 3 greenhouses)	Indoor microbiome (air samples)	Relative humidity, Temperature	Culture, recording of cfu (colony forming units)	Houseplants minimally increased aeroallergens; greenhouses supported higher fungal loads when disturbed.

Table S6. Overview of empirical evidence on how indoor greening interventions influence user productivity, stress reduction, and overall wellbeing across different building types.

References	**Effect of indoor greening on occupants**	**Setting / Context**	**Metrics assessed**	**Sample / Duration**	**Key outcomes**	**Notes / Limitations**
de Vries et al. [63]	Effects of office plants on health, well-being, and workplace satisfaction	Multiple office organisations in the Netherlands	Self-reported health complaints, environmental satisfaction, perceived privacy, dry air perception	Field experiment; pre-post web-based surveys among office employees	Improved perceptions of air dryness, privacy, health-related complaints, and workplace satisfaction after plant introduction	Self-reported outcomes; no control group; short-term assessment limits causal inference
van den Bogerd et al. [64]	Effects of potted plants on mood and cognitive performance	University study rooms with potted plants	Mood; perceived cognitive performance; perceived environmental quality	Students; quasi-experimental pre-post design with control	No significant effects on mood or cognitive performance	Short-term exposure; self-reported measures; limited ecological variation in study environment
Hähn et al. [65]	Effects of office planting on perceived health, well-being, and performance	Offices and breakout rooms with potted plants	Self-reported stress, health, attention, efficiency, creativity, productivity	Office workers; questionnaire-based field study	Increased perceived attention, creativity, and productivity in planted areas; no significant effects on stress, health, or efficiency	Subjective self-reports; no physiological data; limited sample size and exposure duration

van den Bogerd et al. [66]	Effects of indoor plants and green walls on attention and well-being	Secondary and tertiary education classrooms with indoor plants and green walls	Attention, stress, fatigue, vigour, mood, and health complaints	Students; three controlled field experiments	Improved attention among secondary students; no significant changes in stress, fatigue, mood, or health complaints	Real classroom setting; exposure intensity and duration may have limited effects on broader well-being outcomes
Holden & Mercer [67]	Effects of natural elements on memory and mood	University classroom environment	Knowledge retention (immediate and delayed); self-reported mood	Students; controlled experiment with surveys	Improved immediate knowledge retention; no delayed or mood effects	Small sample size; short-term exposure; limited ecological validity
Nakano & Tanabe [68]	Thermal adaptation and comfort perception in semi-outdoor spaces	Urban semi-outdoor environments (Japan)	Thermal measurements; questionnaire survey; behavioural observations	~100 observations/ day over 80 days	Differences in comfort and behavioural adaptation between HVAC and non-HVAC spaces indicate psychological adaptation to environmental control and occupancy duration	Focused on semi-outdoor microclimates; findings inform thermal design but not directly linked to indoor greening or IEQ
Nieuwenhuis et al. [69]	Effects of green vs. lean office environments on well-being,	Large commercial offices in the Netherlands and the U.K.	Perceived air quality, concentration, workplace satisfaction,	Three field experiments (two longitudinal) with office workers	Greened offices showed higher satisfaction, perceived air	Conducted in large corporate settings; focused on short- to

	concentration, satisfaction, and productivity		and objective productivity	across multiple organisations	quality, concentration, and productivity than lean offices	medium-term outcomes; limited generalisability to other workplaces
Beukeboom et al. [70]	Stress-reducing effects of real vs. artificial nature	Hospital waiting room (Radiology Department)	Self-reported stress levels	Patients; field experiment with real plants vs. nature posters (control)	No significant differences between real and artificial nature in stress reduction	Short exposure duration; modest environmental contrast; potential ceiling effects in relaxation response
Saffarinia et al. [71]	Effects of nature-inspired design on anxiety and physiological responses	Hospital waiting room (Khatam-Alanbia Hospital, Iran)	Anxiety; systolic blood pressure; pulse rate	Controlled pre-post design; patients in waiting area with plants, waterfall, and bamboo furniture	Reduced anxiety, systolic blood pressure, and pulse rate after exposure	Multi-element intervention (plants + water + materials); small sample; individual effects of greenery not isolated
Doxey & Waliczek [72]	Impact of classroom plants on student performance and perceptions	University classrooms with potted plants	Course grades; student evaluations of course and instructor	Psychology students; exposure throughout term; control classrooms without plants	No significant differences in performance or evaluations between plant and control classrooms	Small sample; limited environmental control; effect may depend on exposure duration or plant visibility

Park et al. [73]	Effects of hospital room plants on recovery and psychological state	Hospital rooms (post-operative haemorrhoidectomy patients)	Length of stay; analgesic use; vital signs; pain; anxiety; fatigue	Randomised controlled trial; patients assigned to rooms with or without plants	Lower systolic blood pressure, pain intensity, pain distress, fatigue, and anxiety in plant rooms; no differences in LOS or most vital signs	Robust RCT design; limited to one surgery type; short-term recovery context
Park et al. [74]	Effects of classroom plants on stress and health indicators	High school classrooms with potted plants	Self-perceived stress; salivary cortisol; infirmary visits	Students; baseline, mid-, and post-test experimental design	Lower perceived stress and fewer infirmary visits in plant classrooms; no difference in cortisol	Small sample; limited duration; physiological measures not aligned with subjective responses
Lohr et al. [75]	Effects of indoor plants on stress, attention, and productivity	Windowless computer laboratory, Washington State University	Systolic blood pressure; self-reported emotional state; computer task reaction time and errors	96 participants (students, employees, community); short-term exposure (plants vs. no plants)	12% faster reaction times; smaller systolic BP increase during task; higher post-task recovery and attentiveness with plants	Single laboratory setting; short-term exposure; limited ecological validity for real workplaces
Ulrich et al. [76]	Stress recovery and emotional restoration during exposure to	Laboratory experiment (video exposure after stress induction)	Affective self-ratings; physiological indicators (heart period, muscle tension, skin	120 participants; short-term recovery phase	Faster and more complete emotional and physiological recovery in	Laboratory setting with video stimuli only; short-term effects; individual

	natural vs. urban scenes		conductance, pulse transit time)		natural scenes; higher sustained attention	differences in response

Table S7. Summary of studies on the effect of greening measures on IEQ for vulnerable populations living in low-IEQ environments.

References	**Location**	**Indoor greening intervention**	**Vulnerable population**	**Metrics assessed**	**Sample / Duration**	**Key outcomes**
Lee and Park [77]	South Korea	Biophilic residential design (some but not all design elements studied were indoors, but our focus is on indoor parameters)	Older adults	Qualitative measures of direct, indirect experience of nature, health	Dec, 2024 - Feb, 2025	Biophilic residential design was associated with improved health measures
Halbmayer et al [78]	Australia	Co-created greening solutions (GREEN: Cool & Care, e.g, large indoor planters)	Older adults in nursing homes	None	Not reported	Co-created greening solutions for future use and evaluation
Liu et al. [79]	Not reported	Plants in post operative settings	Post operative patients	Anxiety, post operative recovery; stress	Not reported	Reduction in anxiety, stress and quicker post operative recovery
Tomkins et al. [80]	Northern Iraq	Vertical green walls and other outdoor planting approaches	War refugees	Qualitative measures via interviews	May, 2017	Elucidation of refugee stresses and impacts of gardening on community members' resilience.

Table S8. Evidence on engineering barriers in iGI for understanding the technical, spatial, and regulatory constraints that limit their design, installation, and long-term operation across residential, commercial, and institutional contexts.

References	Indoor greening intervention	Setting / Context	Engineering barriers studied	Sample / Duration	Key outcomes	Notes / Limitations
González-Cruz et al. [81]	Vertical wall maintenance	Multi-storey office	Worker safety, damp surfaces	Safety review	Identified hazards for staff working at height	Safety rarely addressed in design
Nasr et al. [82]	Indoor greening in hospitals	Healthcare	Infection-control, fire risk	Policy analysis	Strict requirements limited adoption	Only low-risk displays allowed
Liu & Meng [83]	Ventilated living wall	Controlled chamber	HVAC airflow disruption	Short-term trial	Obstruction of diffusers led to uneven air distribution	Lab-scale only
Kotzen et al. [84]	Fire safety assessments	Institutional (schools)	Lack of fire classification	Regulatory review	No codified fire protocols for iGI assemblies	Approvals inconsistent
Moya et al. [85]	Biofilter living walls	Office ventilation systems	Integration with mechanical ventilation	Technical guideline	Demonstrated potential synergy with HVAC	Guidance still generic
Gunawardena & Steemers [86]	Modular wall & planter integration	Institutional (museum/gallery)	Plumbing restrictions, water risk	Multi-site review	Prohibition of water infrastructure in sensitive facilities	Limited to small modular units
Ascione et al. [87]	LED lighting for indoor gardens	Mixed-use buildings	Energy and glare from lighting	Simulation-based	Case-specific lighting solutions needed to avoid glare	Raised HVAC loads
Wang et al. [88]	Living wall installations	Office environments	Integration with HVAC & lighting	Cross-case analysis	Operational uncertainties overshadow benefits	Absence of design standards

Riley [89]	Living wall prototypes	Commercial office retrofit	Irrigation, pump reliability	Case study observation	Frequent clogging and pump breakdowns noted	No quantitative performance data
Frontczak & Wargocki [90]	Indoor planters	Residential apartments	Structural capacity, plumbing	Occupant survey	Barriers restrict adoption to small-scale systems	No large-scale systems feasible

References

[1] K.-T. Han, L.-W. Ruan, L.-S. Liao, Effects of indoor plants on human functions: a systematic review with meta-analyses, International Journal of Environmental Research and Public Health 19 (2022) 7454.

[2] K.-T. Han, L.-W. Ruan, Effects of indoor plants on air quality: a systematic review, Environmental Science and Pollution Research 27 (2020) 16019–16051.

[3] A. Aydogan, R. Cerone, Review of the effects of plants on indoor environments, Indoor and Built Environment 30 (2021) 442–460.

[4] P. Julinova, D. Beckovsky, Perspectives of moss species in urban ecosystems and vertical living-architecture: A review, Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications (2019) 2370–2375.

[5] A.J. Ghazalli, C. Brack, X. Bai, I. Said, Alterations in use of space, air quality, temperature and humidity by the presence of vertical greenery system in a building corridor, Urban Forestry & Urban Greening 32 (2018) 177–184.

[6] Z. Azkorra, G. Pérez, J. Coma, L.F. Cabeza, S. Bures, J.E. Álvaro, A. Erkoreka, M. Urrestarazu, Evaluation of green walls as a passive acoustic insulation system for buildings, Applied Acoustics 89 (2015) 46–56. https://doi.org/10.1016/j.apacoust.2014.09.010.

[7] A. Balderrama, J. Kang, A. Prieto, A. Luna-Navarro, D. Arztmann, U. Knaack, Effects of Façades on urban acoustic environment and soundscape: A systematic review, Sustainability 14 (2022) 9670.

[8] B.D. Vanicela, M. Nebel, M. Stephan, C. Riethmüller, G.T. Gresser, Quantitative analysis of fine dust particles on moss surfaces under laboratory conditions using the example of Brachythecium rutabulum, Environmental Science and Pollution Research 28 (2021) 51763–51771.

[9] B.-G. Kim, M.-H. Yoon, J. Kim, J.-H. Oh, All-natural moss-based microstructural composites in deformable form for use as graffiti and artificial-porous-material replacement, Materials 15 (2022) 9053.

[10] G. Gecheva, Z. Petkova, S. Damyanov, D. Georgieva, V. Baev, M. Gozmanova, E. Apostolova-Kuzova, G. Yahubyan, Using Moss Walls for Air Quality Monitoring: Extending Their Utility Beyond Traditional Green Infrastructure, International Journal of Plant Biology 16 (2025) 44.

[11] B.M. Eldridge, L.R. Manzoni, C.A. Graham, B. Rodgers, J.R. Farmer, A.N. Dodd, Getting to the roots of aeroponic indoor farming, New Phytologist 228 (2020) 1183–1192.

[12] P.J. Irga, F.R. Torpy, M.D. Burchett, Can hydroculture be used to enhance the performance of indoor plants for the removal of air pollutants?, Atmospheric Environment 77 (2013) 267–271.

[13] Y. Shao, J. Li, Z. Zhou, Z. Hu, F. Zhang, Y. Cui, H. Chen, The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings, Building and Environment 195 (2021) 107766.
[14] N. Shushunova, E. Korol, E. Luzay, D. Shafieva, P. Bevilacqua, Ensuring the safety of buildings by reducing the noise impact through the use of green wall systems, Energies 15 (2022) 8097.
[15] M.W. Akram, S. Madhusudhanan, I. Chandramathy, S. Nallusamy, Mitigation of Urban Air Pollution Through Aeroponic Planting Methods: A Sustainable Approach, International Journal of Civil Engineering 11(8) (2024).
[16] A.A. Alvarado-Alvarado, W. Smets, P. Irga, S. Denys, Engineering green wall botanical biofiltration to abate indoor volatile organic compounds: A review on mechanisms, phyllosphere bioaugmentation, and modeling, Journal of Hazardous Materials 465 (2024) 133491.
[17] M.S. Montaluisa-Mantilla, P. García-Encina, R. Lebrero, R. Muñoz, Botanical filters for the abatement of indoor air pollutants, Chemosphere 345 (2023) 140483.
[18] T. Pettit, P.J. Irga, N.C. Surawski, F.R. Torpy, An assessment of the suitability of active green walls for NO2 reduction in green buildings using a closed-loop flow reactor, Atmosphere 10 (2019a) 801.
[19] F. Torpy, N. Clements, M. Pollinger, A. Dengel, I. Mulvihill, C. He, P. Irga, Testing the single-pass VOC removal efficiency of an active green wall using methyl ethyl ketone (MEK), Air Quality, Atmosphere & Health 11 (2018) 163–170.
[20] Y. Yungstein, D. Helman, Cooling, CO2 reduction, and energy-saving benefits of a green-living wall in an actual workplace, Building and Environment 236 (2023) 110220.
[21] S. Abedi, S.-A. Somayeh, S. Behshad, A.J. Joneidi, R. Yarahmadi, Thermal effects, experimental evaluation of evaporative cooling performance and energy efficiency of active botanical biofilter for indoor air treatment, Journal of Building Engineering (2025) 112950.
[22] P. Wang, Y.H. Wong, C.Y. Tan, S. Li, W.T. Chong, Vertical greening systems: Technological benefits, progresses and prospects, Sustainability 14 (2022) 12997.
[23] T. Pettit, P.J. Irga, F.R. Torpy, The in situ pilot-scale phytoremediation of airborne VOCs and particulate matter with an active green wall, Air Quality, Atmosphere & Health 12 (2019) 33–44.
[24] U.K. Priya, R. Senthil, Enhancing sustainable thermal comfort of tropical urban buildings with indoor plants, Buildings 14 (2024) 2353.
[25] M.J.M. Davis, M.J. Tenpierik, F.R. Ramírez, M.E. Perez, More than just a Green Facade: The sound absorption properties of a vertical garden with and without plants, Building and Environment 116 (2017) 64–72.
[26] J. Bakker, M. Lugten, M. Tenpierik, Applying vertical greening systems to reduce traffic noise in outdoor environments: Overview of key design parameters and research methods, Building Acoustics 30 (2023) 315–338.
[27] F. Borzabadi Farahani, J. Rahimi, S. Khoramipour, E. Dehghanifard, M. Alimohammadi, Environmental modulation enhances benzene phytoremediation by Aglaonema and Dracaena in indoor settings, Scientific Reports 15 (2025) 31559.
[28] A. Katoch, U.C. Kulshrestha, Deposition of anthropogenic secondary anions through indoor dust on Ficus elastica plants in Delhi, India, Arabian Journal of Geosciences 17 (2024) 112.
[29] A. Katoch, U.C. Kulshrestha, Seasonal variations of dustfall fluxes and biochemical parameters in the foliage of selected indoor plants in Delhi, India, International Journal of Phytoremediation 25 (2023) 917–928.

[30] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang, Potted plants can remove the pollutant nitrogen dioxide indoors, Air Quality, Atmosphere & Health 15 (2022) 479–490.
[31] Y. Dockx, M. Täubel, E.M. Bijnens, K. Witters, M. Valkonen, B. Jayaprakash, J. Hogervorst, T.S. Nawrot, L. Casas, Indoor green can modify the indoor dust microbial communities, Indoor Air 32 (2022) e13011.
[32] B.E. Cummings, M.S. Waring, Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies, Journal of Exposure Science & Environmental Epidemiology 30 (2020) 253–261.
[33] J. Ryu, J.J. Kim, H. Byeon, T. Go, S.J. Lee, Removal of fine particulate matter (PM2. 5) via atmospheric humidity caused by evapotranspiration, Environmental Pollution 245 (2019) 253–259.
[34] S. Yin, X. Zhang, A. Yu, N. Sun, J. Lyu, P. Zhu, C. Liu, Determining PM2. 5 dry deposition velocity on plant leaves: An indirect experimental method, Urban Forestry & Urban Greening 46 (2019) 126467.
[35] P.J. Irga, N.J. Paull, P. Abdo, F.R. Torpy, An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system, Building and Environment 115 (2017) 281–290.
[36] F. D'Alessandro, F. Asdrubali, N. Mencarelli, Experimental evaluation and modelling of the sound absorption properties of plants for indoor acoustic applications, Building and Environment 94 (2015) 913–923.
[37] F. Asdrubali, F. D'Alessandro, N. Mencarelli, K.V. Horoshenkov, Sound absorption properties of tropical plants for indoor applications, in: Proceedings of the 21st International Congress on Sound and Vibration, China, 2014.
[38] B.C. Wolverton, A. Johnson, K. Bounds, Interior landscape plants for indoor air pollution abatement, 1989.
[39] F. Liu, Q. Yuan, Y. Ren, X. Meng, Annual assessment of the active plant wall on indoor environment from summer, transition season and winter, Scientific Reports 15 (2025) 18198.
[40] N. Vivekanandan, K. Rajeswari, N.V. Kanna, A CFD-based assessment of Azolla biofilters for sustainable indoor air purification in low-carbon buildings, International Journal on Interactive Design and Manufacturing (IJIDeM) (2025) 1–14.
[41] D. Zhang, L. Zhang, Y. Zhang, Investigation of the indoor CO2 removal efficiency and fresh air energy savings of living walls in office spaces, Journal of Building Engineering 90 (2024) 109422.
[42] F.R. Torpy, M. Zavattaro, P.J. Irga, Green wall technology for the phytoremediation of indoor air: a system for the reduction of high CO2 concentrations, Air Quality, Atmosphere & Health 10 (2017) 575–585.
[43] R. Fleck, R.L. Gill, T. Pettit, P.J. Irga, N.L.R. Williams, J.R. Seymour, F.R. Torpy, Characterisation of fungal and bacterial dynamics in an active green wall used for indoor air pollutant removal, Building and Environment 179 (2020) 106987.
[44] I.Z. Ibrahim, W.-T. Chong, S. Yusoff, The design of the botanical indoor air biofilter system for the atmospheric particle removal, in: MATEC Web of Conferences, EDP Sciences, 2018: p. 02035.
[45] D. Tudiwer, A. Korjenic, The effect of an indoor living wall system on humidity, mould spores and CO2-concentration, Energy and Buildings 146 (2017) 73–86.
[46] K. Rodgers, R. Handy, W. Hutzel, Indoor air quality (IAQ) improvements using biofiltration in a highly efficient residential home, Journal of Green Building 8 (2013) 22–27.
[47] F.R. Torpy, P.J. Irga, M.D. Burchett, Profiling indoor plants for the amelioration of high CO2 concentrations, Urban Forestry & Urban Greening 13 (2014) 227–233.

[48] Y. Shao, J. Li, Z. Zhou, F. Zhang, Y. Cui, The impact of indoor living wall system on air quality: a comparative monitoring test in building corridors, Sustainability 13 (2021) 7884.

[49] F. Carotenuto, A. Bisignano, L. Brilli, G. Gualtieri, L. Giovannini, Low-cost air quality monitoring networks for long-term field campaigns: A review, Meteorological Applications 30 (2023) e2161.

[50] S. Taheri, A. Razban, Learning-based CO2 concentration prediction: Application to indoor air quality control using demand-controlled ventilation, Building and Environment 205 (2021) 108164.

[51] M. Jans-Singh, K. Leeming, R. Choudhary, M. Girolami, Digital twin of an urban-integrated hydroponic farm, Data-Centric Engineering 1 (2020) e20.

[52] A. Reyes Yanes, R. Abbasi, P. Martinez, R. Ahmad, Digital twinning of hydroponic grow beds in intelligent aquaponic systems, Sensors 22 (2022) 7393.

[53] B.G. Lee, K.H. Jeong, H.E. Kim, M.-K. Yeo, Machine learning models for predicting indoor airborne fungal concentrations in public facilities utilizing environmental variables, Environmental Pollution 368 (2025) 125684.

[54] H. Wu, J.W.C. Wong, Temperature versus relative humidity: Which is more important for indoor mold prevention?, Journal of Fungi 8 (2022) 696.

[55] X. Zhang, J. Yang, H. Qu, Z.G. Yu, D.K. Nandakumar, Y. Zhang, S.C. Tan, Machine-learning-assisted autonomous humidity management system based on solar-regenerated super hygroscopic complex, Advanced Science 8 (2021) 2003939.

[56] H. Lan, H.C. Hou, Z. Gou, M.S. Wong, Z. Wang, Computer vision-based smart HVAC control system for university classroom in a subtropical climate, Building and Environment 242 (2023) 110592.

[57] A. Toyoda, Y. Shibata, Y. Matsuo, K. Terada, H. Sugimoto, K. Higashi, H. Mori, A. Ikeuchi, M. Ito, K. Kurokawa, Diversity and compositional differences of the airborne microbiome in a biophilic indoor environment, Scientific Reports 13 (2023) 8179.

[58] L. Soininen, M.I. Roslund, N. Nurminen, R. Puhakka, O.H. Laitinen, H. Hyöty, A. Sinkkonen, Indoor green wall affects health-associated commensal skin microbiota and enhances immune regulation: a randomized trial among urban office workers, Scientific Reports 12 (2022) 6518.

[59] W.A. Wicaksono, T. Reisenhofer-Graber, S. Erschen, P. Kusstatscher, C. Berg, R. Krause, T. Cernava, G. Berg, Phyllosphere-associated microbiota in built environment: do they have the potential to antagonize human pathogens?, Journal of Advanced Research 43 (2023) 109–121.

[60] G. Berg, M. Grube, M. Schloter, K. Smalla, The plant microbiome and its importance for plant and human health, Frontiers Media SA, 2014b.

[61] B.C. Wolverton, J.D. Wolverton, Interior plants: their influence on airborne microbes inside energy-efficient buildings., (1996) 100–105.

[62] H.A. Burge, W.R. Solomon, M.L. Muilenberg, Evaluation of indoor plantings as allergen exposure sources, Journal of Allergy and Clinical Immunology 70 (1982) 101–108.

[63] S. de Vries, T. Hermans, F. Langers, Effects of indoor plants on office workers: a field study in multiple Dutch organizations, Frontiers in Psychology 14 (2023) 1196106.

[64] N. Van den Bogerd, S.C. Dijkstra, S.L. Koole, J.C. Seidell, J. Maas, Greening the room: A quasi-experimental study on the presence of potted plants in study rooms on mood, cognitive performance, and perceived environmental quality among university students, Journal of Environmental Psychology 73 (2021) 101557.

[65] N. Hähn, E. Essah, T. Blanusa, Biophilic design and office planting: a case study of effects on perceived health, well-being and performance metrics in the workplace, Intelligent Buildings International 13 (2021) 241–260.

[66] N. van den Bogerd, S.C. Dijkstra, K. Tanja-Dijkstra, M.R. de Boer, J.C. Seidell, S.L. Koole, J. Maas, Greening the classroom: Three field experiments on the effects of indoor nature on students' attention, well-being, and perceived environmental quality, Building and Environment 171 (2020) 106675.
[67] L.J. Holden, T. Mercer, Nature in the learning environment: Exploring the relationship between nature, memory, and mood, Ecopsychology 6 (2014) 234–240.
[68] J. Nakano, S.I. Tanabe, Prospects of thermal comfort in semi-outdoor environment: Application of thermal adaptation studies to thermal environmental planning in Japanese context, Journal of Environmental Engineering (Japan) 79 (2014) 597–606.
[69] M. Nieuwenhuis, C. Knight, T. Postmes, S.A. Haslam, The relative benefits of green versus lean office space: Three field experiments., Journal of Experimental Psychology: Applied 20 (2014) 199.
[70] C.J. Beukeboom, D. Langeveld, K. Tanja-Dijkstra, Stress-reducing effects of real and artificial nature in a hospital waiting room, The Journal of Alternative and Complementary Medicine 18 (2012) 329–333.
[71] M. Saffarinia, S. Tavakkoli, A. Alipor, Effects of environmental design inspired by nature on psychological and physiological responses of clients in medical spaces, International Journal of Environmental Research 6 (2012) 689–694.
[72] J.S. Doxey, T.M. Waliczek, J.M. Zajicek, The impact of interior plants in university classrooms on student course performance and on student perceptions of the course and instructor, HortScience 44 (2009) 384–391.
[73] S.-H. Park, R.H. Mattson, Ornamental indoor plants in hospital rooms enhanced health outcomes of patients recovering from surgery, The Journal of Alternative and Complementary Medicine 15 (2009) 975–980.
[74] S.-Y. Park, J.-S. Song, H.-D. Kim, K. Yamane, K.-C. Son, Effects of interior plantscapes on indoor environments and stress level of high school students, Journal of the Japanese Society for Horticultural Science 77 (2008) 447–454.
[75] V.I. Lohr, C.H. Pearson-Mims, G.K. Goodwin, Interior plants may improve worker productivity and reduce stress in a windowless environment, Journal of Environmental Horticulture 14 (1996) 97–100.
[76] R.S. Ulrich, R.F. Simons, B.D. Losito, E. Fiorito, M.A. Miles, M. Zelson, Stress recovery during exposure to natural and urban environments, Journal of Environmental Psychology 11 (1991) 201–230.
[77] E.-J. Lee, S.-J. Park, Strategic Biophilic Residential Design Based on Seniors' Health Profiles: A HRQoL-Driven Approach, Buildings 15 (2025) 1792.
[78] K. Halbmayer, J. Hollands, S. Alasu, A. Korjenic, B. Pichler, E. Reitinger, E. Zojer, B. Knoll, A. Renkin, R. Dopheide, GREEN: Cool & Care—Research and Development of Greening Measures in Nursing Homes in Austria. Technical and Social Interconnections, Sustainability 13 (2021) 11469.
[79] F. Liu, L. Yan, X. Meng, C. Zhang, A review on indoor green plants employed to improve indoor environment, Journal of Building Engineering 53 (2022) 104542. https://doi.org/10.1016/j.jobe.2022.104542.
[80] M. Tomkins, S. Yousef, A. Adam-Bradford, C. Perkins, E. Grosrenaud, M. Mctough, A. Viljoen, Cultivating refuge: The role of urban agriculture amongst refugees and forced migrants in the Kurdistan region of Iraq, Urban Agriculture and City Sustainability 131 (2019).
[81] O. Gocer, A. Ramezannia, C. Allison, The practical challenges of living wall implementations in Australia, Intelligent Buildings International (2025) 1–14.

[82] Y. Nasr, H. El Zakhem, A.E.A. Hamami, M. El Bachawati, R. Belarbi, Comprehensive assessment of the impact of green roofs and walls on building energy performance: a scientific review, Energies 17 (2024) 5160.
[83] F. Liu, X. Meng, Integrating the Living Wall with Mechanical Ventilation to Improve Indoor Thermal Environment in the Transition Season, Sustainability 16 (2024) 4300.
[84] B. Kotzen, E.R. Galea, S. Mosco, Z. Wang, J. Ewer, F. Jia, Fire safety risks of external living walls and implications for regulatory guidance in England, Fire Safety Journal 139 (2023) 103816.
[85] T.A. Moya, A. van den Dobbelsteen, M. Ottele, P.M. Bluyssen, Green air conditioning: Using indoor living wall systems as a climate control method, Rehva Journal (2017) 27–31.
[86] K. Gunawardena, K. Steemers, Urban living walls: reporting on maintenance challenges from a review of European installations, Architectural Science Review 63 (2020) 526–535.
[87] F. Ascione, R.F. De Masi, M. Mastellone, S. Ruggiero, G.P. Vanoli, Green walls, a critical review: Knowledge gaps, design parameters, thermal performances and multi-criteria design approaches, Energies 13 (2020) 2296.
[88] H. Wang, C. Lei, A numerical investigation of combined solar chimney and water wall for building ventilation and thermal comfort, Building and Environment 171 (2020) 106616.
[89] B. Riley, The state of the art of living walls: Lessons learned, Building and Environment 114 (2017) 219–232.
[90] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Building and Environment 46 (2011) 922–937.