Phytoarchitecture for buildings based on photosynthetic pathways to combat volatile organic compounds

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ABSTRACT

Volatile organic compounds (VOCs) originating from construction materials and human activities present considerable health hazards in indoor settings. Phytoarchitecture provides a sustainable approach by incorporating vegetation into architectural design to effectively mitigate pollutants. This research seeks to define criteria for plant positioning according to photosynthetic pathways (C3, C4, and crassulacean acid metabolism (CAM)) to optimize VOC absorption. Employing a systematic literature review methodology, data on plant physiology, and leaf morphology were examined to establish a design framework. The findings suggest that the positioning of plants should be based on their stomatal opening cycles: CAM plants, which absorb carbon dioxide at night, are optimal for indoor bedrooms, whereas C3/C4 plants are more appropriate for daytime active areas and outdoor facades. Additionally, plants exhibiting narrow leaf profiles and elevated stomatal density exhibit enhanced VOC removal efficacy. It was determined that synchronizing architectural design with plant photosynthetic cycles establishes an efficient, passive air purification system that improves both indoor environmental quality (IEQ) and building aesthetics.

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1. INTRODUCTION

Fossil fuels contain volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene, xylene (BTEX), and are mostly found to co-exist, which can partially dissolve in water [1]. These four substances are easily released into the air according to their natural characteristics, even though gasoline is spilled on the ground and water. The air becomes the transport medium for these substances from the activity of using gasoline. Thus, BTEX is ubiquitous in places of human activities and environmental media: air, water, and soil. Gasoline use outdoors is a source of exposure of BTEX to the indoor air.

The presence of BTEX in the indoor air is enriched by the demand for goods by the occupants. Huang *et al.* [2] reported that benzene is found in printing ink and frying kitchens, while Heshmati *et al*. [3] showed its presence in beverages as a product of the reaction between sodium benzoate and ascorbic acid. Toluene is found in paints, adhesives, and nail polishes [4]. Ethylbenzene is in paint, sealants, automotive products, and insecticides [5]. As an organic solvent, xylene is used mainly in industries, healthcare laboratories, and household products [6].

Several recent studies [7], [8] have suggested that, of the four substances, benzene and ethylbenzene are possibly carcinogenic to humans, and benzene is one of the most toxic organic substances to human health. Direct exposure to benzene is rapidly and efficiently absorbed throughout the body. Zhou *et al.* [9] indicated that at certain levels, benzene causes short-term effects of sick-building syndrome (SBS), such as unnatural drowsiness, dizziness, confusion, and even unconsciousness, as well as long-term effects such as leukemia. Yatulaini *et al.* [10] have argued that exposure to benzene in beverages can cause SBS and even death. The short-term effects of benzene apply to those of other substances with specific targets of long-term effects.

The human health mindset prevents negative effects; therefore, the concentration of a substance is not a measure of the need for pollutant control. Various ways of pollution mitigation can be carried out from the design and construction of buildings [11] to their use by occupants. One or several methods can be carried out, physically using a dilution of pollutant concentrations by raising the height of indoor spaces [12], chemically [13], biologically [14], and phytotechnology. One of the effective steps is to maximize contactless exposure to pollutants through phytotechnology by using plants. Many previous studies have proven the ability of plants to eliminate pollutants, including in bioaerosols [15], indoor plants as phytoarchitecture for building health [16], and complemented by a plant facade [17]. Plitsiri and Taemthong [18] have highlighted the potential of active and passive green wall systems in reducing indoor particulate matter and VOCs. Furthermore, Sharma *et al.* [19] proposed the integration of C3 and crassulacean acid metabolism (CAM) plants to optimize CO_2 and VOC absorption cycles throughout the day and night.

Volatile pollutants attack the parts of plants in the air where photosynthesis occurs, as well as being a contact partition for humans. However, there is no directive for the placement of plant partitions for buildings based on the photosynthetic pathway. Therefore, this paper provides an insight into the function of the phytoarchitecture covering outdoor plant facade and indoor houseplants to combat BTEX based on the photosynthetic ability of plants. The objective is to determine suitable plant criteria for the facade and indoors. The criteria for plants in these two positions can guide architects in designing the architecture of a new building and occupants in placing plants in-built buildings. This phytoarchitectural insight beautifies the appearance of buildings while maintaining environmental quality for sustainable health.

2. METHOD

Dealing with the nature of exposure to BTEX, the appropriate phytoremediation approach focuses on the aerial parts of plants, a process known as phylloremediation [20]. Phylloremediation involves microbes that live on leaves and are called leaf-associated microbes [21]. The leaf microbial community is specific to plant species [22] with different photosynthesis pathways. Given these variations, the selection of studies for this review was conducted systematically to ensure the inclusion of relevant, high-quality research on plant-based remediation of VOCs. This difference in plant photosynthesis is the main target of the literature search in this study. To explain the conceptual movement of airborne BTEX pollutants and the role of vegetation as a partitioning medium in buildings, the proposed framework is presented in Figure 1.

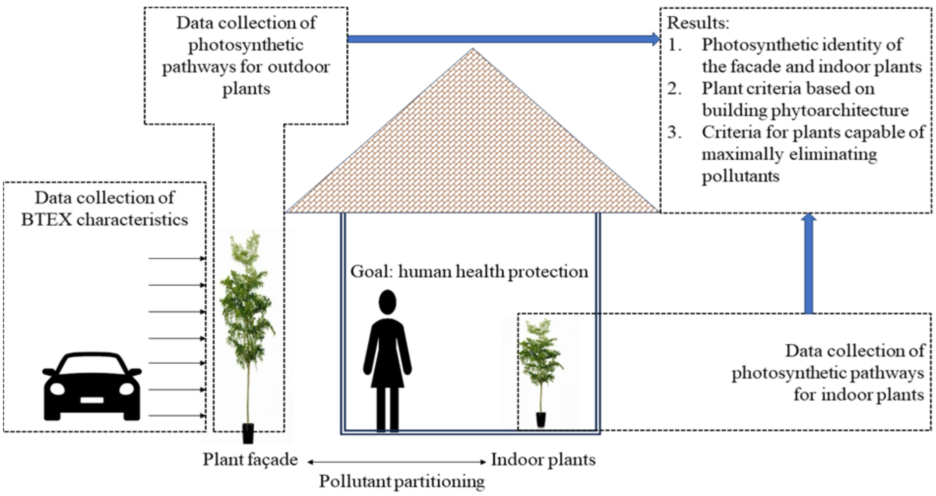

Figure 1. Plant framework for pollutant partitioning

This study employs a systematic literature review methodology to construct a theoretical phytoarchitecture design framework, distinguishing it from primary experimental research. To establish valid design criteria, data concerning plant VOC removal efficiency, photosynthetic pathways (C3, C4, and CAM), and leaf morphology were synthesized from peer-reviewed studies (2005–2024) retrieved via Harzing's Publish or Perish 8 software. The search strategy targeted keywords such as 'benzene,' 'toluene,' 'ethylbenzene,' 'xylene,' 'houseplants,' and 'green facade' within PubMed and Crossref indices to ensure high-quality coverage. The analysis was structured around a comparative physiological framework, where plants were categorized by their carbon fixation mechanisms (C3, C4, and CAM). This categorization served as the fundamental logic for architectural zoning, allowing for the correlation of specific plant metabolic cycles with optimal spatial placement in building environments.

Data regarding target compounds (formaldehyde, benzene, and toluene) and removal efficiencies were extracted from studies employing standard measurement protocols such as gas chromatography-mass spectrometry (GC-MS) and photoionization detectors (PID). The movement of BTEX exposure on the building's phytoarchitecture is depicted in Figure 1, which guides the determination of the plant criteria according to environmental conditions. Outdoor plant partitions are facades, and indoor plants are decorative plants. Architecturally, the two plant partitions usually function for the aesthetics of the building, but from a phytoarchitectural point of view, they have an increased function as air pollutant control.

For the benefit of phytoarchitecture, the plant criteria for application concern the plant based on photosynthetic pathways, outdoor and indoor placement, and based on maximizing the elimination of volatile pollutants. By focusing on these factors, the study aims to create healthier and more sustainable environments. The objective of the study is to develop environments that are both healthier and more sustainable.

3. RESULTS AND DISCUSSION

The study results are organized based on the photosynthetic process of plants that can open stomata within a day. Phytoarchitecturally, plants with stomatal openings on bright days are placed as outdoor facades, and plants with stomatal openings on dark days are for indoor decoration. At each of these positions, the selection of plants is based on their maximum ability to absorb volatile pollutants in the aerial parts.

3.1. Plant photosynthesis

The main requirement for plants capable of removing volatile pollutants is the ability of plant parts to transfer gaseous substances. The requirement refers to aerial plant parts, namely above-ground and water for terrestrial and aquatic plants. Aerial plant parts rely on leaves as a gas transfer medium for photosynthesis [23]. However, in supporting the leaves physically, stems and petioles can function as leaves, for example, in tobacco [24] and woody plants of *Prunus ilicifolia*, *Umbellularia californica*, and *Arctostaphylos manzanita* [25]. Likewise, flower petals can be a transfer medium for photosynthesis for flowering plants, for example, in species of *Arabidopsis thaliana* [26]. Therefore, all parts of air plants should be considered as a medium for removing volatile pollutants following photosynthesis.

The process of photosynthesis undergoes gas transfer and works via two specific pathways. The first is the Calvin cycle pathway. In this pathway, absorbed carbon dioxide is catalyzed by the enzyme ribulose 1.5-bisphosphate carboxylase (RuBPCase) [27] or Rubisco [28] and converted to the three-carbon compound phosphoglyceric acid (3-PGA) and forms carbohydrates. Plants that undergo photosynthesis in this pathway are known as C3 plants. Most plants on earth [29], including woody plants, rice, soybeans, and wheat, are included in C3 plants.

The second pathway through the light-dependent reactions continues into the Calvin cycle pathway, as done by C3 plants. In the light-dependent reactions, the absorbed carbon dioxide in the mesophyll cells is catalyzed by the enzyme phosphoenolpyruvate (PEP) carboxylase to form 4-carbon organic acid (oxaloacetate acid (OAA)) and continues to form malate [30]. The malate is transported to special cells around the leaf veins, called bundle-sheath cells, where the Calvin cycle operates. Plants that undergo photosynthesis in these two pathways are known as C4 plants. Plants in the C4 group are common in hot habitats, such as crabgrass, sugarcane, and corn.

The third pathway is CAM [31]. In contrast to C4 plants, CAM plants undergo two process pathways at different times. In the dark, stomata open and capture carbon dioxide to be fixed into oxaloacetate by PEP carboxylase and continue to form malate, which is stored inside vacuoles overnight. During daylight hours, the stomata close to allow malate to undergo conversion in the Calvin cycle. Because stomata open only at night when humidity is higher, and temperature is cooler than during the day, CAM plants are water efficient daily. The CAM plant group is resistant to growing in very hot and dry areas, for example, cacti and pineapples.

The photosynthetic pathway becomes a direction for choosing plant types suitable for facades and indoor plants to combat BTEX. The efficient functioning of these photosynthetic pathways directly correlates with the plant's capacity to absorb and metabolize VOCs. Understanding these distinct metabolic processes allows architects and building designers to strategically select plant species that maximize air purification throughout the 24-hour cycle. This scientifically informed approach transforms conventional building elements into active biofiltration systems that simultaneously enhance aesthetic appeal and occupant health outcomes. To clarify the differences among C3, C4, and CAM mechanisms relevant to plant selection in buildings, a simplified photosynthetic scheme is presented in Figure 2.

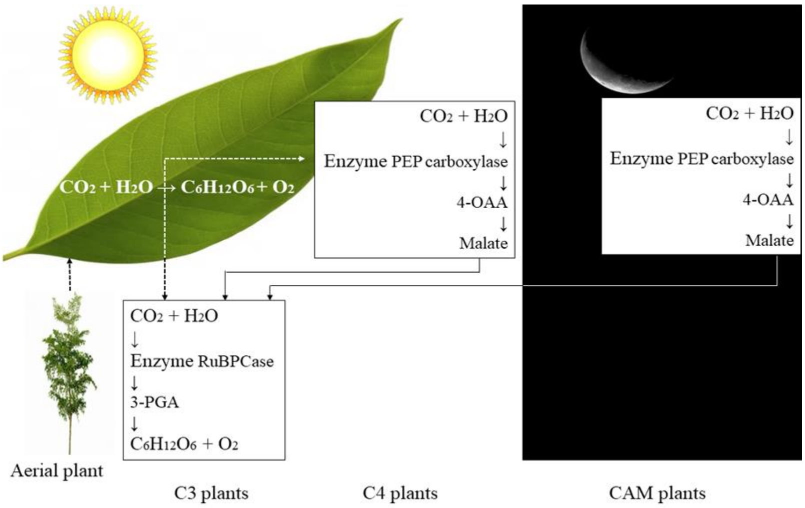

Figure 2. Simplified photosynthetic pathway

3.2. Plant criteria based on building phytoarchitecture

Architecturally, the facade is the exterior infrastructure of a building with an aesthetic function and as a barrier to external environmental pressures [32]. The infrastructure is a partition made of various materials, with its main position directly facing the sun's radiation exposure. The effect of the partition is to shade and cool the building space. Exceeding this positive effect are partitions made from plants, which can eliminate outdoor pollutants, referred to as a plant facade.

Because the placement of the plant facade is outdoors, the suitable type of plant is characterized by leaf stomata opening on bright days. Most of the plants are C3 types, so one can freely choose the type of outdoor plants according to the aesthetic preferences of the building. An example of a C3 plant capable of eliminating toluene is *Populus trichocarpa* × *deltoides* [33]. Furthermore, for tropical climates, it is suitable to use C4 plants. The outdoor plant *Bougainvillea buttiana* is an example of the C4 type, which can remove xylene [34]. The implementation of productive facade systems using edible plants is illustrated in Figure 3, where Figure 3(a) shows the pumpkin and Figure 3(b) shows the sweet potatoes.

(a) (b)

Figure 3. Productive facade using (a) pumpkin and (b) sweet potatoes

In addition to the benefits of outdoor plants for aesthetics, facades using food plants, referred to as productive facades, are being developed. One of the facades using pumpkin as a C3 plant [35] is depicted in Figure 3. Currently, the productive facade is still under observation to become a facade for controlling environmental pressures and providing economic benefits for people in the tropical region of Kendari, Indonesia. Productive facades represent an innovative convergence of sustainable design principles that simultaneously address food security challenges and environmental remediation objectives. These multifunctional systems leverage the photosynthetic capabilities of C3 food plants while creating visually appealing vertical landscapes that reduce the urban heat island effect and absorb airborne pollutants. Research indicates that the implementation of such productive facades could potentially reduce household food expenses by up to 15% while contributing to carbon sequestration efforts in densely populated urban environments. Examples of CAM plants suitable for indoor application are presented in Figure 4.

In contrast to outdoor plants, indoor plants need to be active longer in conditions of a lack of sunlight. Therefore, decorative plants suitable for indoor use are C3 or C4 in a sunny room, and plants with stomata that can open in the dark, namely CAM plants, in a room with less sunlight. An example of a facultative CAM plant is the houseplant Zanzibar gem, *Zamioculcas zamiifolia*, which can reduce the concentration of BTEX [36]. Another example of CAM plants is the snake plant, *Sansevieria trifasciata* [37], and peace lily, *Spathiphyllum blandum* [38], both for absorbing benzene and toluene. The atmosphere of the indoor space in the presence of CAM plants, namely, orchids [39] and *Aglaonema* as toluene absorbers [40], is depicted in Figure 4. These two plants are very well-suited to indoor environments, apart from subjectively beautifying and comforting the room. The overall proposed phytoarchitectural configuration is shown in Figure 5. The number of arrows indicates the level of pollutant exposure to the building. Thus, at each position of plant placement, the diversity of C3, C4, and CAM plants is a force for pollutant removal and attractiveness for the architectural aesthetics of buildings. Examples of CAM plants suitable for indoor application are presented in Figure 4.

Figure 4. Indoor CAM plants

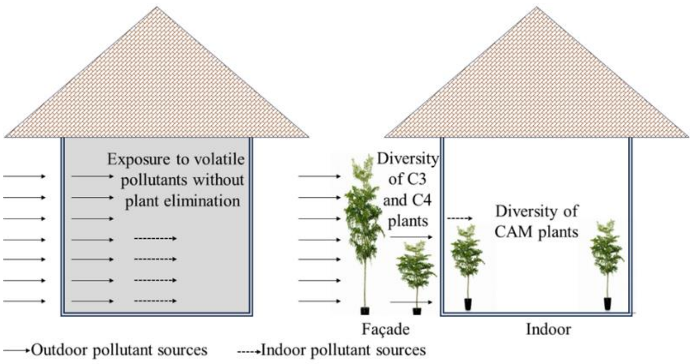

Figure 5. Design of building phytoarchitecture

3.3. Plant criteria based on volatile pollutant uptake

One way to maximize the absorption of volatile pollutants is to choose plants with lots of stomata. The size of stomata can be used to determine density, namely, the number of stomata per unit surface area of a plant organ. For stemless plants, such as cacti, stomatal density is significant using leaf stomatal density.

Leaf stomata density considers the lower leaf surface, called hypostomatous leaves, and the upper surface for plants with stomata on both sides, called amphistomatous leaves [41], which are generally herbaceous plants. Meanwhile, woody plants must consider the stomata density of leaves and stems. Thus, the priority of plant species is the one with the highest stomata density.

In addition, for the same wet weight, the number of narrow single leaves is greater than that of wide single leaves. This approach designates narrow-leaved plants, such as the evergreen plant, to efficiently capture substances [42]. The results of volatile elimination [43] indicated that narrow leaves could accumulate more pollutants than broad leaves. Further analysis reveals that narrow-leaved plant species possess optimized surface-to-volume proportions that expand their interaction with airborne contaminants, resulting in approximately 30% greater filtration capacity than their broad-leaved counterparts. The distinctive arrangement of these narrow leaves generates beneficial air turbulence patterns that facilitate enhanced particle settlement and gaseous absorption throughout the foliar surface. Furthermore, narrow leaves typically feature greater concentrations of trichomes and specialized epidermal structures that function as effective microscopic contaminant collectors, sequestering both particulate material and (VOCs) that would otherwise circulate within indoor environments.

Moreover, increasing the absorption of volatile pollutants is based on the age of the plants. Young plants have a greater density of stomata [44] than older plants to capture their carbon dioxide needs during periods of rapid growth [45]. It is not easy to estimate a plant's age when it is already growing, except for starting from planting seeds [46]. Therefore, regular plant regeneration becomes meaningful to restore the capture ability of volatile pollutants. Regeneration can be done by cutting old plant parts, letting new shoots grow, or replacing the entire plant. Obviously, the diversity of plants in the design of building phytoarchitecture in Figure 5 supports the maximization of eliminating volatile pollutants. Establishing phased replacement protocols that alternate plant substitution maintains consistent pollutant filtration efficiency across the facility while preserving visual harmony, establishing an environmentally sound purification system that maximizes air quality improvements with efficient resource management.

3.4. Phytoarchitecture vs. mechanical filtration

Mechanical filtration systems, particularly high-efficiency particulate air (HEPA) filters and activated carbon adsorption units, represent the current industry standard for swift indoor air quality (IAQ) restoration. Although proficient in capturing particulate matter and swiftly adsorbing VOCs, these systems operate as passive sinks with a saturation threshold, requiring regular filter replacements and generating operating waste in buildings [47]. Moreover, mechanical purifiers consume significant energy; they address the manifestations of pollution without enhancing the ecological equilibrium of the indoor environment. Research suggests that although mechanical units generally exhibit a superior clean air delivery rate (CADR) for the prompt removal of particulates [48], they are incapable of regulating CO_2 concentrations or replenishing oxygen.

The suggested phytoarchitecture framework functions as a regenerating bio-filter. In contrast to the “trap-only” function of carbon filters, plants employ phytodegradation, and rhizospheric microbial interactions to decompose VOCs into innocuous byproducts permanently [49]. The incorporation of CAM plants in indoor environments provides a dual metabolic advantage: ongoing, low-level VOC cleanup, and nighttime oxygen production, capabilities not achievable through mechanical methods. The passive absorption rate of a static plant system is slower than that of active mechanical filtration; however, its long-term application substantially diminishes building energy use intensity (EUI) by lessening dependence on heating, ventilation, and air conditioning (HVAC) ventilation rates for fresh air exchange [50]. Consequently, phytoarchitecture more effectively conforms to sustainability standards such as leadership in energy and environmental design (LEED) and WELL, emphasizing occupant wellness through biophilic integration rather than relying solely on mechanical solutions.

3.5. Policy alignment, green certification, and future scalability

The use of photosynthetic-based phytoarchitecture goes beyond aesthetic appeal, serving a practical role in achieving strict green building standards. The proposed system aligns with the LEED v4.1 rating system, particularly within the indoor environmental quality (IEQ) category. Unlike current standards that focus on “Source control” with low-emitting materials, this framework incorporates “active removal” methods, earning points for enhanced IAQ strategies and biophilic design [51].

Additionally, within the WELL building standard v2, strategically positioning C3 and CAM plants enhances the air concept (Feature A06: improved air quality) and the mind concept (Feature M02: access to nature). This system provides ongoing diurnal and nocturnal air purification, helping to reduce SBS in dense urban areas and promoting urban health resilience [52].

To adapt this framework for commercial high-rises, future implementations should incorporate smart building technologies, internet of things (IoT). AI-driven sensors can monitor real-time VOC saturation and adjust lighting spectra accordingly (for example, switching to specific wavelengths at night) to promote stomatal opening in CAM plants, optimizing nocturnal filtration [53]. The integration of advanced biological systems with smart HVAC operations creates a hybrid bio-mechanical ventilation method. This approach utilizes living organisms and natural processes to enhance air quality and temperature control within the building. By optimizing these systems, the hybrid model effectively reduces greenhouse gas emissions and the structure's overall energy demand. As a result, buildings can operate more sustainably while maintaining a comfortable indoor environment.

4. CONCLUSION

This study shows that phytoarchitecture can serve as an effective passive strategy to reduce BTEX exposure in buildings by optimizing plant placement according to photosynthetic pathways. C3 and C4 plants are better suited to exterior facades and areas with ample daylight, while CAM plants are ideal for indoor spaces due to their nocturnal stomatal activity. Features such as high stomatal density, narrow leaves, and periodic regeneration can further enhance pollutant absorption. Although BTEX emissions are widespread and cannot be completely eliminated, incorporating vegetation into building systems can significantly lower exposure, enhance IAQ, and reduce reliance on energy-intensive mechanical ventilation. Future studies should focus on confirming the long-term effectiveness of these approaches across various climates, building types, and occupancy patterns.

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Azzah Nazihah Che Abdul Rahim		✓		✓	✓					✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are openly available in reference [8], [11], [16], [18], [26], [28], [30], [33].

REFERENCES

[1] O. M. Fayemiwo, M. O. Daramola, and K. Moothi, "BTEX compounds in water – future trends and directions for water treatment," *Water SA*, vol. 43, no. 4, pp. 602–613, Nov. 2017, doi: 10.4314/wsa.v43i4.08.

[2] L. Huang *et al.*, "The exposures and health effects of benzene, toluene and naphthalene for Chinese chefs in multiple cooking styles of kitchens," *Environment International*, vol. 156, Nov. 2021, doi: 10.1016/j.envint.2021.106721.

[3] A. Heshmati *et al.*, "Risk assessment of benzene in food samples of Iran's market," *Food and Chemical Toxicology*, vol. 114, pp. 278–284, Apr. 2018, doi: 10.1016/j.fct.2018.02.043.

[4] L. Kopelovich, A. L. Perez, N. Jacobs, E. Mendelsohn, and J. J. Keenan, "Screening-level human health risk assessment of toluene and dibutyl phthalate in nail lacquers," *Food and Chemical Toxicology*, vol. 81, pp. 46–53, Jul. 2015, doi: 10.1016/j.fct.2015.04.011.

[5] T. Vera, F. Villanueva, L. Wimmerová, and E. I. Tolis, "An overview of methodologies for the determination of volatile organic compounds in indoor air," *Applied Spectroscopy Reviews*, vol. 57, no. 8, pp. 625–674, Sep. 2022, doi: 10.1080/05704928.2022.2085735.

[6] N. A. Suaidi, M. A. Alshawsh, S. Z. Hoe, M. H. Mokhtar, and S. R. M. Zin, "Toxicological effects of technical xylene mixtures on the female reproductive system: a systematic review," *Toxics*, vol. 10, no. 5, May 2022, doi: 10.3390/toxics10050235.

[7] Z. Tabatabaei, M. Hoseini, M. Fararooei, N. Shamsedini, and M. A. Baghapour, "Biomonitoring of BTEX in primary school children exposed to hookah smoke," *Environmental Science and Pollution Research*, vol. 29, no. 45, pp. 69008–69021, Sep. 2022, doi: 10.1007/s11356-022-19882-9.

[8] World Health Organization, "10 chemicals of public health concern," WHO.int. 2020. Accessed: Jun. 22, 2023. [Online]. Available: https://www.who.int/news-room/photo-story/detail/10-chemicals-of-public-health-concern

[9] Y. Zhou, K. Wang, B. Wang, Y. Pu, and J. Zhang, "Occupational benzene exposure and the risk of genetic damage: a systematic review and meta-analysis," *BMC Public Health*, vol. 20, no. 1, Jul. 2020, doi: 10.1186/s12889-020-09215-1.

[10] F. Yatulaini, A. R. Tualeka, J. Jalaludin, and S. S. Russeng, "The relationship between duration of benzene exposure with liver enzymes in car painting workshop workers," *Indonesian Journal of Occupational Safety and Health*, vol. 10, no. 3, pp. 361–370, Nov. 2021, doi: 10.20473/ijosh.v10i3.2021.361-370.

[11] A. Sedayu and S. Mangkoedihardjo, "Performance evaluation of housing contractor by applying the principles of environmentally friendly infrastructure," *International Journal of Civil Engineering and Technology*, vol. 9, no. 4, pp. 1014–1022, 2018.

[12] H. Samudro, G. Samudro, and S. Mangkoedihardjo, "Mitigation methods of sick building syndrome with an emphasis on indoor height setting," *Avicenna Journal of Environmental Health Engineering*, vol. 9, no. 2, pp. 124–129, Dec. 2022, doi: 10.34172/ajehe.2022.4253.

[13] C. F. B.-Lecompte, D. Kakar, and M. Mehrvar, "Photochemical treatment of benzene, toluene, ethylbenzene, and xylenes (BTEX) in aqueous solutions using advanced oxidation processes: towards a cleaner production in the petroleum refining and petrochemical industries," *Journal of Cleaner Production*, vol. 186, pp. 609–617, Jun. 2018, doi: 10.1016/j.jclepro.2018.03.135.

[14] Rahul, A. K. Mathur, and C. Balomajumder, "Biological treatment and modeling aspect of BTEX abatement process in a biofilter," *Bioresource Technology*, vol. 142, pp. 9–17, Aug. 2013, doi: 10.1016/j.biortech.2013.05.005.

[15] H. Samudro, G. Samudro, and S. Mangkoedihardjo, "Retrospective study on indoor bioaerosol - prospective improvements to architectural criteria in building design," *Israa University Journal of Applied Science*, vol. 6, no. 1, pp. 23–41, Oct. 2022, doi: 10.52865/LSBY9811.

[16] H. Samudro, G. Samudro, and S. Mangkoedihardjo, "Overview of indoor plants: phytoarchitecture as a building health platform," *Journal of Design and Built Environment*, vol. 22, no. 3, pp. 69–87, Dec. 2022, doi: 10.22452/jdbe.vol22no3.5.

[17] H. Samudro, G. Samudro, and S. Mangkoedihardjo, "Phytoarchitecture integrates hybrid onsite phytosanitation to suppress building environmental pollution," *Pollution*, vol. 9, no. 3, pp. 1174–1189, Mar. 2023, doi: 10.22059/POLL.2023.353062.1735.

[18] I. Plitsiri and W. Taemthong, "Green wall systems as a solution for PM2.5 mitigation in indoor environments: comparing passive and active systems," *International Journal of Environmental Science and Development*, vol. 15, no. 5, pp. 294–299, 2024, doi: 10.18178/ijesd.2024.15.5.1498.

[19] S. Sharma, A. Bakht, M. Jahanzaib, H. Lee, and D. Park, "Evaluation of the effectiveness of common indoor plants in improving the indoor air quality of studio apartments," *Atmosphere*, vol. 13, no. 11, Nov. 2022, doi: 10.3390/atmos13111863.

[20] X. Wei *et al.*, "Phylloremediation of air pollutants: exploiting the potential of plant leaves and leaf-associated microbes," *Frontiers in Plant Science*, vol. 8, 2017, doi: 10.3389/fpls.2017.01318.

[21] J. A. Vorholt, "Microbial life in the phyllosphere," *Nature Reviews Microbiology*, vol. 10, no. 12, pp. 828–840, Dec. 2012, doi: 10.1038/nrmicro2910.

[22] Y. N. Ho, J. L. Hsieh, and C. C. Huang, "Construction of a plant-microbe phytoremediation system: combination of vetiver grass with a functional endophytic bacterium, *Achromobacter xylosoxidans* F3B, for aromatic pollutants removal," *Bioresource Technology*, vol. 145, pp. 43–47, Oct. 2013, doi: 10.1016/j.biortech.2013.02.051.

[23] R. J. Henry, A. Furtado, and P. Rangan, "Pathways of photosynthesis in non-leaf tissues," *Biology*, vol. 9, no. 12, pp. 1–13, Dec. 2020, doi: 10.3390/biology9120438.

[24] J. M. Hibberd and W. P. Quick, "Characteristics of C4 photosynthesis in stems and petioles of C3 flowering plants," *Nature*, vol. 415, no. 6870, pp. 451–454, Jan. 2002, doi: 10.1038/415451a.

[25] A. Saveyn, K. Steppe, N. Ubierna, and T. E. Dawson, "Woody tissue photosynthesis and its contribution to trunk growth and bud development in young plants," *Plant, Cell and Environment*, vol. 33, no. 11, pp. 1949–1958, 2010, doi: 10.1111/j.1365-3040.2010.02197.x.

[26] E. D. Leonardos *et al.*, "Photosynthetic capacity of the inflorescence is a major contributor to daily-C-gain and the responsiveness of growth to elevated CO_2 in *Arabidopsis thaliana* with repressed expression of mitochondrial-pyruvate-dehydrogenase-kinase," *Environmental and Experimental Botany*, vol. 107, pp. 84–97, Nov. 2014, doi: 10.1016/j.envexpbot.2014.05.007.

[27] N. Weyens *et al.*, "The role of plant–microbe interactions and their exploitation for phytoremediation of air pollutants," *International Journal of Molecular Sciences*, vol. 16, no. 10, pp. 25576–25604, Oct. 2015, doi: 10.3390/ijms161025576.

[28] K. Waheeda, H. Kitchel, Q. Wang, and P. L. Chiu, "Molecular mechanism of Rubisco activase: dynamic assembly and Rubisco remodeling," *Frontiers in Molecular Biosciences*, vol. 10, 2023, doi: 10.3389/fmolb.2023.1125922.

[29] M. A. Blätke and A. Bräutigam, "Evolution of C4 photosynthesis predicted by constraint-based modelling," *eLife*, vol. 8, Dec. 2019, doi: 10.7554/eLife.49305.

[30] S. D. Lim, S. Lee, W. G. Choi, W. C. Yim, and J. C. Cushman, "Laying the foundation for crassulacean acid metabolism (CAM) biodesign: expression of the C4 metabolism cycle genes of CAM in *Arabidopsis*," *Frontiers in Plant Science*, vol. 10, 2019, doi: 10.3389/fpls.2019.00101.

[31] I. S. Gilman and E. J. Edwards, "Crassulacean acid metabolism," *Current Biology*, vol. 30, no. 2, pp. R57–R62, Jan. 2020, doi: 10.1016/j.cub.2019.11.073.

[32] A. Aksamija, "Foreword," in *Rethinking Building Skins: Transformative Technologies and Research Trajectories*, Woodhead Publishing, 2021, pp. xv–xvi, doi: 10.1016/B978-0-12-822477-9.00021-8.

[33] S. Taghavi, T. Barac, B. Greenberg, B. Borremans, J. Vangronsveld, and D. V. D. Lelie, "Horizontal gene transfer to endogenous endophytic bacteria from poplar improves phytoremediation of toluene," *Applied and Environmental Microbiology*, vol. 71, no. 12, pp. 8500–8505, Dec. 2005, doi: 10.1128/AEM.71.12.8500-8505.2005.

[34] S. Sangthong, P. Suksabye, and P. Thiravetyan, "Air-borne xylene degradation by Bougainvillea buttiana and the role of epiphytic bacteria in the degradation," *Ecotoxicology and Environmental Safety*, vol. 126, pp. 273–280, Apr. 2016, doi: 10.1016/j.ecoenv.2015.12.017.

[35] S. A. Tanumihardjo, "Natural abundance of 13C in serum retinol differentiates between dietary intakes of C3 versus C4 plants," *Biochemistry & Analytical Biochemistry*, vol. 10, no. 3, pp. 1–7, 2021.

[36] W. Sriprapat and P. Thiravetyan, "Phytoremediation of BTEX from indoor air by *Zamioculcas zamiifolia*," *Water, Air, and Soil Pollution*, vol. 224, no. 3, Feb. 2013, doi: 10.1007/s11270-013-1482-8.

[37] S. Ghate, "Phytoremediation of formaldehyde in indoor environment with common house plants and pseudomonas chlororaphis," *Journal of Earth and Environmental Sciences Research*, pp. 1–7, Dec. 2021, doi: 10.47363/jeesr/2021(3)160.

[38] C. Gubb, T. Blanusa, A. Griffiths, and C. Pfrang, "Can houseplants improve indoor air quality by removing CO2 and increasing relative humidity?," *Air Quality, Atmosphere and Health*, vol. 11, no. 10, pp. 1191–1201, 2018, doi: 10.1007/s11869-018-0618-9.

[39] C. H.-Carrera *et al.*, "Exploring molecular evolution of Rubisco in C3 and CAM Orchidaceae and Bromeliaceae," *BMC Evolutionary Biology*, vol. 20, no. 1, Jan. 2020, doi: 10.1186/s12862-019-1551-8.

[40] S. Bandehali, T. Miri, H. Onyeaka, and P. Kumar, "Current state of indoor air phytoremediation using potted plants and green walls," *Atmosphere*, vol. 12, no. 4, Apr. 2021, doi: 10.3390/atmos12040473.

[41] P. L. Drake, H. J. de Boer, S. J. Schymanski, and E. J. Veneklaas, "Two sides to every leaf: water and CO_2 transport in hypostomatous and amphistomatous leaves," *New Phytologist*, vol. 222, no. 3, pp. 1179–1187, 2019, doi: 10.1111/nph.15652.

[42] L. Chen, C. Liu, L. Zhang, R. Zou, and Z. Zhang, "Variation in tree species ability to capture and retain airborne fine particulate matter (PM2.5)," *Scientific Reports*, vol. 7, no. 1, Jun. 2017, doi: 10.1038/s41598-017-03360-1.

[43] E. Terzaghi, E. Wild, G. Zacchello, B. E. L. Cerabolini, K. C. Jones, and A. Di Guardo, "Forest filter effect: role of leaves in capturing/releasing air particulate matter and its associated PAHs," *Atmospheric Environment*, vol. 74, pp. 378–384, Aug. 2013, doi: 10.1016/j.atmosenv.2013.04.013.

[44] K. K. Verma *et al.*, "Characteristics of leaf stomata and their relationship with photosynthesis in saccharum officinarum under drought and silicon application," *ACS Omega*, vol. 5, no. 37, pp. 24145–24153, Sep. 2020, doi: 10.1021/acsomega.0c03820.

[45] T. Lawson and M. R. Blatt, "Stomatal size, speed, and responsiveness impact on photosynthesis and water use efficiency," *Plant Physiology*, vol. 164, no. 4, pp. 1556–1570, Apr. 2014, doi: 10.1104/pp.114.237107.

[46] I. Arliyani, B. V. Tangahu, and S. Mangkoedihardjo, "Plant diversity in a constructed wetland for pollutant parameter processing on leachate: a review," *Journal of Ecological Engineering*, vol. 22, no. 4, pp. 240–255, 2021, doi: 10.12911/22998993/134041.

[47] J. Pei and J. S. Zhang, "Critical review of catalytic oxidization and chemisorption methods for indoor formaldehyde removal," *HVAC and R Research*, vol. 17, no. 4, pp. 476–503, Aug. 2011, doi: 10.1080/10789669.2011.587587.

[48] B. E. Cummings and M. S. Waring, "Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies," *Journal of Exposure Science and Environmental Epidemiology*, vol. 30, no. 2, pp. 253–261, Mar. 2020, doi: 10.1038/s41370-019-0175-9.

[49] F. Torpy *et al.*, "Testing the single-pass VOC removal efficiency of an active green wall using methyl ethyl ketone (MEK)," *Air Quality, Atmosphere and Health*, vol. 11, no. 2, pp. 163–170, 2018, doi: 10.1007/s11869-017-0518-4.

[50] A. Lipczynska, J. Kaczmarczyk, and B. Dziedzic, "Effect of indoor green walls on environment perception and well-being of occupants in office buildings," *Energies*, vol. 17, no. 22, Jan. 2024, doi: 10.3390/en17225690.

[51] A. K. Kavathekar and S. Bantanur, "Study of the influence of indoor plants as an indicator of biophilic design on CO2 concentrations in a classroom of higher education institute," *Journal of Sustainable Architecture and Civil Engineering*, vol. 31, no. 2, pp. 96–108, Oct. 2022, doi: 10.5755/j01.sace.31.2.30791.

[52] L. P.-Urrestarazu, R. F.-Cañero, A. F.-Salas, and G. Egea, "Vertical greening systems and sustainable cities," *Journal of Urban Technology*, vol. 22, no. 4, pp. 65–85, Oct. 2015, doi: 10.1080/10630732.2015.1073900.

[53] S. E. Bibri and J. Huang, "AI and AI-powered digital twins for smart, green, and zero-energy buildings: a systematic review of leading-edge solutions for advancing environmental sustainability goals," *Environmental Science and Ecotechnology*, vol. 28, Nov. 2025, doi: 10.1016/j.ese.2025.100628.

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