Healthy building phytoarchitecture requires essential criteria for sustainable phylloremediation of contaminated indoor air

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Article Info

Article history:

Received Dec 23, 2023
Revised Jun 14, 2024
Accepted Jun 19, 2024

Keywords:

Air pollution
Healthy
Housing
Leaves
Mitigation
Plants

ABSTRACT

Various ambient air contaminants can spread into the indoor building through air transport. With the additional generation of contaminants from indoor activities, indoor air quality (IAQ) has the potential to be polluted. Indoor air pollution incidents can occur anytime, which is difficult to predict. Therefore, it is necessary to take action to improve IAQ as early as possible and sustainably. The solution to sustainable remediation is using plants to apply phylloremediation, which functions as leaves and leaf-associated microbial communities to reduce air contaminants. This study aims to provide new practical yet essential criteria for the sustainable operation of phylloremediation. This review is based on the latest results of a literature-based study. An analysis of the fundamental processes of plant life forms the basis for obtaining these criteria. The study emphasizes key criteria for phylloremediation encompassing the selecting plants with high transpiration and leaf-microbe synergy, and conducting maintenance by spraying water on leaves. These measures optimize efficiency and sustain the process for indoor air pollutant reduction. The final result summarises the new criteria for sustainable phylloremediation to maintain plant life. These essential criteria can be used for conducting experiments in empirical research, indoor design, and education for the community.

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1. INTRODUCTION

Greenspace is an essential infrastructure for the built environment to maintain the balance of the ecosystem from the point of view of material and energy input and output, such as contaminants. As a result of the dynamic characteristics of the ecosystem, many contaminants exist in different compartments, i.e., air, water, and soil. These contaminants at a certain concentration level pose a health risk to living organisms known as contaminants [1]. However, the living organisms of plants can eliminate contaminants naturally and sustainably, which directs the essential need for green space. Therefore, the provision of formal greenspaces, apart from their informal existence as wild plants, in urban areas is becoming increasingly crucial for contaminant elimination purposes. Furthermore, indoor environments represent intricate ecosystems with abiotic and biotic components, where the balance of gas emissions and absorption significantly influences air quality and occupant health. Despite the natural propensity of plants to absorb gases, there exists a gap in translating this potential into effective indoor phytoremediation practices, especially concerning architectural design and occupant engagement. Subsequent sections will elucidate our proposed criteria for sustainable indoor phytoremediation, highlighting their relevance in enhancing indoor air quality (IAQ) and ensuring the well-being of building occupants. Through a comprehensive analysis of existing literature and emerging trends, we will demonstrate the efficacy and feasibility of our proposed approach.

The method of improving the quality of a polluted environment using plants, known as phytoremediation has been successfully applied to various environmental media and life activities. Some of the successes of phytoremediation include the remediation of land polluted by organic leachate from the results of waste disposal activities [2], [3], the remediation of waters polluted by inorganic substances from the results of industrial activities [4], and the remediation of air polluted with volatile gases from motorized vehicle emissions [5], [6]. All of these phytoremediation successes are identified by fulfilling the basic needs of plant life while processing contaminants. Meeting the basic needs of water, nutrients, and sunlight, as well as the plant-associated microbial community, is the principal criterion for applying phytoremediation. In addition, various outdoor contaminants are also present in the indoor air of buildings, primarily gaseous contaminants, because they are in equilibrium with the outdoor air, both carried convectively or diffusively. IAQ refers to the condition of indoor air impacting occupants' health, potentially posing risks due to pollutants and building materials, such as respiratory ailments [7]. Meanwhile, indoor activities produce gas contaminants from household activities and the use of room facilities and building materials. Some examples are kitchen space [8] and commercial services [9], offices [10], and social services [11]. Moreover, since humans live the longest in indoor environments [12], [13], there is a high potential for adverse effects of gaseous contaminants in indoor air on the occupants. Perspectively, indoors can be viewed as a small-scale world ecosystem with abiotic and biotic components [14]. The completeness and diversity of abiotic and biotic elements determine the interactions between elements and produce indoor ecosystem quality [15]. Furthermore, the balance of the interaction of gas emission and absorption indoors produces IAQ and determines the health of the occupants [16]. Therefore, the intensification approach to placing gas absorber elements is an urgent and priority solution to maximize gas absorption and reduce occupant exposure. Likewise, active absorbers for indoor gas are plants because of their natural properties mentioned above, apart from being an essential biotic element of the ecosystem [17], their ability as an aesthetic and comfort function [18], and the affordability of their provision by occupants. Thus, the existence and provision of decorative plants as a phytostructure of buildings [12] direct the importance and necessity of their utilization as indoor air phytoremediation functions. More specifically, the elements of plant parts, i.e., leaves and leaf-associated microbes, can process gaseous contaminants. The treatment of contaminants to improve air quality by microbes is known as bioremediation. Bioremediation on the leaf surface is nothing less than phylloremediation [19]. In brief, phytoremediation, employing plants to clean up pollution, has proven effective both outdoors and indoors by addressing plants' needs and leveraging their natural properties, including leaf-associated microbes, to process gaseous contaminants. Hence, it presents a promising solution for improving air quality and reducing pollution in various environments.

There was a lack of helpful direction in applying phylloremedition from the architectural design of a building to its application by occupants. For example, the indoor design also determines the ease of occupants in treating decorative plants to improve IAQ. In addition, a technical yet simple guide can successfully implement indoor phytoarchitecture. This article contributes to addressing the complexities of indoor air pollution by advocating for effective solutions, notably through leveraging plants for indoor phytoremediation. Building upon the successful application of phytoremediation in outdoor settings and recognizing the significance of urban greenspaces, it underscores the pressing issue of indoor gaseous contaminants, their sources, and associated health risks. By acknowledging indoor spaces as intricate ecosystems, the article emphasizes the imperative to optimize IAQ for occupant well-being, thus positioning plants as viable agents for phytoremediation. However, challenges such as the lack of guidance for integrating phylloremediation into architectural design and practical implementation strategies remain prevalent. To overcome these obstacles, the proposed solution involves establishing essential criteria for sustainable indoor phylloremediation, integrating phylloremediation principles into architectural planning, and providing accessible guidelines for occupants. Ultimately, the overarching objective is to enhance IAQ, safeguard occupant health, and foster sustainability within indoor environments. The criteria also strengthen the primary criteria for the basic principles of phytoremediation above.

2. RESEARCH METHOD

2.1. Study idea

Determination of the essential criteria for sustainable phylloremediation operations refers to the activity of living plants through the stoichiometry of living organisms [20] as shown in Figure 1. Living plants as the primary criterion for phytoremediation work by following the stoichiometry. At a glance, the process of photosynthesis is marked with an arrow to the left. In which, the rate of photosynthesis is equal to and more significant than the respiration rate. In addition, an arrow to the right indicates the process of respiration. Moreover, through a literature review and experimental investigations, the study will analyze the role of photosynthesis and respiration in plants, exploring how these processes influence the effectiveness of phylloremediation. By elucidating optimal conditions and requirements, the study seeks to provide recommendations for enhancing phylloremediation strategies and advancing green technologies for air quality improvement.

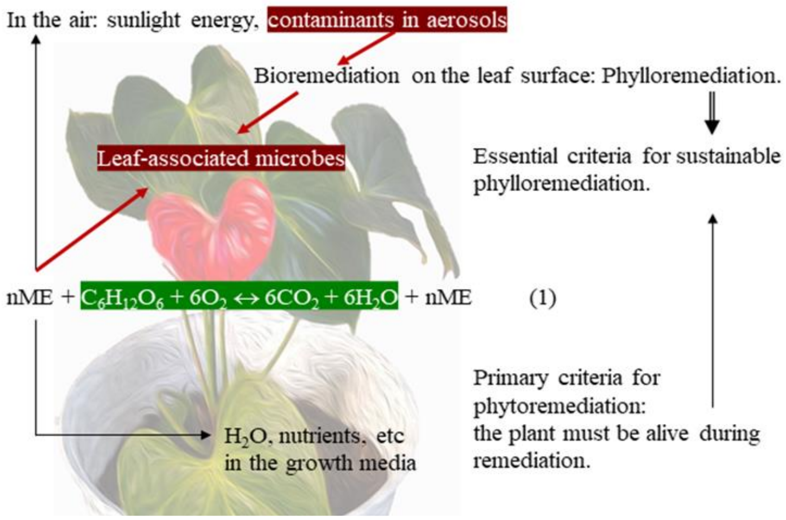

Figure 1. A framework of essential criteria for sustainable phylloremediation

2.2. Critical terminology, framework and criteria

The numbers of materials and energy (nME) term represents various materials and energy associated with living plants. For example, in the growth media, such as water and nutrients are the primary needs for living plants. In the air, sunlight energy is also a significant need for living plants, in addition to the presence of various air contaminants in the form of aerosols that are exposed to plant leaves. Moreover, there is nME in the form of leaf-associated microbes in the leaf surface as a phyllosphere [21]. This framework relies on the phyllosphere's microbial community for bioremediation. Therefore, in the interaction between air contaminants and phyllosphere, leaf microbes can eliminate contaminants to improve air quality. Improving air quality by microbes is known as bioremediation. Hence, microbes on the leaf surface make it a phylloremediation. Furthermore, critical criteria for sustainable phylloremediation include plant diversity, selection based on remediation capabilities, care practices to maintain plant health, and strategic placement for optimal remediation potential. By considering these elements, researchers and practitioners can develop effective strategies for mitigating air pollution through phylloremediation.

2.3. Literature search strategies

Following the definition of phylloremediation as a bioremediation of air on the leaf surface, the literature review targeted previous research findings concerning gas transfer processes in leaves, the physical status of contaminants such as aerosols, leaf morphology, and the composition of leaf-associated microbial communities. The search was conducted using the Mendeley reference management platform to streamline the process and organize retrieved articles efficiently. With the framework, a literature search uses Harzing's Publish or Perish 8 software. Additional literature beyond these sources is needed for issues that are relevant and important in confirming the clarity of a problem. Furthermore, journal articles were the top-targeted article majority. Selection criteria prioritized recent publications, encompassing the past 18 years from 2005 to 2023, to capture retrospective developments in phylloremediation and related phytoremediation processes. By focusing on key topics such as gas transfer processes, contaminant status, leaf morphology, and microbial communities, the literature search aimed to provide a comprehensive understanding of the essential aspects influencing phylloremediation efficacy and sustainability.

3. RESULTS AND DISCUSSION

Following the primary processes of plant life in Figure 1, four aspects determine the application of phylloremediation: plant diversity, plant type selection, plant care, and plant placement. Exploring these four aspects of sustainability has resulted in essential criteria for operational directions for indoor phylloremediation. Plant diversity ensures a broad range of contaminants can be addressed, while plant type selection focuses on choosing species with the best remediation capabilities. Proper plant care is crucial to maintaining the health and effectiveness of the plants over time. Finally, strategic plant placement maximizes the coverage and efficiency of phylloremediation within indoor environments. By integrating these criteria, IAQ can be significantly improved through sustainable phylloremediation practices.

3.1. Plant diversity

The plant diversity assessment is based on the interaction of nME in air contaminants and leaf-associated microbes with plant leaves where the three elements interact. Indoor air contaminants mainly contain particulate matter (PMs), nitrogen oxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and volatile organic compounds (VOCs) [22]. The most abundant VOCs in the air include formaldehyde; and benzene, toluene, ethylbenzene, and xylene (BTEX) [23]. For these organic contaminants, Table 1 summarises the results of selected previous studies, which form the basis for determining the criteria for implementing sustainable phylloremediation.

Table 1. Specific interactions of leaves, microbes, and contaminant removal

Plant leaves	Leaf-associated microbes	Removed contaminants	References
Zamioculcas zamiifolia	*Bacillus cereus*	Formaldehyde	[24]
Clitoria ternatea	*Bacillus cereus*	Formaldehyde	[25]
Chrysopogon zizanioides	*Achromobacter xylosoxidans* F3B	BTEX compounds	[26]
Populus trichocarpa deltoides	*Burkholderia cepacia* VM1468	Toluene	[27]
Azalea indica	*Pseudomonas putida* TVA8	Toluene	[28]
Zamioculcas zamiifolia	*Pseudomonas aeruginosa* and *Bacillus cereus*	Ethylbenzene	[29]
Bougainvillea buttiana	*Enterobacter cloacae* LSRC11, *Staphylococcus* sp. A1 and *Pseudomonas aeruginos*	Xylene	[30]

Table 1 shows the specificity of the interaction between the leaves of certain plants and related microbes and the ability of both to eliminate contaminants. Plant species significantly influence the composition of phyllosphere microbes, which was confirmed by Redford *et al*. [31], who reported that different plant species harbor distinct microbial communities in the phyllosphere. The results were valid for plants in tropical and temperate climates [32], [33]. These results suggest the application of phylloremediation that covers many contaminants by providing various types of plants depicted in Figure 2.

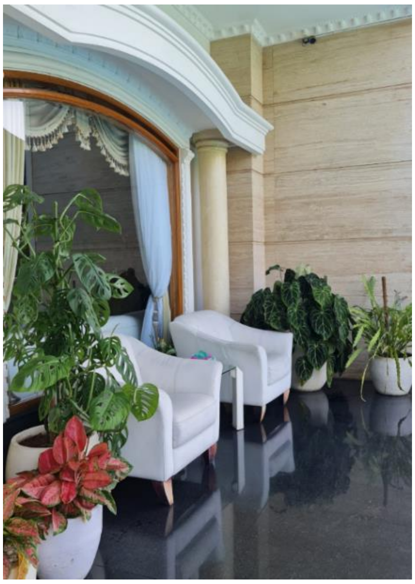

Figure 2. Provision of plant diversity

The findings on plant diversity for phylloremediation highlight the potential for using different plant species to improve IAQ by leveraging natural processes involving leaf-associated microbes. This approach offers sustainable air quality management, integrating plants into indoor environments to remove various contaminants like PM and VOCs. By understanding the specificity of plant-microbe interactions, tailored strategies can be developed for different environments. This not only contributes to healthier indoor spaces but also supports biodiversity conservation and resilience to climate change. In the future, further research can optimize these methods, leading to guidelines for implementation and potentially integrating phylloremediation into building codes and urban planning regulations for widespread adoption.

3.2. Plant selection

Assessment of the potential of plant species is based on the nME in the form of water in the growth media. Water is absorbed to provide a layer of water on the leaves as protection from the effects of air [34]. The process of water absorption from the root zone in the plant growth medium is transpiration. Plants with a high transpiration rate produce an adequate layer of water on the leaves, which plays a leading role in capturing and dissolving aerosols. Su *et al*. [35] have characterized fifty types of plants with high transpiration rates. Using plants with high transpiration provides the added advantage of cooling indoor temperatures. Air cooling due to the transpiration process of plants has been confirmed by Gupta *et al*. [36]. Thus, selecting plants with high transpiration rates can be beneficial for both air purification and temperature regulation indoors.

The term nME can refer to carbon dioxide. The release of carbon dioxide from plants occurs through respiration over time and the absorption of carbon dioxide from the air through the stomata of leaves to undergo photosynthesis on bright days [37]. The rate of photosynthesis, which is greater than the respiration rate, expresses plant growth [38]. While photosynthesis absorbs carbon dioxide, it is accompanied by the absorption of various other gaseous contaminants. Thus, the high growth rate of plants indicates high absorption of air contaminants as long as the leaves are not damaged or die due to contaminant accumulation. In addition to the two nME approaches above, there is an approach to respiration-photosynthesis reactions in the form of leaf physical characteristics such as leaf shape, hairs, and stomata. The leaf acts as an aerosol transfer medium, determining aerosol capture's effectiveness and efficiency. Researchers [39], and [40] reported that needle leaves accumulated more PMs than broad leaves due to small individual leaf areas and abundant wax layer contributing to the capturing effectiveness. The plant species with abundant hairs were Catalpa speciosa, Broussonetia papyrifera, and Ulmus pumila. Thus, for the same leaf canopy area, a narrow leaf produces a more expansive gas transfer medium than a broad leaf. This approach refers to selecting narrow single-leaf plants described in Figure 3, which can capture a more significant number of contaminants than broad single-leaf plants.

Figure 3. Provision of narrow single-leaf plants

The results suggest that the careful selection of plant species based on their capacity for transpiration, efficient photosynthesis, and favorable leaf traits can have significant benefits for enhancing IAQ. By pinpointing plants proficient at capturing and eliminating airborne pollutants such as aerosols and carbon dioxide, indoor spaces can be made healthier and more enjoyable for occupants. This knowledge can inform the integration of indoor greenery across various settings like residences, workplaces, and public areas, bolstering efforts to cleanse the air. Moreover, utilizing plants with high transpiration rates not only assists in air purification but also contributes to natural cooling, potentially reducing reliance on energy-intensive air conditioning systems. Looking forward, this comprehension of plant biology and morphology holds pivotal importance in the design of sustainable buildings and the management of indoor environmental conditions, fostering both human health and environmental sustainability simultaneously.

3.3. Plant care

The mission of sustainable elimination of air contaminants requires plant maintenance to ensure the plants can operate effectively over a long period. Treatment of indoor plants for air remediation must adhere to the principle that the method does not introduce new pollution. A practical approach for occupants involves periodic spraying of water. The living organism stoichiometry in Figure 1, specifically the nME component, necessitates water supply to the plant growth medium to facilitate transpiration. This method should be expanded to include spraying all the leaves, as illustrated in Figure 4. This practice allows leaves to be cleaned of trapped contaminants, enabling them to recover and continue the phylloremediation process effectively. Regular maintenance through these methods ensures the longevity and efficiency of plants in eliminating air contaminants.

Figure 4. Spray water from the leaves every morning

Subsequently, water spray from the leaves that contain contaminants enters the plant growth medium. In this position, the growth medium needs attention regarding its ability to eliminate leaf contaminants so that clean water remains for transpiration. In general, plant growth media is a mixture of materials, at least soil and compost, capable of removing various contaminants [41], [42], but also has the potential to decompose materials. The decomposed material can be diluted in concentration through periodic spraying of water. Therefore, the timing of water spraying is crucial for a sustainable phylloremediation process for leaves and growing media. Based on the living organism stoichiometry in Figure 1, the bright day when the photosynthesis process is working and the absorption time for gaseous contaminants is the right time to supply water. Spraying in the morning for the function of photosynthesis and immobilization of these gaseous contaminants is becoming increasingly important to simultaneously dilute the growing media liquid due to decomposition at night. In the meantime, if someone provides water for plants in the evening, it increases the water content in the growing medium. Under anaerobic conditions, plant growth media materials can be decomposed to produce methane and other gases [43], creating new problems. Moreover, water at night is not needed in photosynthesis and phylloremediation. For certainty, one must abandon supplying plants with water in the evening. Additionally, the morning for leaf cleaning is valid for soil and aquatic plants. The difference is only in the source of water supply. Soil plants get water from external sources, while aquatic plants can use water from the growing medium.

The results emphasize the significance of timing water provision to plants to ensure the efficient elimination of air contaminants and proper plant upkeep. Watering plants in the morning when photosynthesis is active helps cleanse leaves of pollutants and dilutes liquid in the growing medium resulting from overnight decomposition, thereby promoting plant health and remediation efforts. Conversely, watering in the evening can create anaerobic conditions and introduce new pollutants through decomposition, highlighting the need to avoid evening watering practices. Furthermore, recognizing the distinct water requirements of soil and aquatic plants emphasizes the importance of customizing maintenance methods for different plant types to achieve optimal outcomes in sustainable air quality control.

3.4. Plant placement

The phylloremediation process works primarily for the elimination of air contaminants. Thus, the ideal placement of plants can reach most of the building's height. These conditions are met by applying vertical gardens [44], sky gardens [45], and façade for outdoor [46]. In addition, the placement of plants with the help of tall supports illustrated in Figure 5 is also good practice for dealing with indoor air coverage. This strategic placement ensures that the plants can effectively absorb pollutants from various levels of the building, enhancing overall air quality. By integrating these green structures, buildings can achieve a more sustainable and healthier indoor environment.

Figure 5. Plants on tall supports

Elimination of contaminants at their source determines the effectiveness of phylloremediation. In this connection, placing plants is a priority in the toilet and bathroom, kitchen, car space, and bedroom. Toilets and bathrooms generally emit bioaerosols [47], and although the time of occurrence is short, the concentration is significant in a limited volume of space. Activities in the kitchen and car space generally emit fuel-sourced contaminants, especially VOCs [48], their activity time is short, yet the chemical properties of contaminants are toxic [49]. The bedroom is a priority because the occupant's stay is the longest in a day, typically eight hours of rest time. Moreover, the bedroom can produce a variety of volatile chemicals [50] contained in cosmetics, room fresheners, and mosquito repellents.

The authors recognize the difficulty of applying phylloremediation to build rooms with limited space. However, gaseous contaminants fill the entire space, so one can flexibly place plants wherever possible. For example, using the hydroponic method, hanging plants, and placing them in ventilation. This problem is a challenge for architects in designing buildings of various dimensions, simple, small, and large as well as modern ones with an environmental outlook for the future. The results underscore the significance of thoughtfully positioning plants for phylloremediation to enhance IAQ. This method integrates natural air purification into architectural plans, fostering both sustainability and public health. Looking ahead, heightened awareness and further research have the potential to spur innovation, ultimately facilitating the widespread acceptance of plant-based air purification methods across diverse built environments.

3.5. Plant criteria

Based on the primary plant life processes in Figure 1, essential criteria for phylloremediation are produced. In addition, strengthening sustainable phylloremediation practices can pay attention to local wisdom in indoor plants. This local wisdom criterion adds to the criteria for selecting plant species. It indicates a recognition of the importance of indigenous knowledge and the specific needs of plant species in effectively cleaning up environmental pollutants. Therefore, the directions for sustainable phylloremediation can be summarized in Table 2. By incorporating both scientific principles and local wisdom, the effectiveness and sustainability of phylloremediation practices can be significantly enhanced.

Table 2. Essential criteria for sustainable phylloremediation

Aspects	Criteria	Methods
Plant diversity	Elimination coverage of many contaminants	Provision of a variety of plants
Plant selection	High rate of transpiration	Based on the flow of transpiration water released by plants: - Simple gravimetry for soil media plants and aquatic plants by comparing the weight loss of potting media. - Simple hydrometry for aquatic plants by comparing the drop in the water level in the pot.
	Fast growth	Based on plant wet weight: - Simple gravimetry - Visual appearance
	Narrow single-leaf plants	Visual appearance
	Local wisdom	Subjective preferences, for example, medicinal plants [51], aesthetic plants [52], and mixed plants [3], [53].
Plant care	Water spray from leaves	Work consistently
	Morning spraying time and during daylight hours	Work consistently
Plant placement	Air coverage	Reach indoor height by any practical means
	Contaminant sources	Highest emission priority

The essential criteria in Table 2 add to the primary needs of maintaining plant life, including ensuring plant nutrients, treating disease infections, and adequate sunlight. All of these criteria are prerequisites for successful phylloremediation. The several findings are regarding improved environmental remediation practices, enhanced biodiversity conservation, community engagement and empowerment, long-term sustainability, and knowledge sharing and collaboration. Overall, the findings suggest that a diverse selection of plants, chosen based on criteria such as transpiration rate, growth speed, leaf characteristics, and local preferences, along with consistent care and strategic placement, can contribute significantly to the elimination of contaminants from the environment. In summary, incorporating local wisdom and essential criteria into phylloremediation practices offers the potential for more effective and sustainable environmental remediation. This approach acknowledges the importance of indigenous knowledge, promotes biodiversity conservation, engages communities, ensures long-term sustainability, and fosters collaboration between various stakeholders. Overall, it represents a holistic approach to addressing environmental challenges and restoring ecosystems.

4. CONCLUSION

Phylloremediation focuses on the abilities of leaves and their microbes; however, the effectiveness and efficiency of their sustainability are an integral part of phytoremediation. Therefore, besides the principal criteria for phytoremediation, the sustainable phylloremediation process focuses on the essential criteria, covering plant diversity, selection, care, and placement. Recent observations indicate that diverse plant species significantly improve IAQ through specific interactions between plants and leaf-associated microbes, rather than merely the quantity of plants. This underscores the necessity of selecting varied plant types and understanding their microbial relationships for effective indoor air remediation. Additionally, this study emphasizes the need for practical guidelines, integration into architectural designs, and straightforward yet technical implementation methods. While our findings are promising, further empirical research is essential to validate and optimize these practices. Simple methods to fulfill these criteria are needed for ease of implementation for the community. Thus, these essential criteria can be used as educational material for occupants. In addition, indoor designers must provide space facilities that facilitate implementation. Furthermore, the synergistic effect criteria of leaves and leaf-associated microbial communities invite competent experts to provide simple solutions.

ACKNOWLEDGEMENTS

The authors would like to thank Universitas Diponegoro, Semarang; Universitas Islam Negeri Maulana Malik Ibrahim, Malang; Institut Teknologi Sepuluh Nopember, Surabaya, for providing facilities to carry out this work. Special thanks to Ms Ani Astuti Eddy Soeryanto Soegoto, who provided beautiful photos as a model for the phytoarchitecture at her home, Bandung.

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