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PHYTOARCHITECTURE DESIGN REQUIRES A PLANT SELECTION FRAMEWORK TO COMBAT AIR CONTAMINANTS IN BUILDING AREAS SUSTAINABLY

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ABSTRACT
Empowerment of plants to maintain the indoor and outdoor air quality of a building area promises occupant health and sustainable use of the building. In supporting plants' functional role, this study proposes a novel approach for a general framework for selecting plants. The method to achieve the objectives of this study was based on previous empirical studies conducted in various places under different environmental quality conditions. The essential findings of the selected literature became part of the technical feasibility process in selecting plants. Significant results indicate the mechanism of controlling airborne contaminants by plants through aerial parts and growth media. Gaseous pollutants can be absorbed along with carbon dioxide absorption, while particulate matter is deposited on the leaf surface. Some other contaminants enter the plant growth medium, which plants can process with microbes in the root zone. The use of plants for indoor and outdoor phytoremediation is various plant species, sourced and selected from a retrospective study, locally available and standard plants, and popular plants. These findings were developed to include assessments of contaminant-plant interactions and plant-specific experiments. The implications of the plant selection framework can be one of the promising methods in designing sustainable building phytoarchitectures.
Keywords: *air quality, biodiversity, climate adaptation, greenspaces, sustainable building, tree species*

1. Introduction

Architecture emphasizing environmental quality in building design aims to create a healthy, comfortable building performance and sustainable use. The balance of social, economic, and ecological pillars (Purvis et al., 2019) is the platform for sustainable building design. Achieving sustainable building can be done through physical engineering design and the accompanying infrastructure, as well as controlling the factors of sick building syndrome (Nduka et al., 2018). One of the factors causing the syndrome is indoor air quality, with the influence of outdoor air quality in a building. Indoor air quality is an urgent concern, considering that humans spend the most prolonged stay throughout the day, wherever they are. Moreover, indoor air quality determines the comfort performance of a building to make it a sustainable place to live (Bataineh & Al Rabee, 2022).

Spatial comfort is influenced by the selection of the use of building infrastructure media (Schützenhofer et al., 2022). The media consists of abiotic components, such as building materials, furniture, and household chemical products, all emitting contaminants, and biotic ones, predominantly plants, as renewable resources that can combat the pollutants. Plants are the only living organisms capable of providing an essential substance for all living organisms twenty-four hours a day. It is oxygen, which plants produce on a light day from photosynthesis for about twelve hours in the tropics (Handara et al., 2016) and at varying times in non-tropical areas (Abimaje et al., 2018). In line with the absorption of carbon dioxide for oxygen production, plants also absorb airborne substances, reducing air contaminants (Wolverton & Nelson, 2020; Zhang et al., 2020). During oxygen production, plants absorb water from the growth medium through transpiration, which simultaneously absorbs substances carried by the transpiration flow. The transpiration process causes contaminants in the growth medium to be absorbed into the plant, reducing the pollutants in the media (Wolverton & Nelson, 2020). With the processes of photosynthesis and transpiration, plants can process and control the quality of various environmental media (Meili et al., 2021; Oberti & Plantamura, 2017) in addition to providing multiple human psychological advantages when faced with plant scenes (Deng & Deng, 2018; Tao et al., 2020). Thus, providing space for plants and empowering them to process and manage the environmental quality of a building space, which includes indoor and outdoor within the boundaries of the building area, becomes the definition of phytoarchitecture design (Samudro et al., 2022b).

Phytoarchitecture design pays close attention to the selection of plant species due to differences in the ability of plants to absorb various contaminants (Bandehali et al., 2021; Zhang et al., 2020). Some indoor plants can prevent sick building syndrome (L.-Y. Chen et al., 2017), while various outdoor plants can reduce inorganic air contaminants, volatile organic compounds, and particulate matter (Weyens et al., 2015). However, guidelines have yet to be found regarding selecting plant species according to environmental quality conditions indoors and outdoors in a building area. Therefore, this study is intended to propose a general framework for plant selection to provide a tool for designing building phytoarchitecture, accelerating phytoremediation practices, and monitoring plant performance in serving air quality dynamics.

2. Research Methods

The phytoarchitecture design includes a plant service space to control air contaminants within the building area, covering the outdoor and indoor environment (Samudro et al., 2022b), presented in Figure 1. The space includes green fencing or roadside plants and a green facade representing a building's outdoor plants and indoor plants. This area consists of the land boundary of the building owner, which differs in the building size, yard, plants, and infrastructure between buildings (Sedayu & Mangkoedihardjo, 2018). The contaminant area includes the street, building yard, and inside a building.

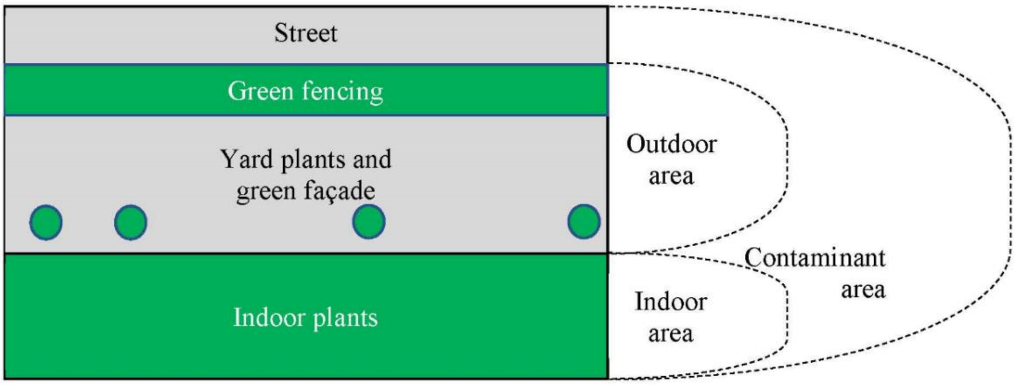

Fig. 1. Phytoarchitecture design of building area

The phytoarchitecture design area becomes the boundaries of this retrospective study, organized as follows. The first part is literature research as the basis for achieving the first objective of this research and uses the reference manager platforms using Harzing's Publish or Perish 8 software, PubMed, and Crossref for indoor used the keywords: indoor, plants, contaminants, and for outdoor used search terms: outdoor, plants, pollutants, green facade, and roadside plants. Selection criteria included open-access journals, entirely in English, empirical research results, and plant response to a contaminant. Next, each piece of literature is reviewed regarding the abstract contents, methods, results, and conclusions.

The second part, but as the core of the idea, discusses the essential findings in the first part and is accompanied by the proposed framework for selecting plant species. This section is supported by current progress in plant selection factors. The literature selection criteria include plant parameters that indicate the ability to absorb and eliminate environmental contaminants. Search keywords were transpiration rate, bioconcentration factor, and phytotoxicity

3. Results and Discussions

Based on research on abstracts, methods, results, and conclusions from each selected literature, essential findings are categorized as indoor and outdoor plants. For example, among the various contaminants, carbon dioxide gas is not included in this report because the gas is a plant's need for growth indoors and outdoors, which plants naturally absorb on sunny days in line with the absorption of other contaminants.

3.1. Indoor plants

Researchers (Sayed, 2020) conducted experiments on the ability of two species of plants to absorb ammonia and formaldehyde gases. With the help of spraying the leaves with the antioxidant glutathione less than 600 mg/L, Golden pothos, and croton plants can absorb ammonia and formaldehyde gases in the indoor air. On the other hand, by spraying the antioxidant bilirubin at the same concentration, photo plants became more resistant to absorbing formaldehyde. The results of this study were also confirmed through other similar studies (Hung et al., 2021).

Two plant species, *Dracaena sanderiana*, and *Epipremnum aureum* can reduce the concentration of total volatile organic compounds (TVOCs), nitrogen monoxide (NO), and nitrogen dioxide (NO_2) gases (Jung et al., 2015). Furthermore, the results of decreasing the concentration of NO and NO_2 gases and ozone gas (O_3) can be processed by two other plant species, *Spathiphyllum wallisii* and *Syngonium podophyllum*, under certain lighting conditions (Pettit et al., 2019). In particular, O_3 gas can also be processed by three other plant species, snake plant (*Sansevieria trifasciata*), spider plant (*Chlorophytum comosum*), and golden pothos (*Epipremnum aureum*), without any differences in the ability of the plant species (Abbass et al., 2017).

Indoors containing volatile organic compounds (VOCs), consisting of benzene, ethylbenzene, xylene, styrene, formaldehyde, acetaldehyde, acrolein with acetone, and toluene can be effectively reduced by Rubber trees, Rhapis, and Happy trees. However, indoor particulate matter (PM) is not significantly reduced due to the influence of outdoor PM (Hong et al., 2017). This study was also confirmed by three other similar studies (Torpy et al., 2018). Meanwhile, the use of water lettuce (*Pistia stratiotes*), water hyacinth (*Eichhornia crassipes*), and water coin (*Hydrocotyle umbellata*) were able to reduce airborne dust (PM_{10}) and fine dust ($PM_{2.5}$), as well as formaldehyde (Park & Lee, 2020). In addition, spider plants can accumulate PM in their leaf blades (Gawrońska & Bakera, 2015). Similarly, particles $(NH_4)_2SO_4$ can effectively deposit in several species of plants *Kerria japonica*, *Sophora japonica*, *Philadelphus pekinensis*, *Gleditsia sinensis*, and *Prunus persica* (Chen et al., 2017).

There was research on screening 28 plant species based on leaf area to reduce five volatile indoor pollutants: aromatic hydrocarbons (benzene and toluene), aliphatic hydrocarbon (octane), halogenated hydrocarbon trichlorethylene (TCE), and terpene (α-pinene). It was found that plant species could reduce specific contaminants and did not depend on leaf area. Therefore, it is crucial and necessary to use various species of plants to mitigate various volatile contaminants (Morgan et al., 2022). Furthermore, the results of this study were strengthened by the results of studies using five other different plant species (*Spathiphyllum wallisii*, *Philodendron hederaceum*, *Ficus pumila*, *Tradescantia pallida*, and *Chlorophytum comosum*) (Suárez-Cáceres & Pérez-Urrestarazu, 2021).

There was research on four species of medicinal plants *Vitex trifolia*, *Vernonia amygdalina*, *Cassia alata* and *Strobilanthes crispus* to ward off two species of fungi *Aspergillus niger* and *Penicillium oxalicum*. The results showed that *S. crispus* extract was the most effective against both fungi. However, this is not the case when the active compounds of these plants' flavonoids, alkaloids, and terpenoids are separated (Abas et al., 2020).

Meanwhile, researchers (Gunasinghe et al., 2021) suggest using plants and microflora in their growth media to reduce indoor air contaminants significantly. When plants process pollutants from the air and their growth media, microorganisms play a role in degrading contaminants and supporting plant growth.

3.2. Outdoor plants

There was a study of lead (Pb) and cadmium (Cd) accumulation in two species of roadside plants *Pongamia pinnata* (L.) Merrill and *Peltophorum pterocarpum* D.C. Backer ex K. Metal accumulation mainly in leaves. Each plant has a different ability to accumulate each type of metal contaminant (Shafiq et al., 2012), which may be due to differences in leaf area. Other similar studies provide the same confirmation that the accumulation of zinc (Zn) and copper (Cu) is different between plant species (Malinowska et al., 2015). Likewise, other species of local plants give different responses to the species of metal contaminants originating from outdoor and transportation activities, i.e., Pb, Zn, Cu, Cd, iron (Fe), manganese (Mn), magnesium (Mg), nickel (Ni), cobalt (Co), chromium (Cr), and arsenic (As) (He et al., 2021; Ögutucu et al., 2021; She et al., 2022).

Regarding gaseous contaminants, several researchers found the accumulation of polyaromatic hydrocarbons (PAHs) in the soil around the roadside (Omores et al., 2017), including the surrounding vegetation that absorbs it. In addition, the leaves of various plants can accumulate these substances (Keyte et al., 2016; V. Kumar et al., 2019).

Most outdoor PM can be trapped in plant leaves (Kováts et al., 2021; Kwon et al., 2020). Among several species of plants, *Alstonia schlolaris, Bauhinia variegata, Ficus benghalensis, Ficus religiosa, Cassia fistula*, and *Mangifera indica*, there are tolerant plant species, so they are suitable as biofilters (Tak & Kakde, 2019). The green facade is one of the PM biofilter media (Varghese & Ghosh, 2016). Many plants functioning as facades, green roofs, grasslands, and living walls effectively controlled PM (Wróblewska & Jeong, 2021).

Some outdoor decorative plants *Fuchsia hybrida* cv. Deutsche Perle, *Fuchsia hybrida* cv. Orange Crush, *Fuchsia hybrida* cv. Genii, *Fuchsia hybrida* cv. Green and Gold, *Fuchsia magellanica* cv. Aurea. They were suitable for growing in containers (Toderas, 2021).

3.3. Important findings

The following essential findings are obtained based on previous empirical research results. First, the mechanism of controlling airborne contaminants by plants is through aerial parts and growth media. Gaseous contaminants can be absorbed along with carbon dioxide absorption (Razif et al., 2006), while the particulate matter is deposited on the leaf surface. Some other contaminants enter the plant growth medium, which plants can process with microbes in the root zone.

Second, is the need for plant biodiversity to eliminate contaminants realistically present in indoor and outdoor environments. This finding is strengthened by the results of other similar studies for indoor plants (Dhanraj, 2020; Gong et al., 2019; Saxena & Sonwani, 2020) and outdoor plants (Yao et al., 2019; Toderas, 2021). However, biodiversity must still pay attention to the synergistic relationship between various species of plants. This result reinforces the importance and necessity of plant selection in applying phytoarchitecture in a building environment.

Third, the species and amounts of indoor contaminants differed from outdoor contaminants, which determined the placement of plant species. This difference may be due to differences in the time of people's activities between spaces (Branco et al., 2014; Kapalo et al., 2018; Luo et al., 2019), the contents of the space, characteristics of contaminants, and contaminant transport mechanisms (Mangkoedihardjo, 2007), which are influenced by the local microclimate (Leung, 2015; Rodríguez-Chávez et al., 2021). These complex conditions reinforce the need for biodiversity in plant placement.

Fourth, most studies use plants based on literature research and common plants in place, especially outdoor plants. This fact points to the need and importance of empirical research that is published, documented, and easily accessible to everyone who needs it. In addition, literature research is an inseparable part of selecting plant species, which is included in the plant selection framework (Figure 2).

Fifth, special attention needs to be paid to specific research. For example, it uses medicinal plants to eliminate contaminants, accompanied by a toxicity test. The latter is a consequence of using new plants to look at the potential for contaminant elimination. In addition, the post-harvest quality of the plant is considered (Hu et al., 2013; Mohanty, 2016) when the plant has accumulated contaminants, making it a hazardous material. Moreover, the association between plants and microbes is essential. It must be considered because phytoremediation processes always accompany bioremediation processes in the root zone (Kotoky & Pandey, 2020). In addition, biodiversity in the rhizosphere determines the increase in associative processes of bioremediation and phytoremediation.

3.4. Plant selection framework

The plant selection framework is partly developed based on significant findings from previous empirical studies, presented schematically in Figure 2. This framework can be divided into two assessment approaches: the retrospective study with a non-experimental system and the future research with an experimental approach. This framework is used not only for the provision of new plants in the phytoarchitecture design but also for those already used for regeneration purposes.

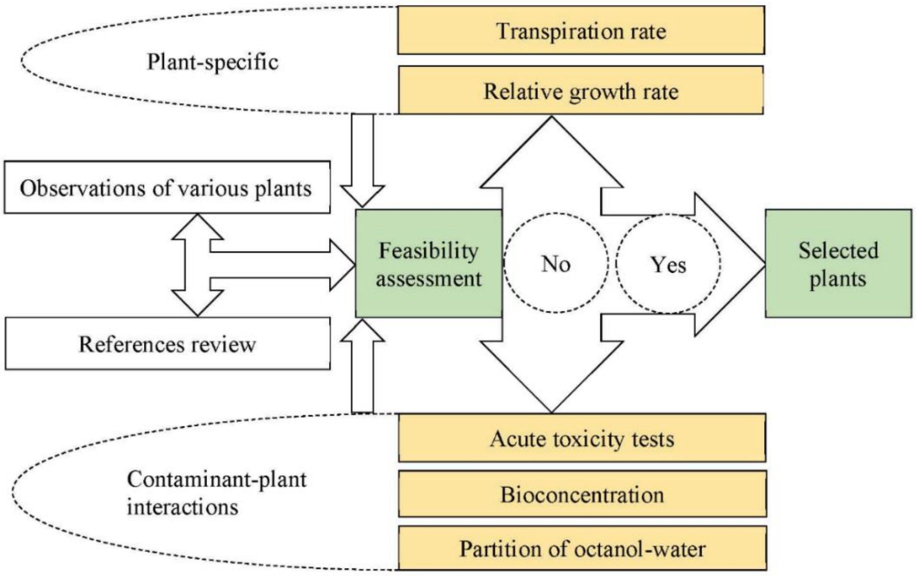

Fig. 2. Plant selection framework

3.5. Retrospective study

In Figure 2, a feasibility assessment includes observations of various plants addressed to plants that already exist in the area of a building or common and popular plants around the building. Observations on the existing plants aim to nominate plant species that have adapted to the place (Kotta et al., 2018; Samudro et al., 2022b), physiologically and psychologically acceptable to building users and the surrounding community (Buru et al., 2019; Hassan et al., 2019; Tao et al., 2020). This observation work needs to be accompanied by reference studies for the existing plants concerning technical aspects of the ability of plants to treat environmental pollution. Elements of the reference study also include post-harvest safety because, at certain times, plants need to be regenerated. In contrast, the replaced plants have accumulated pollutants and can become hazardous materials. If all observation and reference considerations are sufficient, one can define a variety of selected plants.

In some places, one might consider local wisdom plants (Du et al., 2020; S. Kumar et al., 2018), such as using medicinal plants. The food plants can be nominated to eliminate environmental contaminants. However, further research is needed on the toxicity of post-harvest plants.

3.6. Prospective study

In Figure 2, retrospectively selected plants are then further investigated regarding the ability of plants to overcome environmental pollution and to explore the potential for sustainable use of various plants. The investigation is conducted through the following two experiments.

Plant-specific experiments investigate plants' transpiration rate from their growth medium, which is an indicator of the ability of plants to absorb contaminants from their growth media (Eichelmann et al., 2022). This transpiration rate is essential, considering airborne pollutants can spread to the plant growth medium and expose the root zone. Under these conditions, transpiration can transport contaminants from the growing medium into the plant.

In addition, an investigation of the relative growth rate of plants is required to assess the effects of contaminant-plant interactions. Growth rate measurement can use a simple method with plant parameters (Burnett et al., 2016; Pérez-Sánchez et al., 2015), such as plant height, leaf area, stem diameter, and others so that plants do not need to be treated during the experiment. Furthermore, by measuring the parameters over time, the relative growth rate can be known (Li et al., 2018).

For contaminant-plant experiments, it investigates the effects of contaminants on plants by conducting acute toxicity tests for single pollutants and a mixture of contaminants on plant responses. This test predicts the maximum concentration of substances that plants can process. Thus, plants can perform their functions as contaminant processors without causing death. The acute toxicity test results in the concentration of the contaminant that causes harmful effects on the biota (Erhirhie et al., 2018). The concentration of harmful effects is used to compare the level of toxicity between contaminants (Dong et al., 2019; Fischer et al., 2020; Sharonova & Breus, 2012) for certain plant species. The low level indicates that the contaminant is more toxic than contaminants with a high level (Gillio Meina et al., 2019; Wang et al., 2021).

Moreover, investigation of the bioconcentration factor to predict the portion of the contaminant absorbed by the plant and remaining in the growth medium (Kosiorek & Wyszkowski, 2019). This factor indicates the ability of plants to accumulate pollutants from their growth media (Ludang & Mangkoedihardjo, 2009; Riza & Hoque, 2021). An example of a bioconcentration factor was obtained at about 50 on the investigation of cadmium accumulation in the *Impatiens glandulifera*, making the plant a cadmium hyperaccumulator (Coakley et al., 2019).

Furthermore, investigating the octanol-water partition coefficient to predict the potential for bioaccumulation of contaminants (Niu et al., 2021) so that it can be correlated with the bioconcentration factor (Ratnayake, 2016). In addition, it can predict the portion of contaminants in the plant biomass and dissolved in the plant solution, which also determines the translocation of contaminants in plant parts

4. Conclusion

Based on the results of previous empirical research shows that the selected plant determines the effectiveness of indoor and outdoor phytoremediation. Plants were selected based on their presence in the place, common plants, popular plants, and based on literature research. These findings form the basis for developing plant selection methods, with an in-depth study of plant transpiration and growth coupled with plant and contaminant interactions. The application of biodiversity can reduce various contaminants in the air, both those absorbed through aerial parts and their growth media. The need for empirical research related to plant and microbial interactions in the growth media is recommended to increase the effectiveness and efficiency of indoor and outdoor phytoremediation. This plant selection framework is an integral part of the phytoarchitecture design of a building.

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