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Plant and Plant Associated Microflora: Potential Bioremediation Option of Indoor Air Pollutants

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Abstract
Indoor air pollution is a significant problem today because the release of various contaminants into the indoor air has created a major health threat for humans occupying indoors. Volatile Organic Compounds (VOCs) are pollutants released into the environment and persist in the atmosphere due to its low boiling point values. Various types of indoor activities, sources, and exposure to outdoor environments enhance indoor VOCs. This poor indoor air quality leads to adverse negative impacts on the people in the indoor environment. Many physical and chemical methods have been developed to remove or decompose these compounds from indoors. However, those methods are interrupted by many environmental and other factors in the indoor atmosphere, thus limit the applications. Therefore, there is a global need to develop an effective, promising, economical, and environmentally friendly alternatives to the problem. The use of the plant and associated microflora significantly impact reducing the environmental VOC gases, inorganic gases, particulate matter, and other pollutants contained in the air. Placing potted plants in indoor environments not only helps to remove indoor air pollutants but also to boost the mood, productivity, concentration, and creativity of the occupants and reduces stress, fatigue, sore throat, and cold. Plants normally uptake air pollutants through the roots and leaves, then metabolize, sequestrate, and excrete them. Plant-associated microorganisms help to degrade, detoxify, or sequestrate the pollutants, the air remediation, and promote plant growth. Further studies on the plant varieties and microorganisms help develop eco-friendly and environmentally friendly indoor air purifying sources.

Keywords: Plants, Microorganisms, VOC, Air pollution, Biological remediation

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Introduction
People spend the bulk of their lifetime indoors, either in residential or public areas. Number of pollutants in the indoor air are higher than the outdoor air; hence poor air quality in these indoor environments will lead to several health issues. Today, it has become one of the biggest environmental threats [1]. Therefore, most studies have been disclosed the connection between indoor air pollution and associated adverse health effects [2,3]. Continuous exposure of individuals to poor indoor air quality can lead to "sick building syndrome" (SBS); health problems such as headache, fatigue, eye and skin irritation, or respiratory illnesses, etc. [4]. In 2012, World Health Organization (WHO) reported that indoor air pollution by households cooking over coal, wood, and biomass stoves caused about 4.3 million deaths worldwide [5].

Indoor air contaminants are generated through several sources such as occupational activities, household products, chemical reactions indoors, pets, materials, underground garages, and outside air sources [6,7]. Particles, biological agents, radon, asbestos, and gaseous contaminants such as CO, CO_2, NOx, SOx, aldehydes, and Volatile Organic Compounds (VOC) are released as main indoor air contaminants from the sources as mentioned above [8]. Removing the pollutant generating sources from indoors, increasing the ventilation rates, improving air distribution and cleaning the indoor air, etc. are the primary air purifying principles at indoors. Increasing the ventilation rate is the easiest way to reduce indoor air pollutants. However, it is usually affected by outdoor weather and external pollution condition [9]. Other current strategies used to remove indoor air pollutants are filtration, electrostatic precipitator with ionization, adsorption, ozonization, photolysis, photocatalysis etc. [8]. Among the above mentioned treatment strategies, some are very much expensive and complex methods. However, biological purification is a simple, low cost, and environmental friendly technique. Therefore has been investigated in many studies [10,11]. This review covers the potential use of plant and plant associated microflora for indoor air pollutant removal and degradation.

Indoor Air Quality

An average person needs 30 lb of air per day to live. However, he needs only 1.360 kg (3 lb) and 0.680 kg (1.5 lb) of water and food per day [12]. It indicates why air becomes the foremost necessary thing for the survival of humans and other living beings. According to the U.S. National Institute for Occupational Safety and Health (NIOSH) reports in 2007, the average total VOCs concentration in air samples could reach 2.90 mg m^{-3}[13]. Inadequate building ventilation is the leading cause of the high level of pollutant content indoors [14], and high pollutant content also causes severe public health threats [1]. Humans spend most of their time indoors, thus more researches are focused on indoor air quality and related studies.

Ambient air is often contaminated with high amounts of indoor air pollutants like particulate matter (PM), VOCs like benzene, toluene, ethylbenzene, xylene, polyaromatic hydrocarbons (PAHs), formaldehyde, and inorganic pollutants as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and Ozone (O_3). Although many of those compounds are outdoor air pollutants, can also be found indoors in higher amounts than outdoors [15]. Benzene is a ubiquitous trace element in indoor air [16], and its indoor concentration is higher than outdoors. A safe level for benzene exposure cannot be recommended. PAHs presence in the atmosphere is typically attached to air particles and present as complex mixtures. Therefore, the composition of PAH may vary from site to site. However, WHO (2000) reported that 8.7×10^{-5} ng/m^3 of PAHs have a risk for lung cancers. Exposure of 0.01 mg/m^{-3} Naphthalene is described as a safe level. Still, long term inhalation can cause respiratory tract lesions leading to inflammation and malignancy of animals. Formaldehyde exposure of 0.36 mg/m^{-3} for 04 hours causes sensory irritations of the eyes in humans [17]. Furniture, carpets, construction materials, sprays, cleaning, restoration activities, and surrounded industries are the foremost sources of the various volatile organic compounds, aliphatic and aromatic hydrocarbons, alcohols, and aldehydes, and chlorinated compounds [6,7,18,19]. Inorganic gaseous pollutants, SO_2, NO_x, CO, and CO_2 are generated through the combustion of fossil fuels, gas fired appliances (stoves and ovens), kerosene heaters, tobacco smoking [7,20,21], and outdoor sources exposure [22].

Potential health hazards

The presence of toxic volatiles and other pollutants in indoor air can cause various illnesses in humans. The European Environmental Agency has shown that indoor air quality is one of the priority considerations in children's health [23]. Prevalence of SBS is higher in buildings with air conditioners than in natural ventilation systems [24]. Typically this has been reported in offices, schools, aged care homes, and apartments like building-associated environments [2]. SBS is often associated with various symptoms such as headache and nausea, nasal congestion (runny nose, stuffy nose, shortness of breath, wheezing, sneezing, sinus, chest tightness, and chest congestion), throat problems (dry throat, sore throat, hoarseness), eye problems (dry eye, itching, tearing, blurry vision, burning eyes, sore eyes, and problems with contact lenses), fatigue (sleepiness, or drowsiness and unusual tiredness,), chill and fever, muscle pain (aching muscles or joints, pain or stiffness in the lower back, pain or stiffness in the upper back, and pain or numbness in shoulder/neck), and even neurological symptoms (feeling depressed, difficulty remembering or concentrating, and tension or nervousness), dry skin, and dizziness as well [25].

Apart from these illnesses, sometimes poor indoor air conditions also cause adverse health effects like respiratory tract illnesses, lung cancers, and heart diseases [26]. Potential harmful effects of benzene, toluene, xylene, and formaldehyde exposure were summarized below (Table 01). Prevalence of illnesses due to indoor air contaminants depends on factors like individual sensitivity to the contaminant, concentration of the contaminant, current physical health state of the individual, and also duration of exposure to the contaminant [27]. According to the International Agency for Research on Cancer (IARC), benzene is a toxic chemical proven as a carcinogen [28]. Benzene can cause most hematological diseases, such as acute and chronic lymphocytic leukemia, acute and myeloid leukemia, non-Hodgkin's lymphoma, multiple myeloma, and aplastic anemia even at the low dose of exposure [29–31]. The safe level for benzene exposure is still unknown, but the European Union recommended in 2000 that the benzene concentration in the ambient air should not exceed 5 μg m^{-3} [32]. Impure indoor air with particulate matter (PM≤10 μm) is often correlated with cardiovascular or respiratory disorders, and recently it is revealed that exposure to PM during the period of pregnancy or early life may cause autism spectrum disorder (ASM) [33,34]. These potential health hazards associated with poor indoor air quality highlight the need to review indoor air pollution and purification methods more seriously.

Table 1 Potential health hazards - Benzene, Toluene, Xylene, and formaldehyde exposure.

VOCs	Limit of Exposure (µg m^{-3})		Potential health hazards	Ref
	Short term	Long term		
Toluene	15,000 (8h)	2,300 (one day average)	*Short-term exposure* – Eye, nose, and throat irritation, dizziness, headaches, and feelings of intoxication. *Long term exposure* –Neurological effects including reduced scores in tests of short-term memory, attention, and concentration	[35]
Benzene	No safe level of exposure recommended .	No safe level of exposure recommended	Carcinogenic chemical (Group1) to humans- Cause adult acute myeloid leukaemia. Positive associations have been observed for non-Hodgkin lymphoma, chronic lymphoid leukaemia, multiple myeloma, chronic myeloid leukaemia, acute myeloid leukaemia in children Lung cancer	[36]
Xylene	-	100 (1year)	Irritation to the lungs, throat, and nose. Severe inhalation exposure can cause dizziness, headache, confusion, liver and kidney damage, heart problems, and coma	[35]
Formaldehyde	100 (30 min)	10 (1year)	Sensory irritation of eyes, nose, and throatexposure-dependent discomfort, lachrymation, sneezing, coughing, nausea, and dyspnoea. Human carcinogenic chemical. Long-term exposure linked to nasal cancer.	[36]

How to avoid indoor air pollutants?

Many strategies can be used for the reduction of indoor air pollutants. Those are supported by several efforts, such as removing the pollutant source from indoors, enhancing the ventilation rate, improving indoor air distribution, and cleaning [37]. Many industries have taken steps to scale down the usage of possible sources of indoor air pollutants during their product manufacturing cycle.

Current strategies applied to remove or reduce indoor air pollutants are filtration, electronic precipitator with ionization, adsorption, ozonation, photolysis, and photocatalysis [8,38]. Manipulation of filtration is suitable for particle removal in indoor air [39]. However microbial colonization on the filters will hinder the filtration. During electrostatic precipitation, by generating an electrical field, charged particles of air can be trapped. However, there is a risk of generating hazardous charged particles. Removing air pollutants using adsorption might be a highly specific technique, which is used as a post-treatment. The problem associated with oxidizing the pollutant may be the generation of unhealthy toxic products. Researchers are still proposing strategies to address this case with non-adverse impacts. Membrane separation, enzymatic oxidation, botanical purification, biofilters, and biotrickling filters are number of those strategies. Out of those plants and plant associated microflora, lowering the toxicity of contaminants in indoor environments is becoming a popular alternative as an economical air restoration technology [38].

Indoor pollutant removal capability of plants

Plants remove VOC, through aerial plant parts and plant associated microflora. Growing media and plant roots are also capable of removing VOC in the air. Recent studies showed that plants are one of the best air pollutant absorbing and metabolizing agents [40]. Plant volatile organic matter removal or degradation rate and efficiency rely upon the plant species, light, temperature, growing media, and VOC (concentration, identity, and VOC mixture effects). Stomata, cuticle, and adsorption to the plant wax layer are the critical VOC removal sites of the aerial plant parts. After entering into the leaf, the compound often undergoes degradation, storage, excretion, and translocation to alternative plant elements. Microorganisms present in the plant pot soil and plant root also can remove VOC from indoor air [41]. These plant pollutant removal and degradation strategies have been confirmed using several plant species using radiolabeling [42,43]. Several studies on plants with ^{14}C labeled aromatic hydrocarbons revealed that aromatic rings of those hydrocarbons were cleaved during their metabolic transformations and utilization of aromatic hydrocarbons under sterile conditions [44].

Plants can sink air pollutants through their large surface area of foliage and canopies because it provides a surface for the pollutant substances. Also, plant leaves can sorb several gaseous substances as nutrients or as micronutrients [45]. The plant uses processes like complexation, precipitation, and oxidation-reduction to detoxify or utilize those substances as nutrients. These plant and atmospheric interactions result in the reduction of these harmful particulate substances and VOC's [46]. VOCs removal and degradation capability of many indoor and outdoor plant species have been recorded in the literature. As reported in the literature,

Table 2 Plant species and their potential for Toluene removal.

Plant species	Results	Ref
Zamioculcas zamiifolia	Toluene uptake per unit area of *Z. zamiifolia* plant leaf at 72 h of exposure 0.93±0.02 mmol m^{-2}	[48]
Hemigraphis alternate, Hedera helix, Hoya carnosa, Asparagus densifloru Tradescantia pallida, Fittonia argyroneura	Removal efficiency of toluene and total VOC by twenty-eight selected ornamental plants varied substantially among the species tested, Range of pollutant removal, Toluene - 1.54 - 9.63 µg m^{-3} m^{-2} h^{-1} Total VOC - 5.55 -44.04 µg m^{-3} m^{-2} h^{-1}.	[6]
O. microdasys, D. dermensis	Time taken for the complete removal of 2 ppm toluene from an airtight chamber was 55 h and 120 h, respectively for *O. microdasys* and *D. dermensis* plants.	[49]
Dieffenbachia maculate, Spathiphyllum wallisii Asparagus densiflorus	Toluene removal rate constant ranged from 3.4 to 5.7 L $h^{-1}m^{-2}$ leaf area when exposed to 20.0 mg m^{-3} of toluene	[50]
Hedera helix ,Spathiphyllum wallisii Syngonium podophyllum, Cissus rhombifolia	Toluene (initial 1 µL L^{-1}) removal efficiencies of *H. helix* -220.2 ± 31.8 ng m^{-3} h^{-1} cm^{-2} *S. podophyllum*, - 161.6 ± 19.2 ng m^{-3} h^{-1} cm^{-2} *S. wallisii* - 203.7 ± 24.3 ng m^{-3} h^{-1} cm^{-2} Lowest efficiency - *C. rhobifolia*. - 85.7 ng m^{-3} h^{-1} cm^{-2}	[51]
Herbs *Aloysia triphylla, Brittonz Melissa officinalis Mentha piperita , Mentha piperita Mentha suaveolens ,Mentha suaveolens Pelargonium graveolens, Plectranthus tomentosus Rosmarinus officinalis ,Salvia elegans* Herbaceous foliage plants *Begonia maculata ,Davallia mariesii Farfugium japonicum, Fittonia verschaffeltii Hedera helix Philodendron spp. Soleirolia soleirolii* Woody foliage plants *Ardisia crenata , Ardisia japonica Ardisia pusilla, Cinnamomum camphora Schefflera elegantissima, Eurya emarginata , Ilex cornuta, Ligustrum japonicum, Pinus densiflora, Pittosporum tobira, Rhododendron fauriei*	Efficiency of toluene removal ranged from 378 to 16.6 µg m^{-3} h^{-1} m^{-2}	[52]
Fatsia japonica, Draceana fragrans	Volatile toluene and xylene removal efficiencies were increased as the plant's root zone volume increased.	[53]
Schefflera actinophylla, Ficus benghalensis	Toluene and total xylene (m, p, o) removal efficiency of leaf area over a 24h period in *S. actinophylla*, - 13.3 µg m^{-3} m^{-2} *F. benghalensis* - 7.0 µg m^{-3} m^{-2}	[54]
Phoenix roebelenii	Purification capability (Pa) increased with an increase in room temperature from 21 to 26°C , reaching a range of 15–35 (V/h) Initial toluene 1.5 ppm, Pa for toluene was 6.5 (V/h)	[55]
Azalea indica	Time taken to remove 339 mg m^{-3} of Toluene 76 h	[56]
Epipremnum aureum, Spathiphyllum	Removal rate for TVOC was 74%, and 68%respectively	[57]
Epipremnum aureum, Davallia fejeensis	*Epipremnum aureum* plant had a positive impact on mixed VOC(decane, toluene, 2 ethylhexanol, benzene, octane, xylene, α- pinene) filtration than *Davallia fejeensis*	[58]

plant species and their potential in removing or detoxifying toluene (**Table 2**), benzene (**Table 3**), xylene (**Table 4**), and formaldehyde (**Table 5**) removal or degradation are summarized below.

However, there could be some deleterious effects like impairment of plant physiological activity and plant injuries due to these chemicals. Chronic exposure to higher concentrations of air pollutant substances can affect plant photosynthesis, vitality, and productivity. This stress makes the plant more susceptible to diseases and insect infections [47]

Table 3 Plant species and their potential for Benzene removal.

Plant species	Results	Ref
Howea forsteriana, Spathiphyllum floribundu, Dracaena deremensis , Spathiphyllum sensation, Dracaena marginata, Epipremnum aureum , Scheflera actinophylla	From seven potted plant species, benzene removal was ranged from 12-28 ppm day^{-1}.	[59]
Dracaena deremensis, Spathiphyllum wallisii	Benzene removal per leaf area of *Dracaena deremensis* - 606 ± 155 mg m^{-3} d^{-1} m^{-2} *Spathiphyllum wallisii* 686 ±73 mg m^{-3} d^{-1} m^{-2}; *Howea forsteriana* 537± 69 mg m^{-3} d^{-1} m^{-2}.	[60]
Zamioculcas zamiifolia	Benzene uptake per unit area of *Z. zamiifolia* leaf was 0.96± 0.01 mmol m^{-2}	[48]
Crassula portulacea, Hydrangea macrophylla, Cymbidium, Ficus microcarpa var. fuyuensis, Dendranthema morifolium, Citrus medica var. sarcodactylis, Dieffenbachia amoena, Spathiphyllum, Nephrolepis exaltata, Dracaena deremensis	Removal of benzene was in the range of 22.1- 561.3 µg m^{-2} min^{-1}	[61]
Superior removal efficiency *Hemigraphis alternate, Hedera helix Tradescantia pallida, Asparagus densifloru Hoya carnosa* Intermediate removal efficiency *Ficus benjamina, Polyscias fruticose, Fittonia argyroneura, Sansevieria trifasciata Guzmania spp., Anthurium andreanum, Schefflera elegantissima*	Benzene removal efficiency of *Hemigraphis alternata* -5.54 µg m^{-3} m^{-2} h^{-1} *Tradescantia pallida*- 3.86 µg m^{-3} m^{-2} h^{-1} *Hedera helix* - 3.63 µg m^{-3} m^{-2} h^{-1} *Fittonia argyroneura* -2.74 µg m^{-3} m^{-2} h^{-1} *Asparagus densiflorus*,- 2.65 µg m^{-3} m^{-2} h^{-1} *Hoya carnosa* - 2.21 µg m^{-3} m^{-2} h^{-1}	[6]
Dracaena deremensis Opuntia microdasy	Removal rates of 2 ppm of benzene from the test chambers by *O. microdasys* -3.2 mg/ m^3 d^1 *D. dermensis* - 1.46 mg/ $m^3$$d^1$	[49]
Hedera helix, Spathiphyllum wallisii Syngonium podophyllum, Cissus rhombifolia	Highest removal efficiency -*S. wallisii.* Medium level removal efficiency - *S. podophyllum* and *H. helix* lowest removal efficiency - *C. rhombifolia*	[51]
Chamaedorea seifrizii, Scindapsus aureus Sansevieria trifasciata, Philodendron domesticum Ixoraebarbata craib, Monster acuminate Epipremnum aureum, Dracaena sanderiana	highest benzene uptake *D. sanderiana* - 10.00 ±1.04 mmol of benzene at 72 h Crude wax 46 % and stomata 54 %	[62]
Syngonium podophyllum	Benzene removal - 25 ppmv from the test chambers within 7 days	[63]
Epipremnum aureum, Davallia fejeensis	*Epipremnum aureum* plant had a positive impact on mixed VOC (decane, toluene, 2 ethylhexanol, benzene, octane, xylene, α- pinene) filtration than *Davallia fejeensis*	[58]

Diversity of plant associated microflora

Microbial reservoirs like soil, rhizosphere, phyllosphere, anthosphere (external environment of flower), spermosphere (the exterior of germinating spores), and carposphere (external area of the fruit) indicate plant microbial relationships [77]. Diverse groups of bacterial taxa namely proteobacteria, acidobacteria, actinobacteria, bacteroidetes, Verrucomicrobia, Planctomycetes, Cloroflexi, Firmicutes, and Gemmatimonatedes are present as root endophytes [78,79]. Among those, a representative amount of taxa have been derived from the soil environments [80]. Plant root microbiota is mostly transferred horizontally. However, bacteria can sometimes be transferred via seeds by relocating microorganisms to proliferating plants [81,82]. The narrow layer of soil on plant roots has high microbial diversity, it's one of the most complex ecosystems and is called as a rhizosphere [83]. Root exudate containing organic acids, phenolic compounds, plant growth regulators, sugars, sterols, vitamins, amino acids, fatty acids, and nucleotides ensures good microbial growth around roots [84,85]. Plant root endophytes enter into tissues through passive mechanisms (root cracks or emerging points of lateral roots) or active mechanisms [86].

Aerial plant tissues are different in ecology from belowground parts; however, it's a good source for phyllosphere and endosphere bacteria. Normally endophytes spread systemically to the leaves, fruits, and stems via the xylem. In addition, endophytes enter plant tissues through aerial plant parts; as fruits and flowers. Phyllosphereic bacterial community is highly dependent

Table 4. Plant species and their potential for Xylene removal.

Plant species	Results	Ref
Alternanthera bettzickiana, Drimiopsis botryoides, Aloe vera, Chlorophytum comosum, Aglaonema commutatum, Cordyline fruticose, Philodendron martianum, Sansevieria hyacinthoides, Aglaonema rotundum, Fittonia albivenis, Muehlenbeckia platyclada, Tradescantia spathacea, Guzmania lingulata, Zamioculcas zamiifolia, Cyperus alternifolius	best xylene removing plant - *Zamioculcas zamiifolia* 88% xylene removal within 72 hours. xylene uptake was 0.81 ±0.01 mmol m^{-2} leaf area as	[64]
Zamioculcas zamiifolia	At 72 h of xylene exposure, *Z. zamiifolia* leaf uptake about 0.86±0.07 mmol m^{-2} per unit area.	[48]
D. deremensis *O. microdasys*	Time taken for complete removal of 2 ppm xylene from the airtight chamber of *O. microdasys* and *D. dermensis* plants were respectively 47 hours and 98 hours.	[49]
xora coccinea, Muraya paniculat, Ficus benjamina, Euphorbia milii, Adenium obesum, Millingtonia hortensis, Dalbergia cochinchinensis, Pterocarpus indicus, Phyllanthus acidus, Cassia fistula, B. buttiana, Gardenia jasminoides, Ehretia microphyllaLam	Uptake of xylene by *B. buttiana* plant parts stems 53.1±1.9% epicuticular waxes 32.3±0.9% plant stomata - 14.6±0.0%	[65]
Fatsia japonica *Draceana fragrans*	Volatile toluene and xylene removal efficiencies were increased as the plant's root zone volume increased.	[53]
Schefflera actinophylla *Ficus benghalensis*	Toluene and total xylene (m, p, o) removal efficiency leaf area over a 24-h period was in *S. actinophylla*- 13.3 μg m^{-3} m^{-2} and 7.0 μg m^{-3} m^{-2} *F. benghalensis* - 13.0 μg m^{-3} m^{-2} and 7.3 μg m^{-3} m^{-2}	[54]
Phoenix roebelenii	Purification capability (Pa) increased with an increase in room temperature from 21 to 26 °C, reaching a range of 15–35 (V/h)	[55]
Epipremnum aureum *Spathiphyllum*	Removal rate for TVOC -74% Odor - 68%.	[57]
Epipremnum aureum *Davallia fejeensis*	*Epipremnum aureum* plant had a positive impact on mixed VOC (decane, toluene, 2 ethylhexanol, benzene, octane, xylene, α- pinene) filtration than *Davallia fejeensis*	[58]

Table 5. Plant species and their potential for Formaldehyde removal.

Plant species	Results	Ref
Osmunda japonica, Selaginella tamariscina, Davallia mariesii, Polypodium formosanum, Psidium guajava, Lavandula spp., Pteris dispar, Pteris multifidi, Pelargonium spp	Formaldehyde removal 86 plant species were analyzed and *Osmunda japonica* showed the best 6.64 μg m^{-3} formaldehyde/cm^2 of leaf area over 5 h	[66]
Hedera helix, Chrysanthemum morifolium Dieffenbachia compacta Epipremnum aureum	90% removal by -*Hedera Helix, Chrysanthemum morifolium, Dieffenbachia compacta, Epipremnum aurenum* (from the initial amount of 1.63 ppm within 24 hours).	[67]
Fatsia japonica *Ficus benjamina*	Time interval required to reduce 50% of benzene from the initial concentration (2 μL L^{-1}) *F. japonica* - 96 min *F. benjamina*.- 123 min	[68]
Tillandsia velutina	The plant decreased Formaldehyde concentration by 22.51 % in 12 h	[69]
Phoenix roebelenii	Purification capability (Pa) increased with an increase in room temperature from 21 to 26 °C, reaching a range of 15–35 (V/h)	[55]
Schefflera arboricola Nephrolepis exaltata	These plants reported a high air purification ability	[70]
Fatsia japonica	Reducing rate, 225 μg m^{-3} the first 2 h around 80 μg m^{-3} for the final 3 h.	[71]
Epipremnum aureum	Removal rate for	[57]

Spathiphyllum	TVOC - 74% Odor - 68%.	
Nicotiana tabacum	Transgenic plants increase formaldehyde removal by 20 %	[72]
Chlorphytum comosum *Aloe vera* *Epipremnum aureum*	Formaldehyde removal efficiencies; spider plant-soil system at the light intensities of 90%, 92%, and 95% were respectively 80 μmolm^{-2}s^{-1}, 160 μmol m^{-2} s^{-1}, and 240 μmol m^{-2} s^{-1} in the daytime.	[73]
Aglaonema commutatum, Spathiphyllum floribundum, Commutatum, Agave potatorum, Dracaena fragrans, D. reflexa, Cordyline fruticose, Gasteria gracilis, D. angustifolia , D. sanderiana, D. deremensis, Sansevieria trifasciata, A.commutatum , Alocasia macrorrhiza, S. trifasciata, Aloe nobilis, Scindapsus aureus, D. amoena, A.commutatum, Scindapsus pictus, Philodendron sodiroi, Syngonium podophyllum , Asparagus setaceus, Aloe aristata, Chlorophytum comosum, Philodendron martianum , Zamioculcas zamiifolia, Philodendron selloum	*Scindapsus aureus, Asparagus setaceus, S. trifasciata, C. comosum, A. commutatum, A. commutatum , A. commutatum, S. pictus, G. gracilis, and P. sodiroi* reported a high formaldehyde purification capabilities with less damages.	[74]
Chamaedorea elegans	Initial formaldehyde concentration - 14.6 mg m^{-3} Maximum formaldehyde elimination capacity of 1.47 mg/m^{2}h	[75]
Hedera helix	*Hedera helix* reported a 70% reduction of the required time to reach 0.5 ppm of gaseous HCHO when compared with natural dissipation	[76]

on environmental factors such as temperature, humidity, and air pollutants [87,88]. Plant associated microflora plays a crucial role in VOC degradation by increasing the bioavailability of VOCs to plants via the production of biosurfactants and the formation of biofilms [89]. These microbial associations with plants increase the ability of microorganisms to metabolize large numbers and varieties of organic compounds, together with improving plant strength of VOC remediation. Therefore, many studies have focused on the ability of microbial air remediation and its potential applications.

Role of microflora during air pollutant removal and degradation

Plant associated microbial flora helps the growth and development of the plant by enhancing the availability of nutrients through the production of siderophores, organic acids, and plant growth promoters (Indole Acetic Acid (IAA)). It helps the plant's survival in biotic and abiotic stress conditions. As an example, during stressful conditions, ethylene is produced from 1-aminocyclopropane-1-carboxylate (ACC). Bacteria can produce 1-amino cyclopropane-1-carboxylatedeaminase and degrades ACC into ammonia and α-ketobutyrate and lowers the amount of ACC inside the plant resulting in the reduction of ethylene production and stress [10,90,91]. They not only support phytoremediation; through the detoxification, degradation, and sequestration of the contaminants, but also promote plant growth [92]. Phyllosphere bacteria facilitate the absorption of pollutants into the plants. Endophytes and phyllosphere bacteria can degrade absorbed pollutants by detoxification, transformation, or sequestration [93]. In soil pollution, root endophytes can decrease phytotoxicity by enhancing the pollutant accumulation inside the plant [94]. Biological nitrogen fixation of *Rhizobium* bacteria incorporate carbon and nitrogen into the soil. These plant root nodule associated bacterial flora provide nutrients to plants. Natural behaviors of bacteria improve the nutrient availability to the plant and the environmental tolerance [95] through remediation of organic and metal contaminants by absorbing, accumulating, detoxifying, and degrading those pollutants [94]. Plant associated microflora detoxifies the PM, which the host plant absorbs. PM activates Reactive Oxygen Species (ROS) that adversely affect bacteria, but bacteria have mechanisms to detoxify ROS toxicity [96,97]. Microorganisms have degradation pathways to degrade and reduce the phytotoxicity of pollutants. Therefore it reduces the evapotranspiration of volatile pollutants [93].

In some cases, plants produce biogenic volatile organic compounds. Thus VOC degrading microorganisms should present in the phyllosphere. However, a limited number of studies are available about phyllosphere microflora since they are transient flora that occupies the phyllosphere temporarily, and the diversity changes depending on various factors. Therefore, the study of this transient flora is somewhat difficult. Many root associated VOC degrading microflora are used to treat groundwater and soil and air remediation [10,92,98,99].

Air-remediation through soil is somewhat different; there are trapped air and moisture inside the soil particles. Once soil contains low moisture conditions air particles with pollutants penetrates through the soil so that the soil microflora can degrade those pollutants. After the water is supplied to the soil, cleaned air is released into the atmosphere. This is how soil and rhizosphere microflora contribute to removing indoor air pollution [59]. Microbial pollutant degrading capabilities are enhanced when they are associated with plants [100]. Air pollution due to inorganic pollutants (NO_x, SO_x, and O_3, etc.) also remediated through the microorganisms. It is a well understood fact that chemoorganotrophic bacteria (nitrogen producers, sulfur depositors, photosynthetic bacteria) use these inorganic compounds to generate energy. Ozone is a toxic compound to bacteria, and it is used as a bactericidal agent. Therefore the use of bacteria in detoxifying ozone is difficult [96,97].

Metabolic activities of bacteria in bioremediation of air pollutants

Several aromatic compounds have become significant air pollutants. Their persistence and widespread occurrence throughout the environment are facilitated by the thermodynamic stability of the benzene ring [101]. Microorganisms adapted to use these pollutants as their carbon sources through their catabolic pathways [102]. During aerobic respiration of microbes, oxygen is the final electron acceptor, and it provides energy yield to the cell. In addition, oxygen helps to activate the substrates via oxygenation reactions [103]. Most of the *Pseudomonas* sp. are aerobic therefore, many studies have been conducted on its ability to degrade many environmental contaminants aerobically [104].

Bacterial biodegradation of VOC relies on the type of degrading enzymes and the microorganisms [105]. In the aerobic catabolic funnel, most of the peripheral pathways involve oxygenation reactions which are carried out by monooxygenases and hydroxylating dioxygenases and generate dihydroxy aromatic compounds such as catechol, homogentisate, protocatechuate, gentisate, homoprotocatechuate, hydroquinone, and hydroxyquinol. These intermediate compounds are the substrates for ring cleavage enzymes. These enzymes use oxygen to open the aromatic ring between the two hydroxyl groups like ortho cleavage, catalyzed by intradiol dioxygenases or proximal to at least one of the two hydroxyl groups (catalyzed by extradiol dioxygenases, and meta cleavage) [102].

According to Murray (1972) and Williams (1974), *Pseudomonas putida* mt-2 strain utilizing toluene also grown on the substrates like 1,2,4-trimethylbenzenem-ethyltoluene, m-xylene, and p-xylene and oxidize all these substrates to corresponding benzylalcohols, benzaldehydes [106,107]. Subsequently, the above products were mineralized by meta-cleavage pathways. *P.mendocina* KR1, *Ralstonia picketti* PKO1, and *Burkholderia vietnamiensis* G4 reported degradation of benzene as well as toluene using toluene-4-monooxygenase (TmoA), toluene 3-monooxygenase (TbuA1), and toluene 2-monoocygenase (TomA), respectively [108–110]. *Nitrosomonas europea* produced amminomonooxygenase enzyme, which activates by ammonia and oxidize BTEX compounds [111].

Bacterial mobile genetic elements like plasmids and transposons contain genes responsible for these catabolic activities. Once bacteria are exposed to the contaminated environment, they facilitate the horizontal gene transformation and rapid adaptation to utilize the pollutants [104]. Bacterial natural adaptations and pollutant remediation is a slow and time-consuming process. However, their utilization for *in-situ* bioremediation of polluted sites, and biotransformation of toxic compounds into non-toxic compounds such as fine chemicals and other value added products, development of *in-situ* high sensitive biomonitoring devices such as biosensors are the techniques that can be used to enhance the remediation process [112–114].

Conclusion

Several methods have been proposed to reduce the indoor air pollution caused by various chemicals released into the air due to anthropogenic activities occurring indoors. Although chemical and physical methods are available, most of them have issues in efficiency, short-life span, high cost, need for recovery systems, high maintenance demand, and secondary pollutants generated during VOC removal. Use of plants and their associated microflora provides a solution to these issues as an economical and environmentally friendly alternative. This review provides an overview of the use of ornamental plants and their associated microflora in removing the air pollutants indoors. According to the literature *Zamioculcas zamiifolia, Spathiphyllum wallisii, Sansevieria trifasciata, Hedera helix, and Ficus benjamina* plants can be suggested as the effective plants for benzene, toluene, xylene, and formaldehyde removal. Microbial associations with plants benefit in VOC remediation because it increases the microbial capability in metabolizing large numbers and varieties of organic compounds. Also microflora influence the plant strength during VOC remediation. More laboratory and field studies are needed to increase the efficiency in using plants for indoor air purification as well as to understand their mechanisms of air purification.

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Author's Contribution

The authors confirm contribution to the paper as follows: study conception and design: Y.H.K.I.S.Gunasinghe, I.V.N.Rathnayake, and M.P.Deeyamulla; draft manuscript preparation: Y.H.K.I.S.Gunasinghe; Review, and editing the final draft: Y.H.K.I.S.Gunasinghe, I.V.N.Rathnayake; All authors read and approved the final manuscript.

Competing Interest

The authors declare that they have no competing interest, which includes personal, financial, or any other kind of relationship with people or organizations that could inappropriately affect this review.

Ethics approval

Not applicable.

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