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REVIEW ARTICLE

Phytoremediation of volatile organic compounds by indoor plants: a review

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Abstract

Air quality in homes, offices, and other indoor spaces has become a major health, economic, and social concern. A plant-based removal system for volatile organic compounds (VOCs) appears to be a low-cost, environment-friendly solution for improving indoor air quality. This review presents and assesses VOC removal mechanisms that use plants and their associated microorganisms as well as the factors that influence the rate and efficiency of VOC removal. To increase removal efficiency, it is important to have a thorough understanding of the mechanisms of VOC degradation by plants and their associated microorganisms. The potential of plants and their associated microorganisms, whether present in pots or forced-air systems, to remove VOCs from indoor environments have been supported by a number of studies. Variations in removal efficiency depend on the plant species used, the chemical properties of the volatiles in question, and a cross-section of other internal and external factors. It is thus critical to select the right plants and use methods that reflect in vivo conditions. Indoor plants with superior air-purifying abilities have been extensively studied; however, the low rates of VOC removal efficiency in interior environments entail the need of more studies. For instance, factors that modulate VOC removal by plants, such as air circulation rate, light intensity, moisture status, and season need to be explored. Improving the efficiency of plants and their associated microorganisms for VOC remediation of indoor air is necessary to ensure sustainable and healthy indoor environments.

Keywords Botanical biofiltration · Foliage plants · Indoor air quality · Pollutant removal

1 Introduction

Indoor air quality is an important aspect of home, school, and office life. The content and nature of indoor air affect the well-being of people, most of whom spend > 85% of their time indoors (Kleipeis et al. 2001). It has been reported that many pollutants are 5–10 times higher in indoor spaces than in the outdoor air (U.S. EPA 2017). For this reason, indoor air quality in homes, schools, offices, and other interior spaces has become a major health concern. In fact, the World Health Organization has reported that indoor sources of air pollution are responsible for 4.3 million deaths worldwide in 2012 (WHO 2014).

One major class of air pollutants in indoor environments are volatile organic compounds (VOCs). VOCs can cause irritation of the eyes, nose, and throat, headaches, nausea, and loss of coordination. Serious injuries from VOC exposure include damage to the liver, kidneys, and central nervous system. VOCs have been found to cause cancer in animals and some types have been associated with human cancers (U.S. EPA 2017). The severe damage caused by these pollutants necessitates their removal from indoor air.

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Several methods have been introduced and developed to improve indoor air quality (U.S. EPA 2017).

Phytoremediation, the use of plants with their associated microorganisms to remove pollutants from the soil, water, and air, is considered a "green," cost-effective, and eco-friendly technology. The majority of phytoremediation research and associated technologies have focused on soil and water cleanup (reviewed by Lee 2013), while fewer studies have focused on air phytoremediation. The crucial role of plants in air purification has led to efforts to identify efficient indoor plant species suitable for phytoremediation. Although more than 100 species of indoor plants have been tested for their ability to purify indoor air, better understanding of the mechanisms and pathways of VOC removal is still needed to select for plants with enhanced VOC removal efficiency. The application of laboratory results to actual indoor environments is still in its early stages. Plants also produce or emit volatile organic compounds, sometimes referred to as biogenic VOCs; however, this review focuses on the five most common anthropogenic VOCs such as formaldehyde, benzene, toluene, ethylbenzene, and xylene.

The aims of this review are to examine the potential use of plants and their associated microorganisms for air purification. The mechanisms and pathways of phytoremedation are revisited, and the biological and physical factors influencing VOC removal rates and efficiency are discussed. The review briefly presents the recent innovations in VOC removal using plant-based remediation, which paves the way for future research to improve phytoremedation and ensure sustainable indoor air quality.

2 Indoor air quality

The quality of air space inside and around buildings and other structures affects the well-being of inhabitants. Nowadays, poor indoor air quality is considered to be a major health, environmental, and economic problem. Weschler (2009) reviewed the changes in indoor air since the 1950s and documented that the content of consumer products, the materials used in construction, and the habitual lifestyle of people have contributed to changes in indoor air quality, including the presence of toxic volatiles. The air quality is ever-changing with many of the chemicals found in indoor environments to only appear in the last five decades. Accordingly policies and standards of air quality and pollution have also been modified throughout the years (U.S. EPA 2017).

Indoor air pollution can be classified in four categories: pollution involving particulate matter; biological pollution (for example, dust mites); physical pollution caused by agents such as temperature and electromagnetic fields; and chemical pollution, including VOCs in addition to carbon monoxide, radon, and other nonorganic chemicals (Luengas et al. 2015). VOCs are the most hazardous pollutants in indoor air spaces (Koppmann 2007). The U.S. National Institute for Occupational Safety and Health (NIOSH) reported in 2007 that the average concentration of total VOCs in area air samples could reach 2.90 mg m^{-3}. VOCs are compounds with a boiling point in the range of 50–60 °C at room temperature and atmospheric pressure (U.S. EPA 2017) and include contaminants of low molecular weight such as aromatic-, fatty-, halogenated-, and oxygenated-hydrocarbons. VOCs can be generated indoors with the use of pesticides as well as from flooring, insulating and wood-based materials, coatings, paints, combustion sources, solvents, adhesives and disinfectants (Huang et al. 2016). Additionally, VOCs can penetrate from outdoor sources via air exchange (Huang et al. 2016). This review will focus on five VOCs, namely formaldehyde, benzene, toluene, ethylbenzene, and xylene that form the BTEX group.

VOCs have been identified as the cause of health problems associated with indoor air quality and "sick-building syndrome" (Wieslander et al. 1997; Jones 1999; Yu and Crump 1998; Wallace 2001; Erdmann and Apte 2003; Tsai et al. 2012). Moreover, exposure to VOCs has been associated with respiratory ailments, including asthma, and some VOCs have been identified to have carcinogenic properties. People respond differently to VOC exposure; some people may not be affected, while others can be hypersensitive and experience serious symptoms or injuries (Kobayashi et al. 2007). Of the BTEX hydrocarbons, benzene is the most toxic compound and according to the International Agency for Research on Cancer (IARC), has been classified to Group I and proven carcinogen. Benzene can cause hematological diseases, such as acute myeloid leukemia, acute and chronic lymphocytic leukemia, non-Hodgkin's lymphoma, multiple myeloma, and aplastic anemia (Collins et al. 2003; Snyder 2012) that further emphasize the importance of the removal of VOCs from indoor air.

Remediation treatments to improve indoor air quality include three basic strategies: (1) controlling the source of pollution; (2) improving room/building ventilation; and (3) purifying the air (U.S. EPA 2017). The latter strategy includes physical, chemical, mechanical, and biological technologies such as mechanical filtration, electronic filtration, adsorption, ozonation, UV photolysis, photocatalytic oxidation, cold plasma or non-thermal plasma, membrane separation, biofiltration, and botanical purification (Guieysse et al. 2008; Luengas et al. 2015). Phytoremediation, the use of plants and their associated microorganisms to reduce the level or toxicity of pollutants in the environment, is a cost-effective environmental restoration technology (Greipsson 2011). Phytoremediation provides an alternative to the more destructive and expensive technologies used for contaminant removal. Yet, many knowledge gaps have to be filled regarding the potential of phytoremedation for air purification, as most of the research has solely been focused on soil and water restoration.

3 Phytotoxicity of volatile organic compounds

Phytotoxic effects of VOCs have been observed and it is, therefore, important to identify plants that are particularly effective in overcoming the phytotoxicity of VOCs during the uptake and degradation of these pollutants. Several papers have analyzed the phytotoxicity of a small group of VOCs at low or high concentrations as summarized by Cape (2003). van Haut and Prinz (1979) reported 20% reduction in the yield of several plant species when they were exposed to an annual mean concentration of 20 μg m^{-3} formaldehyde. Exposure to 100 ppm (μL L^{-1}) formaldehyde for 5 h caused necrosis in the leaves and stems of three air-purifying plants, named *Epipremnum aureum*, *Fatsia japonica*, and *Rhapis excelsa*, in a decreasing order of severity. Moreover, structural changes at the cellular level were detected and included the destruction of the palisade and spongy parenchyma cells of these three plant species (Kim et al. 2013). Enzymatic activities are also altered with *R. excelsa* showing higher catalase and peroxidase activities at 100 ppm compared to *E. aureum* and *F. japonica*. It was notable that about 80% of the stomata of *E. aureum* were closed at 100 ppm formaldehyde, while only about 40% of the stomata of *F. japonica* and *R. excelsa* were closed. After exposure to benzene and toluene, the photosynthetic rate, stomatal conductance, and transpiration rate of *Hedera helix, Spathiphyllum wallisii, Syngonium podophyllum,* and *Cissus rhombifolia* were substantially reduced (Yoo et al. 2006). However, the amount of intercellular CO_2 and respiratory rates varied among the species tested. The plant characteristics that may be most sensitive to VOC exposure are growth habit as well as the timing and extent of flower and fruit production (Cape 2003). So far, studies with VOCs have indicated their degradation within plant tissues and not their accumulation. A Fourier transform infrared (FT-IR) analysis investigated the effect of indoor pollutants, including formaldehyde, BTEX and others on structural changes in three indoor ornamental plants, named *Dracaena deremensis*, *Sansevieria trifasciata*, and *Ficus elastica* (Husti et al. 2016). It was suggested that the plants maintained their structure by adjusting their metabolism resulting to a reduction in protein amount and an increase in polysaccharide content. The exposure of *C. comosum* to 350–35,000 μg benzene for 7 days resulted in yellow leaf tips, necrosis, and hydrosis (Sriprapat and Thiravetyan 2016). Another study showed that even low levels of formaldehyde can cause oxidative stress in petunia plants (Sun et al. 2015). Altogether these studies assessed the adverse effects of VOCs on plant health and suggested that the VOC phytotoxicity depends on the tolerance of each plant species, the level of VOC(s) present, and the length of exposure.

4 Plant-based removal of indoor VOCs

Exploration of the potential of plants to purify air from pollutants started in the early 1980s. The pioneer works of Wolverton and McDonald (1982), using *Scindapus aureus*, *Syngonium podophyllum*, and *Ipomoea batatas* to remove formaldehyde and Wolverton et al. 1984 using *Chlorophytum elatum* (Ait.) (R.Br.) var. *vittatum* Hort., *S. aureus*, and *S. podophyllum* to remove other VOCs, highlighted the potential for utilizing plants for air purification in indoor environments. To date more than 60 plant species have been studied and identified for use in formaldehyde removal as well as 60 for benzene, 67 for toluene, and 15 for xylene. Table 1 lists indoor plants with superior air-purifying ability, based on screening or comparison studies carried out by various laboratories. The ability of plants to deeply degrade or oxidize organic pollutants makes them good candidates for environmental cleanup (Kvesitadze et al. 2006).

4.1 Pathways and mechanisms for VOC removal by plants

A plant's ability to detoxify volatiles is determined by the uptake capacity of the plant cells and their ability to metabolize the pollutants while maintaining their normal metabolic processes. To determine the mechanisms of entry, transformation and localization of pollutants in plant cells, radiolabeling has been carried out using several plant species (Giese et al. 1994; Ugrekhelidze et al. 1997; Schmitz et al. 2000; Zhang et al. 2014). A number of plants have been reported to absorb and metabolize airborne VOCs, such as benzene and toluene (Cornejo et al. 1999; Cape et al. 2000; Collins et al. 2000), toluene and xylene (Oyabu et al. 2005; Chun et al. 2010; Kim et al. 2012, 2014), and formaldehyde (Wolverton and McDonald 1982; Wolverton et al. 1989; Oyabu et al. 2003; Kim et al. 2008, 2009, 2010; Kim and Lee 2008; Xu et al. 2010, 2011; Aydogan and Montoya 2011). The uptake of VOCs by plants is primarily through the leaves. The role of the roots and rhizosphere microbes will also be discussed later. The entry of the pollutants in the leaf tissue occurs either via the open stomata on the leaf epidermis or by diffusion through the epidermis that is covered by a waxy cuticle (Kvesitadze et al. 2006). Entry through stomata has been assessed by several studies addressing the impact of stomatal density on VOC removal efficiency of various plant species (Treesubsuntorn and Thiravetyan 2012; Sriprapat and Thiravetyan 2013; Sriprapat et al. 2014b). The rates at which indoor plants, such as *Chlorophytum*

Table 1 Indoor plants with superior VOC purifying abilities; based on screening studies and other comparison studies conducted by various laboratories

Plant species[z]	Authors
Benzene	
Gerbera jamesonii 23.50 (μg cm^{-2} d^{-1}); *Chrysanthemum morifolium* 18.20; *Hedera helix* 10.4; *Spathiphyllum* 'Mauna Loa' 5.2; *Aglaonema modestum* 4.7; *Dracaena marginata* 4.0	Wolverton et al. (1989)
Pelargonium domesticum 8.5 μg g^{-1} d^{-1}	Cornejo et al. (1999)
Dracaena deremensis "Janet Craig" 194 (mg m^{-3} d^{-1} kg^{-1} potting mix); *Spathiphyllum wallisii* Schott 'Petite' 171	Wood et al. (2002)
Dracaena deremensis "Janet Craig" 188 (ppm d^{-1} m^{-2} leaf area); *Dracaena marginata* 337; *Spathiphyllum* "Petite" 212; *Howea forsteriana* 167; *Schefflera* "Amate" 123; *Epipremnum aureum* 88.7; *Spathiphyllum* "Sensation" 59	Orwell et al. (2004)
Spathiphyllum wallisii 174.5 (ng m^{-3} h^{-1} cm^{-2} leaf area); *Syngonium podophyllum* 103.4; *Hedera helix* 102.8	Yoo et al. (2006)
Crassula portulacea 724.9 (μg m^{-2} d^{-1}); *Hydrangea macrophylla* 293.7; *Cymbidium* "Golden Elf" 267.4; *Ficus microcarpa* var. *fuyuensis* 255.2; *Dendranthema morifolium* 204.9; *Citrus medica* var. *sarcodactylis* 166.7; *Dieffenbachia amoena* "Tropic Snow" 115.2; *Spathiphyllum* "Supreme" 106.9; *Nephrolepis exaltata* cv. Bostoniensis 73.5; *Dracaena deremensis* cv. Variegata 59.0	Liu et al. (2007)
Dracaena sanderiana 59.67 nmol cm^{-2} d^{-1}	Treesubsuntorn and Thiravetyan (2012)
Zamioculcas zamiifolia 0.32 mmol m^{-2} d^{-1}	Sriprapat and Thiravetyan (2013)
Toluene	
Dieffenbachia amoena "Tropic Snow" 33 (% in 3 h with initial concentration of 8, 669 μg m^{-3} under light condition)	Porter (1994)
Dracaena deremensis "Janet Craig" 549 (mg m^{-3} d^{-1}); *Spathiphyllum* "Sweet Chico" 231	Orwell et al. (2006)
Spathiphyllum wallisii 203.7 (ng m^{-3} h^{-1} cm^{-2} leaf area); *Hedera helix* 202.2; *Syngonium podophyllum* 161.6	Yoo et al. (2006)
Sansevieria trifasciata 3.39 μmol d^{-1}; *Kalanchoe blossfeldiana* 3.37; *Dracaena deremensis* "Lemon Lime" 3.26	Sriprapat et al. (2014a, b)
Zamioculcas zamiifolia 0.31 mmol m^{-2} d^{-1}	Sriprapat and Thiravetyan (2013)
Ethylbenzene	
Chlorophytum comosum 3.70 (μmol d^{-1}); *Sansevieria ehrenbergii* 3.67; *Aglaonema commutatum* 3.60; *Sansevieria hyancinthoides* 3.57	Sriprapat et al. (2014a, b)
Zamioculcas zamiifolia 0.31 mmol m^{-2} d^{-1}	Sriprapat and Thiravetyan (2013)
Zamioculcas zamiifolia 133.9 μmol m^{-2} d^{-1}	Toabaita et al. (2016)
Xylene	
Zamioculcas zamiifolia 0.86 mmol m^{-2} d^{-1}	Sriprapat and Thiravetyan (2013)
Phoenix roebelenii 610 μg $plant^{-1}$ h^{-1}	Wolverton and Wolverton (1993)
Dracaena deremensis "Janet Craig" 336 (mg m^{-3} d^{-1}); *Spathiphyllum* "Sweet Chico" 105	Orwell et al. (2006)
Formaldehyde	
Syngonium podophyllum 1283 (μg d^{-1}); *Scindapsus aureus* 1291.3	Wolverton and McDonald (1982)
Nephrolepis exaltata 1863 (μg $plant^{-1}$ h^{-1}); *Chrysanthemum morifolium* 1450; *Phoenix roebelenii* 1385	Wolverton and Wolverton (1993)
Ficus benjamina 0.51 (mg m^{-3} cm^{-2}); *Fatsia japonica* 0.51	Kim et al. (2008)
Sedirea japonicum 1.36 μg m^{-3} ml^{-1}	Kim and Lee (2008)
Epipremnum aureum 5.7 (mg m^{-3} h^{-1} m^{-3} plant volume); *Rosmarinus officinalis* 6.6	Kim et al. (2009)
Osmunda japonica 6.64 (mg m^{-3} cm^{-2} leaf area); *Selaginella tamariscina* 4.84; *Davallia mariesii* 4.15; *Polygonum senticosum* var. *formosanum* 3.62; *Pteris dispar* 1.95; *Pteris multifida* 1.92; *Microlepia strigosa* 1.49; *Botrychium ternatum* 1.42; *Psidium guajava* 2.39; *Rhapis excelsa* 1.67; *Zamia pumila* 1.32; *Chlorophytum bichetii* 1.25; *Dieffenbachia amoena* "Marianne" 1.24; *Tillandsia cyanea* 1.23; *Anthurium andraeanum* 1.22; *Nandina domestica* 1.58; *Dendropanax morbifera* 1.5; *Ardisia crenata* 1.46; *Laurus nobilis* 1.40; *Lavandula* spp. 2.12; *Pelargonium* spp. 1.87	Kim et al. (2010)
Epipremnum aureum 94 (% d^{-1} with initial concentration of ~ 1.63 ppm); *Chrysanthemum morifolium* 84; *Hedera helix* 88; *Dieffenbachia compacta* 96	Aydogan and Montoya (2011)
Chlorophytum elatum var. *vittatum* 0.38 μg cm^{-2} h^{-1}	Wolverton et al. (1984)
Tillandsia velutina 50 ng m^{-3} cm^{-2}	Li et al. (2015)

Table 1 (continued)

Plant species[z]	Authors
Benzene and toluene	
Tradescantia pallida 3.86, 9.10 (mg benzene, mg toluene m^{-3} m^{-2} h^{-1}); *Hedera helix* 3.63, 8.25; *Hemigraphis alternate* 5.54, 9.63; *Hoya carnosa* 2.21, 5.81; *Asparagus densiflorus* 2.65, 7.44; *Fittonia argyroneura* 2.74, 5.09	Yang et al. (2009)
Hedera helix 57.5 ng benzene, 112.2 ng toluene m^{-3} h^{-1} cm^{-2} leaf area	Yoo et al. (2006)
BTEX	
Opuntia microdasys 1.18 mg benzene; 0.54 mg toluene; 1.64 mg ethylbenzene; 1.35 mg xylene m^{-2} d^{-1}	Mosaddegh et al. (2014)
Zamioculcas zamifolia 0.32 mmol benzene; 0.31 mmol toluene; 0.1 mmol ethylbenzene; 0.29 mmol xylene m^{-2} d^{-1}	Sriprapat and Thiravetyan (2013)

[z]Values following plant species names are VOC removal rates or percentages; units in parentheses

comosum and *Sansevieria trifasciata*, removed ethylbenzene and toluene were not significantly correlated with the number of stomata per leaf (Sriprapat et al. 2014b). Benzene and toluene are taken up mainly through the stomata (Ugrekhelidze et al. 1997; Sriprapat and Thiravetyan 2013), however, few studies concluded that the role of the stomata in VOC removal was insignificant (Schmitz et al. 2000). The alternative route of entry is through the cuticle, which is permeable to both lipophilic and hydrophilic molecules. The pollutants become adsorbed onto the lipophilic surface of the leaves' waxy layer resulting in their accumulation on the cuticle to a certain extent that in turn allows their gradual penetration into the leaves (Kvesitadze et al. 2006). Benzene removal through wax adsorption represented 46% of the total benzene uptake by *Dracaena sanderiana* (Treesubsuntorn and Thiravetyan 2012). Benzene, toluene, ethylbenzene, and xylene removal by *Zamioculcas zamiifolia* through cuticular adsorption accounted for 20, 23, 25, and 26%, respectively (Sriprapat and Thiravetyan 2013). Treesubsuntorn et al. 2013 investigated the amount and composition of wax materials of different indoor plants and found that the ability of the plant to remove benzene was dependent on the composition of the wax but not on the amount of wax present on leaves. In contrast, both the quantity and composition of the wax affected the efficient removal of xylene from indoor air by plants (Sangthong et al. 2016). Other avenues by which pollutants may enter the leaves have also been recognized. Kvesitadze et al. (2006) found that trichomal cells, which greatly increase the surface area of the leaves, may have a role in the uptake of chemicals. In the epiphytic plant *Tillandsia velutina*, superior formaldehyde uptake was observed to be aided by the trichomes (Li et al. 2015). The ectodesmata have also been described as a route by which a toxic compound may enter the leaves (Kvesitadze et al. 2006). Mechanisms of cuticular wax adsorption and other leaf structures as well as the entry via stomata are interesting features that should be further explored in the hope of bettering the VOC removal efficiency of indoor plants.

When VOCs enter the leaves, they may be translocated to different parts of the plant. After the entry of the pollutants through the stomata or cuticle, they reach the sieve tubes of the phloem that allow their translocation, together with photosynthates, to roots or the rest of the shoot tissue (Kvesitadze et al. 2006). It has been reported that the translocation of VOCs via the stem to the root zone depends on the concentration of VOCs in the indoor space or test chamber (Godish and Guindon 1989; Wolverton et al. 1989; Kim et al. 2008). Wolverton and Wolverton (1993) speculated that plant leaves can potentially absorb formaldehyde and xylene from the air and translocate them, via the phloem/xylem, to the plant roots where they are degraded by microorganisms. However, sterile plants were also found to metabolize VOCs arguing against the VOC degradation by microorganisms (Khaksar et al. 2016a; Ugrekhelidze et al. 1997). The role of microbes in the phytoremediation of VOCs is further discussed in the subsequent sections. Formaldehyde is absorbed by *Chlorophytum comosum* and then transported to the plant rhizosphere solution through downward transport. However, when the formaldehyde concentration in the air diminishes the absorbed formaldehyde is readily released back into the air (Su and Liang 2015).

After absorption, the VOCs may be sequestered, degraded in situ or transported to other locations in the plant to be degraded or metabolized (Giese et al. 1994; Schmitz et al. 2000). Plants can resist toxic compounds through excretion, conjugation with molecules or degradation to cellular metabolites and, in some cases, to carbon dioxide (Kvesitadze et al. 2006). The latter mechanism is ideal for phytoremediation purposes. Figure 1 shows a simplified diagram depicting the benzene, toluene, xylene (BTX), and formaldehyde metabolism by plants (Giese et al. 1994; Ugrekhelidze et al. 1997; Hanson and Roje 2001; Kvesitadze et al. 2006, 2009;

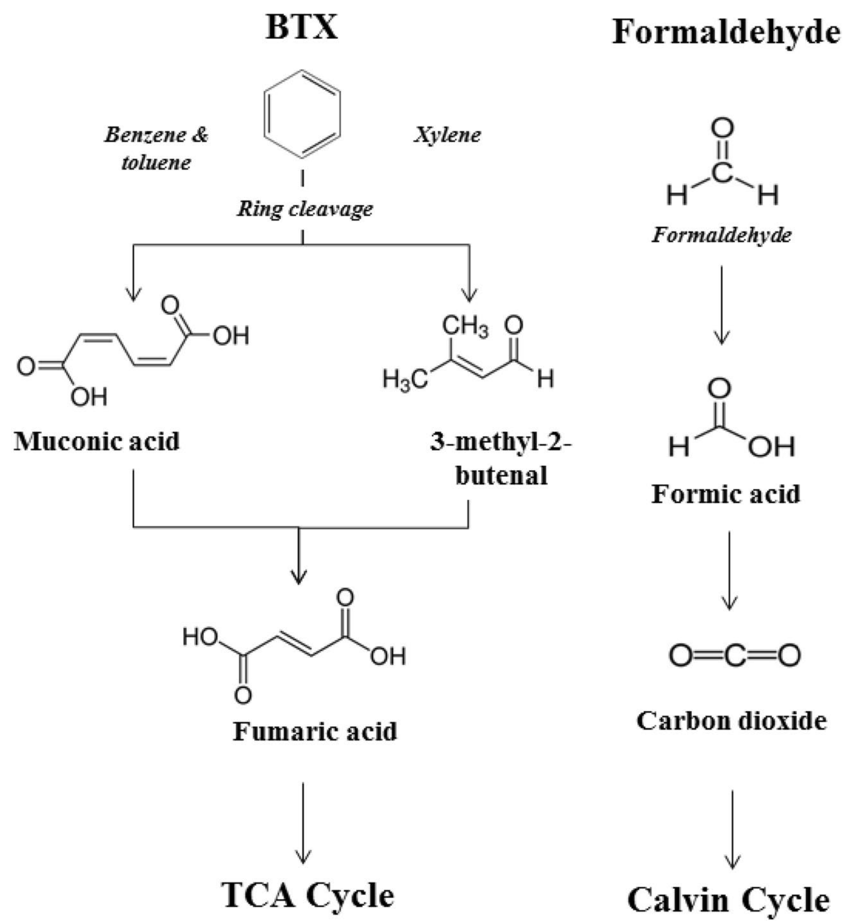

Fig. 1 The metabolism of benzene, toluene, xylene (BTX) and formaldehyde in plants. The oxidative degradation of BTX starts with a ring cleavage, followed by the formation of muconic acid in benzene and toluene (Ugrekhelidze et al. 1997; Kvesitadze et al. 2006, 2009) and of 3-methyl-2-butenal in xylene (Sangthong et al. 2016). Further oxidation may lead to the formation of fumaric acid, which is a key intermediate in the tricarboxylic acid cycle or Krebs cycle. The oxidation of C_1 units from formaldehyde produces formic acid, which is typically further oxidized into CO_2. Carbon dioxide may then enter the Calvin cycle (Giese et al. 1994; Hanson and Roje 2001; Zhang et al. 2014; Sun et al. 2015)

Zhang et al. 2014; Sangthong et al. 2016). The degradation of BTX starts with a ring cleavage, which forms intermediates that may undergo deep oxidation to form compounds that can enter the tricarboxylic acid cycle (TCA). In plants, therefore, degradation of organic compounds is facilitated by oxidative enzymes. For aromatic hydrocarbons, such as benzene and toluene, hydroxylation is the first conversion step. After the ring cleavage, the oxidation of benzene forms muconic acid, which can be further oxidized to fumaric acid, which in turn enters the TCA cycle (Ugrekhelidze et al. 1997; Korte et al. 2000; Kvesitadze et al. 2006). For toluene, oxidative cleavage may occur through either (a) oxidation of the methyl group to carboxyl group, followed by ring hydroxylation resulting to α-carboxymuconic acid or (b) ring hydroxylation without oxidation of the methyl group, where the cleavage product is α-methylmuconic acid (Ugrekhelidze et al. 1997). Xylene degradation in plants has been less studied. Sangthong et al. (2016) proposed that after ring cleavage of xylene, the product is 3-methyl-2-butenal, which can be further degraded into maleic acid and fumaric acid. Since fumaric acid is known to enter the TCA cycle, it is assumed that the product of xylene degradation ultimately enters the TCA cycle. Formaldehyde metabolism in plants, on the other hand, has been proposed to occur either independently or simultaneously through the C_1 metabolism or the Calvin cycle (Giese et al. 1994; Hanson and Roje 2001; Song et al. 2013; Zhang et al. 2014; Sun et al. 2015). Formic acid is one of the products of formaldehyde oxidation. Further oxidation of formic acid generates carbon dioxide, which can enter the Calvin cycle. Several studies have suggested other pathways to be also involved in the degradation of formaldehyde (Zhang et al. 2014; Wang et al. 2016). Monitoring the alteration of ^{14}C labeled formaldehyde in *Glycine max* cells indicated that formaldehyde was first oxidized and then underwent C_1 metabolism (Giese et al. 1994). Different metabolic pathways for formaldehyde may be at work among various species, depending on the external conditions (Schmitz et al. 2000). For instance, at low levels, gaseous formaldehyde is metabolized by petunia plants producing glucose while formic acid is formed after 10 min and reaches its maximum level at 4 h followed by a substantial increase in the glycine production. When plants were grown in the presence of light and as the concentration of formaldehyde increases so did the generation of formic acid, glutamine, glucose and fructose, whereas glycine production was decreased (Sun et al. 2015). A different pattern has been observed for plants grown under dark conditions. Formaldehyde uptake was greatly reduced, followed by a decrease in glucose synthesis. On the contrary, formic acid generation, in the dark, was not affected at low levels of formaldehyde. When formaldehyde levels were augmented the formation of formic acids was weaker in petunia plants in the dark than in those grown in light conditions. Zhang et al. (2014) showed that liquid formaldehyde metabolism in petunia plants under low formaldehyde levels generated methionine as the main metabolite. Under high levels of formaldehyde, petunia plants produced substantial amounts of formic acid and glycine via C_1 metabolism and less glucose entered the Calvin cycle.

4.2 Factors affecting the efficiency of plant-based VOC removal

The efficiency of plants in removing VOCs from indoor air spaces is related to or affected by several factors. These factors can be biological, physical, or even mechanical in nature; most of which have been reviewed by Dela Cruz et al. (2014a). Here we explore several of these factors and briefly describe their impact on VOC removal.

As mentioned above, the uptake and metabolism of VOCs depends on the plant species. A diversity of indoor plants from of varying growth types exhibited differential capacities for air purification. As shown in Table 1, a wide range of indoor plant species can effectively remove indoor pollutants. Yang et al. (2009) have screened 28 indoor ornamental plants and found variation in their removal efficiency of five VOCs (benzene, toluene, octane, trichloroethylene, and terpene). Some species demonstrated a superior ability to remove all five VOCs, including *Hemigraphis alternata*, *Hedera helix*, *Hoya carnosa*, and *Asparagus densiflorus*. Other species, such as *Ficus benjamina,* effectively removed octane and terpene. Kim and Lee (2008) evaluated six species of orchids and found *Sedirea japonicum*, *Dendrobium phalaeonopsis*, and *Phalaeonopsis* sp. being the most effective in removing formaldehyde. Of the 73 ornamental plant species studied by Liu et al. (2007), only 10 were found to be effective in removing benzene. Moreover, Kim et al. (2010) assessed 86 plant species, including herbs, ferns, woody foliage plants, herbaceous foliage plants, and Korean native plants, and found that only 9 showed extremely high (> 1.2 mg m^{-3}) formaldehyde removal efficiency per cm^{-2} of leaf area. Among the different plant types studied, ferns displayed two- to three-fold greater removal efficiency on a leaf-area basis. Additionally, some fern species were shown to excel in the remediation of several metals and organic compounds, which can be found in contaminated soil and water, a property that designated them as hyperaccumulators (e.g. *Pteris vittata* for arsenic, Niazi et al. 2016). The different VOC removal capacities among plant species has been associated with differences in their water status, stomatal conductance (Liu et al. 2007) and selectivity for specific air pollutants. For example, *Kalanchoe blossfeldiana* removed benzene preferentially over toluene (Cornejo et al. 1999). Collins et al. (2000) demonstrated that the uptake of benzene was higher in blackberry and apple leaves than in cucumber leaves. Comparative studies using the indoor plant (spider plant- *Chlorophytum comosum*) and tobacco plant indicated elevated levels of formaldehyde uptake (10 μL L^{-1}) in the indoor species. Schmitz et al. (2000) have concluded that indoor plants do not actually contribute significantly to indoor air purification. This finding was based on their assessment of the capacity of plants to metabolize formaldehyde, which decreased stomatal conductance. However, other authors have argued in favor of several indoor plants to reducing volatile formaldehyde levels in the air. The controversy of these studies emphasizes on the importance of the conditions used to carry out the assessment the VOC removal efficiency of various plant species. Several researchers have proposed using a mixture of plant species to increase the removal of VOCs from indoor air (Yang et al. 2009; Sriprapat et al. 2014a).

The uptake and removal of VOCs also varies within the plant, where the different plant tissues displaying differential VOC removal efficiencies. Apple and cucumber fruits found to have significantly higher benzene concentrations than their leaves, while blackberries showed higher benzene levels in the leaves (Collins et al. 2000). Similarly, the above- and below-ground tissues showed different rates of VOC removal suggesting that both tissues contribute significantly to phytoremedation (Kim et al. 2008, 2014, 2016; Wolverton and McDonald 1982). Figure 2 shows the contribution of aerial plant parts versus the rhizosphere to VOC removal. Plant shoots (the aerial parts), roots, soil/media, and microorganisms are all involved in VOC removal. Formaldehyde removal by aerial plant parts versus the root zone is 1:1 by day and 1:11 by night (Kim et al. 2008). Wolverton and Wolverton (1993) reported that xylene removal during the day is 1:1 for aerial plant parts and root zone, whereas the ratio for formaldehyde removal was 37:63 and 40:60 during the day and night, respectively. The ratio between aerial parts and the root zone also affected the removal efficiency of toluene and xylene in different plant species. Ratios of 21:2 in *Dracaena fragans* and 21:3 in *Fatsia japonica* represented the highest removal levels for toluene and xylene (Kim et al. 2014). However, many of these studies did not distinguish the VOC removal efficiency between the belowground parts and their associated microorganisms.

It is clear that the number or volume of plants occupying a room is crucial to the effective VOC removal (Fig. 2). However, these parameters are highly variable and depend on the VOC composition and emanation rate, air exchange rate and many other factors associated with each room/house/building assessed pointing to the need of careful assessment of the in situ application of phytoremediation.

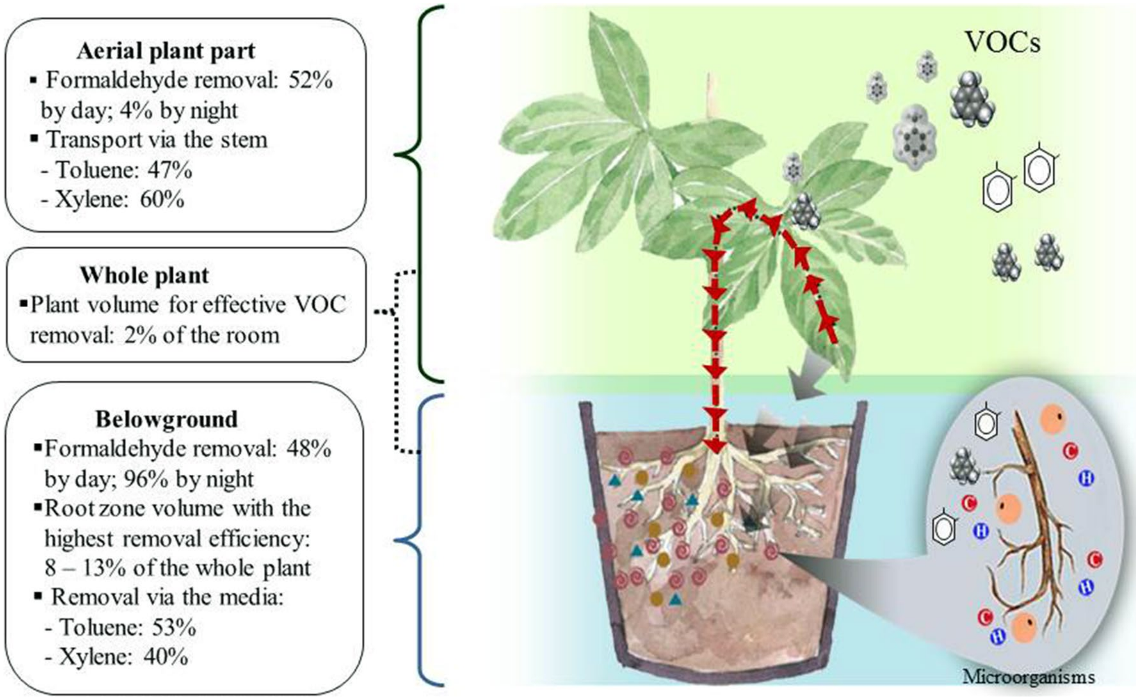

Fig. 2 The contribution made by different plant parts in VOC removal. Volatile organic compounds can be readily taken up by plant leaves, where they can be metabolized or translocated via the stem to other parts of the plant or to the rhizosphere, where they will be degraded by the plant or microorganisms (Kim et al. 2008, 2014, 2016)

Plant and leaf age also influence the efficiency of uptake and the removal of pollutants. For many species, the accumulation of epicuticular wax increases as the leaf age does. Ugrekhelidze et al. (1997) demonstrated that younger spinach, apple, and grape leaves had higher uptake of benzene and toluene than older leaves. Additionally, the capacity of *C. comosum* to remove formaldehyde was also shown to be dependent on the leaf age (Su and Liang 2015). Leaf extracts from fully developed leaves were 25 times more effective in removing formaldehyde than leaf extracts from mature leaves.

Since the uptake of VOCs is thought to be influenced by stomatal conductance, the type of photosynthetic system of each plant may also play an important role in VOC uptake and removal. *Kalanchoe blossfeldiana*, which has a facultative crassulacean acid metabolism (CAM), displays selectivity in benzene uptake over toluene (Cornejo et al. 1999). CAM plants are known to have temporal separation of C_3 and C_4 pathways during photosynthesis—i.e. CO_2 is fixed during the night while the 4-carbon intermediate from the C_4 is stored during the day, when the stomata are closed to reduce transpiration (Yamori et al. 2014). This partitioning mechanism allows the fixed carbon to be released and re-fixed within the plant via the C_3 pathway during the day. Sriprapat et al. (2014a) studied different combinations of C_3, C_4, CAM plants to identify the most effective combination of plants for xylene removal. For indoor conditions, a facultative CAM, constitutive CAM and C_3 plant combination was the most efficient system for xylene removal. Kim and Lee (2008) also compared different species of orchids with C_3 or CAM photosynthetic systems, with the C3 orchids exhibiting higher formaldehyde removal than the CAM orchids. However, this result was thought to reflect the high removal capacity of the root zone rather than the foliage. Interestingly, CAM orchids removed more formaldehyde during the day than they did at night, even though they were expected to have a higher efficiency at night when their stomata were open. The amount of time the stomata are open versus closed is a further factor to be considered when analyzing variations in VOC removal efficiency. In contrast, stomatal conductance did not limit the removal efficiency of benzene and toluene (Yoo et al. 2006).

Volatile organic compounds are usually found as a mixture in indoor air. Studies with single, binary, and mixed VOCs suggested that exposing plants to a mixture of benzene and toluene had a synergistic and deleterious effect in comparison with exposing plants to each pollutant separately (Yoo et al. 2006). However, the experiment used different concentrations for single and binary treatments (1 $\mu L\ L^{-1}$ each of benzene or toluene in comparison in comparison with 5 $\mu L\ L^{-1}$ benzene + 5 $\mu L\ L^{-1}$ toluene). Furthermore, some plant species may display selectivity for VOC removal, when the VOCs are present in mixtures (Cornejo et al. 1999).

Pre-exposure to VOCs as well as the frequency of exposure also stimulates subsequent VOC removal rates. Leaf extracts of *C. comosum* plants that were pre-exposed to formaldehyde were tested for their removal capacity of formaldehyde upon recurrent exposure to this VOC. Leaf extracts of the control plants were unable to remove formaldehyde, while those previously exposed to the formaldehyde treatment displayed a variable ability to dissipate the added formaldehyde (Su and Liang 2015). Kim et al. (2011) evaluated changes in toluene removal among 28 species/cultivars after exposed to the VOC once, twice, or three times. Most of the species displayed increasing removal efficiency as the exposure frequency increased up to three times, however, subsequent exposures did not further increase the rate of removal. The mechanism for this increased removal efficiency was not identified though the role of microorganisms was implied.

The efficiency of plants to removing a particular VOC is influenced by the molecular weight (Oyabu et al. 2001; Sawada and Oyabu 2008) and other physicochemical properties of the molecule. The difference in logarithm of the octanol–water partitioning coefficient (log K_{ow}) of ethylbenzene and toluene contributed to ethylbenzene being more readily adsorbed than toluene by cuticular wax (Sriprapat et al. 2014b).

Potting soils and media have the capacity to absorb VOC. Wolverton et al. (1984) observed that pots filled with commercial potting mixture were able to reduce formaldehyde in the air of a closed chamber. This finding suggested that the soil or potting media can act as a sink for volatile chemicals (Insam and Seewald 2010). Indeed, the type and volume of soil or media also influenced VOC removal efficiency. *Epipremnum aureum* planted in vermiculite removed more formaldehyde than plants planted in perlite or peat moss. The influence of root volume on removal efficiency was also assessed, and a positive correlation between the VOC removal rate and root volume was identified (Kim et al. 2014). The increment of removal, however, differed among the plant species studied, and this may be due to differences in root system structure.

Potting media and soil are known to contain microorganisms some of which can metabolize volatile organic compounds. Figure 3 illustrates the state of VOCs in the soil or growth medium of indoor plants. Some of the volatiles may adhere to solid particles and/or exist dissolved in a liquid film that in turn facilitates microbial degradation. Volatile organic compounds that remain in air pores within the soil or media may be degraded by microbes or dispersed via diffusion, conductivity and moisture movement within the media. Pollutant removal may be enhanced in several ways, for example through air circulation or ground covers as shown in Fig. 3. Increasing the air circulation (1–2 L min^{-1} L^{-1}) in the root zone increased VOC removal as much as 2–4 times (Kim 2016). Forcing polluted air from inside the house into the media, by pumping the air into the media or pulling the air through the container using a vacuum, allowed greater access of microorganisms to the VOCs enhancing their degradation.

The material covering or growing on the surface of the media can affect the movement of volatiles into the media. For example, planting *Selaginella tamariscina* as a ground cover increased formaldehyde removal by *Dieffenbachia amoena* by 50% compared to other materials (gravel, sand, and sphagnum peat moss) (Kim et al. 2011). However, the effect of the different ground covering materials was less evident in the case of *Chrysalidocarpus lutescens,* while a fine gravel cover on *Ficus benjamina* had a similar effect with that of *S. tamariscina*. Collectively, the VOC removal rate for all three plants species increased by 25% using *S. tamariscina* (Fig. 3).

5 Microbial-mediated phytoremediation of VOCs

The role of microorganisms, especially those associated with the root system, has been well established in pollution remediation due to their ability to metabolize a wide range of organic compounds (Weyens et al. 2015). Soil microorganisms have also been implicated in the removal of VOCs by indoor plants (Wolverton and McDonald 1982, Wolverton et al. 1984; Wolverton and Wolverton 1993) as they are able to effectively metabolize a wide number of indoor volatile contaminants. Little is known about the involvement of microbial communities, population dynamics or gene expression in enhancing VOC removal from indoor air. However, a number of studies have focused on mechanisms for degrading soil or water pollutants using bacteria. Several bacteria were isolated from the rhizosphere of *Epipremnum aureum* and identified as *Arthrobacter aurescens* TC1, *Arthrobacter oxydans*, *Leisfonia xyli* subsp. *xyli* str. CTB07, *Bacillus cereus*, *Pseudomonas putida,* and *Bacillus* spp. Among the isolates, *A. aurescens* TC1 displayed superior formaldehyde removal eliminating 86% of this pollutant from the test chamber within 24 h (Huang et al. 2012). The ability of *A. aurescens* TC1 to remove formaldehyde was associated with its enhanced enzymatic metabolism rather than due to the physical absorption of the compound. However, the specific enzyme(s) and mechanism of alteration have yet to be identified. The inoculation of *A. aurescens* TC1 in a biofilter bed with *E. aureum* demonstrated that the formaldehyde was degraded by the bacteria (Wang et al. 2014), albeit it was not clear whether the microbial community was the dominant contributor in the biofilter system responsible for formaldehyde removal. Zhang et al. (2013) isolated and identified several toluene-metabolizing bacteria from the rhizospheres of *Fittonia verschaffeltii* var.

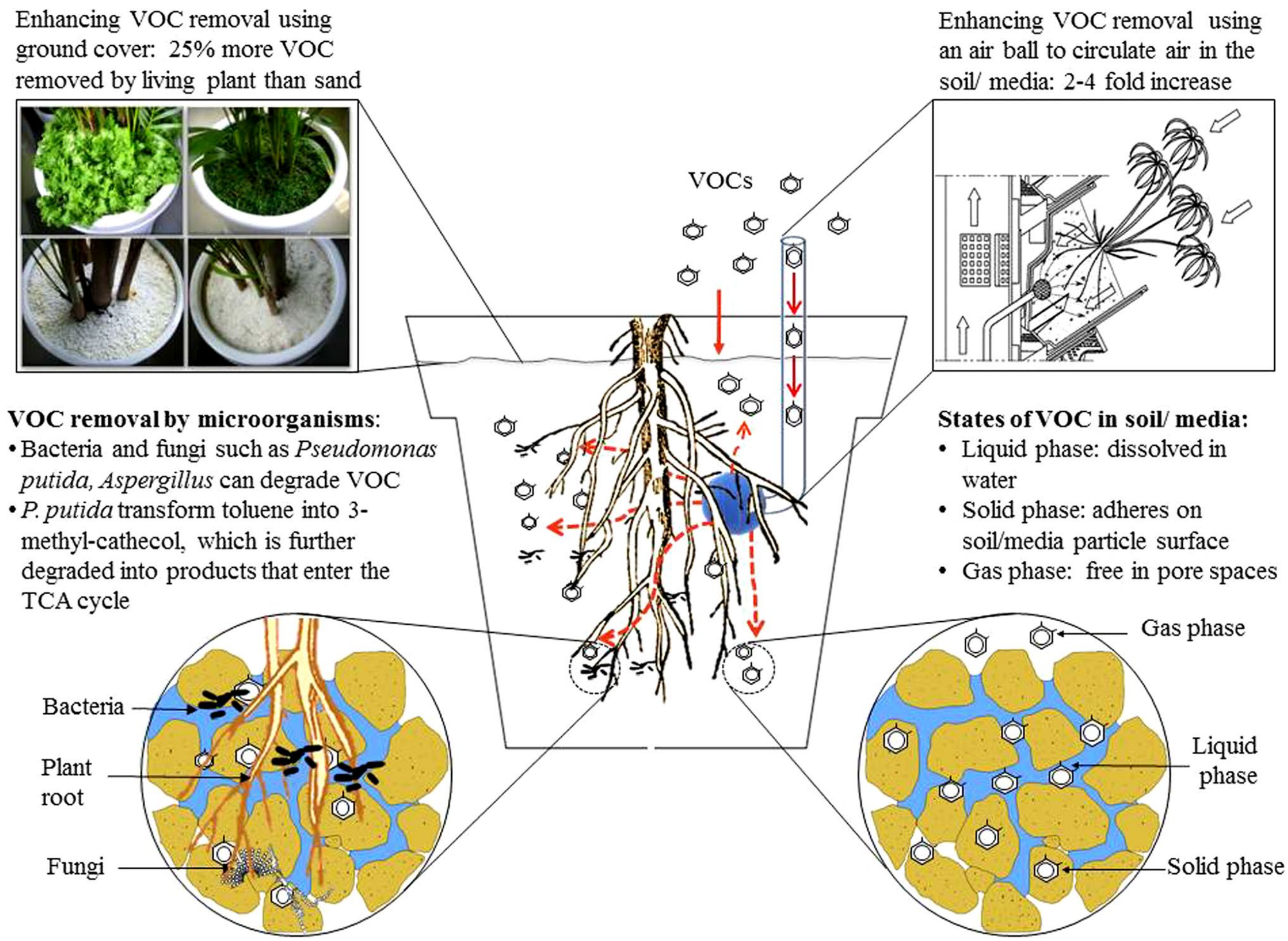

Fig. 3 The state of VOCs in the soil or growth media; microbial degradation of VOCs; and enhancing VOC removal in the rhizosphere. The soil or growth media serves as a sink for VOCs in indoor air. The VOCs can adhere to soil/media particles be in an aqueous phase that microorganisms may easily degrade. VOCs may exist in the pore spaces as free VOCs (Wang et al. 2012). Plant root exudates serve as a carbon source for many of the rhizosphere microorganisms, which can degrade the VOCs into products that enter the TCA cycle. The efficiency of VOC removal by the soil may be increased by circulating air through the soil/media using an air ball at the appropriate speed (Kim 2016) or by using the appropriate ground cover (Kim and Yoo 2011)

argyroneura and *Hoya carnosa*, with *F. verschaffeltii* rhizosphere harboring more diverse bacterial community than *H. carnosa*. However, the presence of diverse toluene-metabolizing bacteria in the root zone of *F. verschaffeltii* did not increase its efficiency for toluene removal when compared to *H. carnosa*. Moreover, comparing different bacterial isolates from different plant parts indicated that root endophytes had higher formaldehyde removal efficiency (Khaksar et al. 2016a). Inoculation of endophytic bacteria into a non-host indoor plant resulted to an enhancement of its efficiency of formaldehyde removal. For example, inoculation of *B. cereus* ERBP, isolated from *Clitoria ternatea*, enhanced the removal of formaldehyde by *Z. zamiifolia*, however, *E. milii*, inoculation appeared to hinder the removal of the same pollutant (Khaksar et al. 2016b).

Bacterial inoculation also affected the stomata opening process, where stomata of endophyte-inoculated plants were open during the night and therefore further influencing formaldehyde uptake (Khaksar et al. 2016b). Inoculation of the media with bacteria also had an ameliorating effect on the phytotoxicity of formaldehyde on indoor plants (Khaksar et al. 2016a). During the biodegradation process, the concentration of VOCs in the micro-environment of the microorganisms had a profound impact on microbial activity and the pollutant removal rate. Daisey et al. (1994) reported that gaseous toluene must move into an aqueous phase before being biodegraded.

Microbes are known to have the ability to detoxify and degrade a range of toxic substances, and the mechanisms underlying these processes have been investigated at the molecular level. Within the BTEX group, toluene is the most widely studied compound for the mechanisms governing its degradation by microorganisms. The aerobic degradation of BTEX molecules usually starts with oxidation of the methyl group, ring monooxidation, and/or ring dioxidation, depending on the bacterial species involved (Jindrova et al. 2002). The bacterial species most studied for their BTEX degradation capacity were *Pseudomonas putida* and *Pseudomonas* spp. (Jindrova et al. 2002). Cleavage of the aromatic ring of BTEX molecules ultimately leads to the production of acetaldehyde and pyruvate, which enter the TCA Cycle. Some fungal species are also able to transform and utilize aromatic hydrocarbons (Parales et al. 2008). For instance, *Aspergillus* sp. HUA, isolated from the sewage of a furniture factory, showed high efficiency for formaldehyde degradation (Yu et al. 2015). Thus, enhancing plant–microbe interactions in indoor air-purification systems can be a good strategy for improving phytoremediation efficiency of indoor plants (Xu et al. 2010). In fact, several studies have addressed the role of phyllosphere and endophyte bacteria on VOC removal as well as the mechanisms of plant-bacteria interactions (Weyens et al. 2015; Khaksar et al. 2016b; Ijaz et al. 2016; Wei et al. 2017).

6 Transgenic plants for enhanced indoor air purification

The use of transgenic plants to enhance the removal of VOC from indoor air space has been explored in several laboratories with the focus predominately being on formaldehyde. Genes and enzymes in plants, bacteria, and yeast facilitating the metabolism of different pollutants have been isolated and identified. Some of these genes have been incorporated into plants to increase their rate of formaldehyde metabolism (Achkor et al. 2003; Chen et al. 2010; Tada and Kidu 2011; Xiao et al. 2012; Nian et al. 2013; Zhou et al. 2015). Overexpression of dihydroxyacetone synthase and dihydroxyacetone kinase from methylotrophic yeasts increased their presence in the tobacco host plant's chloroplasts enhancing its photosynthetic formaldehyde-assimilation pathway (Zhou et al. 2015). Similarly, overexpression of glutathione dependent formaldehyde dehydrogenase (FALDH) from *Arabidopsis*, rice and *C. comosum* (golden pothos) increased the uptake of formaldehyde by about 25–40% in *Arabidopsis* compared to wild-type plants (Achkor et al. 2003; Tada and Kidu 2011). Moreover, expression of CYP2E1, a mammalian Cytochrome 450 in transgenic tobacco (*Nicotiana tabacum* cv. *Xanthii*) resulted to increased removal rates of VOCs, including benzene and toluene (Andrew James et al. 2008).

7 Application of botanical-based indoor air purification

While the knowledge on plant-microorganism interactions and their potential to remove pollutants from indoor air has been widely studied, its application to real-life settings is slowly emerging due to the limitations in translating the findings from sealed chamber experiments to strategies improving the air space of homes and offices. Llewellyn and Dixon (2011) argued that extrapolating static chamber phytoremediation results does not actually reflect the requirements for plants in specific indoor environments. The authors concluded that an active botanical biofiltration system, where air is pumped through the system, was more effective than solitary potted plants. Dela Cruz et al. (2014a) pointed out factors that are not taken into consideration in sealed chamber experiments such as the discontinuous VOC emission, VOC concentration, light intensity and lack of air exchange. Dela Cruz et al. (2014b) proposed a new semi-dynamic and dynamic experimental set up that can simulate a more realistic indoor environment, where the relative humidity, air exchange rate and VOC concentration were controlled to mimic the highly variable in situ conditions.

Biofilters and biotrickling filters are widely used as large scale air purification systems of waste gases and as odor treatment. In biofilters and biotrickling filters, gas flows through a fixed bed that is irrigated with a nutrient solution in an occasional or continuous manner, respectively. Degradation of the pollutants such as VOCs takes place in biofilms, which are synthesized by the microflora (Delhoménie and Heitz 2005). In order to enhance the performance of plants for indoor air purification, a hybrid of biofiltration and phytoremediation, called botanical biofiltration, was introduced (Soreanu et al. 2013). Such plant-based systems are available from commercial companies in the United States, Canada, the United Kingdom, India, and South Korea. Botanical biofiltration is an environment-friendly technology in which green plants are integrated into the biofilter structure. The plants and their root-associated microorganisms remove the pollutants from a moving contaminant stream (Soreanu et al. 2013). The term "Biowall" has recently emerged referring to a vertical garden that acts as a natural air filtration system, where the air is cleaned as it moves through the wall and is then distributed throughout the building using a traditional HVAC system (Butkovich et al. 2008).

Botanical biofiltration systems with the appropriately selected plants are suitable for the removal of BTEX and formaldehyde (Soreanu et al. 2013). The plants and their root-associated microorganisms convert harmful VOCs into carbon dioxide, water, and biomass. The production of carbon dioxide during the metabolism of some VOCs (e.g. formaldehyde) by plants should not be a concern, since the amount is generally relatively low and part of it is taken up by the plants to be used for photosynthesis. The energy consumption of botanical biofilters is also lower than that of other technologies used for indoor air purification (Luengas et al. 2015). Although some botanical biofilters are marketed, this technology still strives for acceptance. Table 2 presents a comparison of passive and active biofiltration techniques used for air purification. Many

Table 2 Comparison of passive and active techniques for phytoremediation of VOC from indoor air. *Sources*: Wolverton (1996), Kim et al. (2009), Soreanu et al. (2013), Thomas et al. (2015), Kim (2016), Liu et al. (2017)

Parameter	Techniques for phytoremediation	
	Passive biofiltration	Active biofiltration
Application	Potted plants, living walls/vertical gardens/green walls/vegetated façade (system where plants are grown on a vertical surface)	Biowalls, botanical biotrickling filters, vacuum pots, potted plants with air ball
Air circulation	No forced air, however, convection currents created through transpiration may cause air flow	Air is diffused through the plant shoots or through the media Air flow direction and rate may be modulated
Energy requirement	None	Required
Removal efficiency	Efficient in sealed chamber studies and some field studies	2–4 × more efficient than passive systems
Removal coverage	More plants needed to cover wide areas (e.g. 360 or 750 *Gardenia jasminoide* or *Rosmarinus officinalis* to reduce VOC by 67% in a 300 m^3 house; plants must occupy 1% of the room to result in 7% formaldehyde reduction)	Wider area covered
Rhizosphere micro-organism action on VOC	VOC transported from the shoots to the roots VOC dissolved from evapotranspiration droplets	VOC transported from the shoots to the roots VOC dissolved from evapotranspiration droplets VOC in gas phase in media
Cost	Affordable	Cheaper than other air filtration techniques
Other advantages	Eco-friendly	Eco-friendly; no production of ozone or nitrogen oxides

aspects, including increased relative humidity, possible pathogenic spore contamination, potential bacterial proliferation, the fertigation flow rate, nutrient concentration, water sources, air flow flux, plant species and light requirements, need to be addressed and balanced against the VOC present and its concentration. Potted plants generally act as passive biofilters, while botanical filters, such as the biotrickling filters used in biowalls, are active biofiltration systems. However, there are patents for individual pot systems, where a partial vacuum is created at the base of the pot forcing the air into the plant and down through the media containing microorganisms. The choice between a passive potted plant and a botanical biofilter depends on several factors including the availability of funds, the building location and the infrastructure limitations. Potted plants are the simplest and most economical choice for indoor air purification, although they remove pollutants at a slower rate. If passive potted plant systems are designed to exhibit greater VOC removal rates, then their benefits will be experienced from people inhabiting locations with poor electricity access. In contrast, botanical biofiltration offers better performance when high air-flow rates need to be purified, though these systems (e.g. biowalls) are more complex and often require professional establishment and maintenance.

8 Conclusion

Phytoremediation is the ability of plants and their associated microorganisms to remove pollutants from the environment. It is a cost-effective and environment-friendly technique for environmental cleanup. This review has discussed the mechanisms and factors that influence VOC removal efficiency. The current limitations of the technologies used for VOC removal have been highlighted. The removal of VOCs from indoor air by plants has evolved from passive filtration using potted plants to active filtration using botanical biofilters. Studies with potted plants in closed chambers continue to be useful for isolating factors that may enhance removal efficiency and therefore contribute towards the improvement of plant-based systems. Plants and their associated microorganisms have been proved to highly important for the bettering of indoor air quality and therefore further research on such strategies becomes a necessity.

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