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REVIEW ARTICLE

Can ornamental potted plants remove volatile organic compounds from indoor air? — a review

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Abstract Volatile organic compounds (VOCs) are found in indoor air, and many of these can affect human health (e.g. formaldehyde and benzene are carcinogenic). Plants affect the levels of VOCs in indoor environments, thus they represent a potential green solution for improving indoor air quality that at the same time can improve human health. This article reviews scientific studies of plants' ability to remove VOCs from indoor air. The focus of the review is on pathways of VOC removal by the plants and factors affecting the efficiency and rate of VOC removal by plants. Laboratory based studies indicate that plant induced removal of VOCs is a combination of direct (e.g. absorption) and indirect (e.g. biotransformation by microorganisms) mechanisms. They also demonstrate that plants' rate of reducing the level of VOCs is influenced by a number of factors such as plant species, light intensity and VOC concentration. For instance, an increase in light intensity has in some studies been shown to lead to an increase in removal of a pollutant. Studies conducted in real-life settings such as offices and homes are few and show mixed results.

Keywords Indoor air · Volatile organic compounds · Plants · Pollutants · Removal · Purification

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Introduction

Indoor air quality has become a major issue in recent years. Danish people spend up to 90 % of their time indoors (Gunnarsen et al. 2006) and factors such as exposure to volatile organic compounds (VOCs), thermal comfort and noise in the indoor environment have been identified as stressors that can cause both short- and long-term effects on humans (Bluyssen et al. 2011). VOCs in indoor air have received appreciable attention due to their adverse health effects on humans (Jones 1999). Examples are formaldehyde, which can cause sensory irritation and nasopharyngeal cancer and has a 30-min average concentration guideline value of 0.1 mg/m^3, and benzene, which can cause blood dyscrasias and where no safe level of exposure can be recommended (World Health Organization 2010).

In a recent study, indoor residential concentrations of VOCs were compared to health guidelines set by a number of agencies including the World Health Organization and the United States Environmental Protection Agency (Logue et al. 2011). For 18 out of 59 VOCs the indoor concentrations were higher than at least one guideline value (Logue et al. 2011). In addition, VOCs are often recognized as odours before they reach levels that can affect human health, thereby contributing to the perception of indoor air quality (Wolkoff et al. 2006). The level and composition of VOCs that a person is exposed to on a daily basis varies according to personal activities and indoor sources (Edwards et al. 2001). Furthermore, VOC concentrations in indoor environments vary according to season and are highest in the wintertime (Rehwagen et al. 2003; Schlink et al. 2004). The main reason for this observation may be a reduction in air exchange rate during winter due to closed windows (Schlink et al. 2004).

VOCs are emitted from materials such as carpets, wallpaper, office chairs, and electronic equipment (Destaillats et al. 2008; Wolkoff 1995; Yu and Crump 1998), with highest

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emissions when the material is new (Yu and Crump 1998). The emission of a chemical from a certain material depends on the concentration of the chemical in the material, the concentration of the chemical in the room holding the material, the room air exchange rate, and the total surface area of the material compared to the volume of air in the room (Yu and Crump 1998).

The level of VOCs in indoor air can be reduced by using low-emission products and dispersing and diluting the emitted VOCs by means of ventilation (World Health Organization 2010). If further reduction of the pollution is needed, techniques such as filtration and adsorption to e.g. activated charcoal or silica gel exist (Yu et al. 2009). An alternative way to reduce the level of VOCs in indoor air is the use of plants. Several ornamental potted plant species have the ability to absorb VOCs from indoor air (Yang et al. 2009). Thereby, the plants act as sinks and consequently reduce the VOC concentration in the air. In addition, decorating offices with plants can decrease levels of discomfort such as cough and fatigue and improve health (Fjeld et al. 1998). These effects may in part be caused by the plants removing VOCs from the air. Plants also have the advantage that they can have psychological and social benefits for humans (Bringslimark et al. 2009; Thomsen et al. 2011).

The aim of the present review is to provide insight into how VOCs are removed by a potted plant and which factors affect the efficiency and rate of VOC removal by plants. The review is organized by firstly presenting the section "Summary of laboratory and field studies", which is divided into four subsections. The first section ("Pathways for VOC removal") describes how VOCs are removed by potted plants and is divided into "Removal of VOCs by aboveground plant parts", "Removal of VOCs by microorganisms", and "Removal of VOCs by growing media and roots". The second section ("Factors affecting the efficiency and rate of VOC removal by plants") deals with how factors such as light and VOC concentration can influence VOC removal and is divided into "Plant species", "Growing media", "Light", "Temperature", "VOC concentration", "VOC identity", and "VOC mixture effects". The third section ("VOC removal in real-life settings") is a summary of studies conducted in indoor settings with the intention of evaluating if VOC removal by plants is of value in real-life situations. The fourth section ("Plant modifications for enhanced VOC removal") evaluates if VOC removal can be enhanced by genetically modifying plants. At the end of the review, "Supplementary comments and future research needs" discusses additional information obtained in the reviewed literature studies, the applicability of laboratory studies for real-life simulations, and suggest future research needs. Finally, the "Conclusion" is presented.

The review is limited to indoor plants' ability to remove VOCs including formaldehyde. This means that only organic pollutants that are mainly in their gas phase are the focus of the review. The literature regarding indoor VOC removal by plants is limited and studies dealing with outdoor VOC removal by plants as well as removal of polycyclic aromatic hydrocarbons (PAHs) and pesticides are in some cases included to provide a more in depth analysis. However, outdoor removal of VOCs, PAHs, and pesticides is not the focus of this review. In addition, mechanical strategies to enhance indoor VOC removal by plants such as drawing air through the potting mix of plants are not included.

To our knowledge, no review deals only with indoor potted plants' ability to remove VOCs. Reviews exist on general biological treatment of indoor air which include active biofiltration, but also deals to some extent with potted plants (Guieysse et al. 2008; Soreanu et al. 2013). In addition, there are several reviews on bioremediation and phytoremediation which focus on remediation of soils (Arthur et al. 2005; Juwarkar et al. 2010; McGuinness and Dowling 2009; Salt et al. 1998), as well as reviews of modelling on xenobiotic accumulation in edible plants (Collins and Finnegan 2010; Trapp 2004; Zebrowski et al. 2004). Recently, a review has been published dealing with deposition of atmospheric PAHs in plants (Desalme et al. 2013). The review by Desalme et al. (2013) offers valuable insight into deposition, accumulation, mechanisms of transfer, and ecological and physiological effects of PAHs.

To help the reader throughout this review, two terms for removal of VOCs are used: (1) removal rate (the amount of VOC removed per unit time per leaf area) or (2) removal efficiency (percentage of VOC removed per unit time per leaf area). There is an inconsistency in the units used in the reviewed literature but for many purposes the conclusions obtained are not affected by this. However, the terms become important when evaluating effects of VOC concentration. For further help throughout the review, suggestions for botanical names are given in brackets following the common English name for those studies where it was not included by the researchers. In addition, light intensities have been converted from lux to μmol/m^2/s (Enoch and Kimball 1986) and VOC concentrations have been converted to μg/m^3 where possible under 101,325 Pa and temperature given in the study.

Summary of laboratory and field studies

More than 100 plant species have been examined to estimate their ability to remove VOCs from indoor air (see Table 1). The results of the reviewed literature document that plants in general are able to remove VOCs. As an example, seven plant species removed 59–337 ppm/m^2/day of benzene (Table 1), which, with a chamber size of 0.216 m^3, corresponds to a removal rate of 43.8–205.6 mg/m^2/day (Orwell et al. 2004). In addition, three plant species removed 3,371–4,759 μg formaldehyde in 7 h (Table 1) (Wolverton and Mcdonald 1982).

Table 1 Overview of studies conducted in laboratories on VOC removal by indoor plants

Reference	Plant species	VOC	VOC concentration ($\mu g/m^3$)	Removal rate or removal efficiency
Aydogan and Montoya (2011)	*Chrysanthemum morifolium*, *Dieffenbachia compacta*, *Epipremnum aureum*, *Hedera helix*	Formaldehyde	2,000	81–96 % in 24 h
Baosheng et al. (2009)	*Epipremnum aureum*, *Phoenix roebelenii*	Formaldehyde, acetone, benzene, toluene, xylene, styrene	5,650–9,787	2.5–34 V/h[a]
Chun et al. (2010)	*Ficus elastica*, *Pachira aquatica*, *Syngonium podophyllum*	Benzene, toluene, *m/p-xylene*, *o*-xylene	15,116	28–91 % in 12 h[a]
Cornejo et al. (1999)	*Chlorophytum comosum*, *Dracaena deremensis*, *Ficus elastica*, *Kalanchoë blossfeldiana*, *Magnesia* sp., *Pelargonium domesticum*, *Primula sinensis*, *Saxifraga stolonifera*, *Tradescantia fluminensis*	Benzene, pentane, toluene	33,543	0.6–8.5 μg/g/day
De Kempeneer et al. (2004)	*Azalea indica*	Toluene	339,000	DT95%: 7–76 h
Godish and Guindon (1989)	*Chlorophytum comosum*	Formaldehyde	N/A	29–90 %
Hasegawa et al. (2003)	*Schefflera arboricola*	Formaldehyde	N/A	N/A
Hasegawa et al. (2004)	*Schefflera arboricola*, *Nephrolepis exaltata*	Formaldehyde	80,600	N/A
Irga et al. (2013)	*Syngonium podophyllum* 'White Butterfly'	Benzene	80,360	739–14,44 $\mu g/m^3/h$ per pot
James et al. (2008)	*Nicotiana tabacum*	1,1,1-Trichloroethane, benzene, bromodichloromethane, carbon tetrachloride, chloroform, perchloroethylene, toluene, trichloroethylene, vinyl chloride	2,500–22,000,000	0–157 μg/d[a]
Jin et al. (2013)	*Hedera helix*, *Melissa officinalis*	Formaldehyde	2,500	2.22–25.06 $mg/m^2/h$
Kim and Kim (2008)	*Ardisia japonica*, *Epipremnum aureum*, *Spathiphyllum* sp., *Stephanotis floribunda*, *Syngonium podophyllum*	Formaldehyde	2,488	0.14–0.88 $\mu g/m^3/cm^2$ in 5 h
Kim and Lee (2008)	*Cymbidium* sp., *Cymbidium* Meglee 'Ms Taipei', *Dendrobium phalaenopsis*, *Ficus benjamina*, *Oncidium* sp., *Phalaenopsis* sp., *Sansevieria trifasciata*, *Sedirea japonica*	Formaldehyde	2,472	0.14–1.36 $mg/m^3/cm^2$ in 5 h[a]
Kim et al. (2008)	*Fatsia japonica*, *Ficus benjamina*	Formaldehyde	2,472	T50%: 96 min — not reached
Kim et al. (2009)	*Epipremnum aureum*, *Gardenia jasminoides*, *Rosmarinus officinalis*	Formaldehyde	2,472	3.4–6.6 $mg/m^3/h/m^3$ plant volume
Kim et al. (2010)	86 plant species divided into five groups: woody foliage plants, herbaceous foliage plants, Korean native plants, ferns and herbs	Formaldehyde	2,472	0.13–6.64 $mg/m^3/cm^2$ in 5 h
Kim et al. (2011b)	*Aloysia triphylla*, *Ardisia crenata*, *Ardisia japonica*, *Ardisia pusilla*, *Begonia maculata*, *Cinnamomum camphora*, *Davallia mariesii*, *Eurya emarginata*, *Farfugium japonicum*, *Fittonia verschaffeltii*, *Hedera helix*, *Ilex cornuta*, *Ligustrum japonicum*, *Melissa officinalis*, *Mentha piperita*, *Mentha piperita* 'Citrata', *Mentha suaveolens*, *Mentha suaveolens* 'Variegata', *Pelargonium graveolens*,	Toluene	5,000	−4.3 to 950.3 $\mu g/m^3/h/m^2$

Table 1 (continued)

Reference	Plant species	VOC	VOC concentration ($\mu g/m^3$)	Removal rate or removal efficiency
	Philodendron sp. 'Sunlight', *Pinus densiflora*, *pittosporum tobira*, *Plectranthus tomentosus*, *Rhododendron fauriei*, *Rosmarinus officinalis*, *Salvia elegans*, *Schefflera elegantissima*, *Soleirolia soleirolii*			
Kim et al. (2012)	*Ardisia crenata*, *Ardisia japonica*, *Begonia maculata*	Toluene	4,896–13,181	2.5–40 $\mu g/m^3/h/m^2$ [a]
Kondo et al. (1995)	*Nerium indicum*	Formaldehyde	43–300	9.5–135 $ng/dm^2/h/ppb$[a] 4–40 $\mu g/dm^2/h$[a]
Kondo et al. (2005)	*Nerium indicum*	Trichloroethylene, tetrachloroethylene	250–420	No removal
Lim et al. (2009)	*Fatsia japonica*	Formaldehyde	2,400	700 $\mu g/m^3$ in 5 h
Liu et al. (2007)	*Citrus medica* 'Sarcodactylis', *Crassula portulacea*, *Cymbidium* 'Golden Elf', *Dendranthema morifolium*, *Dieffenbachia amoena* 'Tropic Snow', *Dracaena deremensis* 'Variegata', *Ficus microcarpa* 'Fuyuensis', *Hydrangea macrophylla*, *Nephrolepis exaltata* 'Bostoniensis', *Spathiphyllum supreme*	Benzene	479	59–724.9 $mg/m^2/day$
Orwell et al. (2004)	*Dracaena deremensis* 'Janet Craig', *Dracaena marginata*, *Epipremnum aureum*, *Howea forsteriana*, *Schefflera actinophylla* 'Amate', *Spathiphyllum floribundum* 'Petite', *Spathiphyllum floribundum* 'Sensation'	Benzene	80,000	59–337 $ppm/day/m^{-2}$
Orwell et al. (2006)	*Dracaena deremensis* 'Janet Craig', *Spathiphyllum* 'Sweet Chico'	Toluene, *m*-xylene	758–437,000	0.68–1,014 $mg/m^2/day$
Oyabu et al. (2001)	*Epipremnum aureum*	Acetone, benzene, ethyl alcohol, formaldehyde, toluene, trichloroethylene, xylene	6,184–61,842	1.6–23 V/h[a]
Oyabu et al. (2003a)	*Epipremnum aureum*, *Ficus elastica*, *Nephrolepis exaltata*, *Sansevieria trifasciata*	Formaldehyde	6,200–49,600	10–35 V/h[a]
Oyabu et al. (2003b)	*Epipremnum aureum*	Acetone, formaldehyde	2,394–24,758	7–41 V/h[a]
Oyabu et al. (2003c)	*Epipremnum aureum*	Gasoline	0.01–0.05 ml liquid in a 300-l chamber	3.7–7.5 V/h[a]
Oyabu et al. (2005)	*Epipremnum aureum*, *Spathiphyllum*	Formaldehyde, toluene, xylene	3,805–9,920	8–42 V/h[a]
Porter (1994)	*Dieffenbachia amoena* 'Tropic Snow'	Benzene, toluene	8,669 or 43,345	5.11–35 % in 3 h
Sawada et al. (2007)	*Nicotiana tabacum*	Formaldehyde, styrene, toluene, xylene	5,612–24,387	10.6–108 h^{-1}[a]
Sawada and Oyabu (2008)	*Epipremnum aureum*	Formaldehyde, toluene, xylene	5,726–10,268	23.5–90 $V/h/m^2$
Sriprapat and Thiravetyan (2013)	*Zamioculcas zamiifolia*	Benzene, ethylbenzene, toluene, xylene	62,392–84,806	86–96 $mmol/m^2$ in 120 h 28–68 $mmol/m^2$ in 7 days
Tani and Hewitt (2009)	*Epipremnum aureum*, *Spathiphyllum clevelandii*	Acetone, benzaldehyde, *iso*-butyraldehyde, *n*-butyraldehyde, crotonaldehyde, diethyl ketone, methacrolein, methyl ethyl ketone, methyl isobutyl ketone, methyl isopropyl ketone, methyl *n*-propyl ketone,	33–3,357	0–13.2 $mmol/m^2/s$ Normalized to inlet concentration

Table 1 (continued)

Reference	Plant species	VOC	VOC concentration ($\mu g/m^3$)	Removal rate or removal efficiency
		propionaldehyde, *iso*-valeraldehyde, *n*-valeraldehyde		
Tani et al. (2007)	*Epipremnum aureum*	Methyl isobutyl ketone	307–3,071	0.8–2.4 $nmol/m^2/s$ [a]
Treesubsuntorn and Thiravetyan (2012)	*Chamaedorea seifrizii*, *Scindapsus aureus*, *Sansevieria trifasciata*, *Philodendron domesticum*, *Ixora barbata* 'Craib', *Monster acuminate*, *Epipremnum aureum*, *Dracaena sanderiana*,	Benzene	62,392	43–77 % in 72 h
Wolverton and Mcdonald (1982)	*Ipomoea batatas*, *Scindapsus aureus*, *Syngonium podophyllum*	Formaldehyde	19,425–23,067	3,371–4,759 μg in 7 h
Wolverton and Wolverton (1993)	*Aechmea fasciata*, *Aglaonema* 'Silver Queen', *Aloe barbadensis*, *Anthurium andraeanum*, *Calathea ornata*, *Chamaedorea elegans*, *Chlorophytum comosum* 'Vittatum', *Chrysanthemum morifolium*, *Cissus rhombifolia*, *Cyclamen persicum*, *Dendrobium* sp., *Dieffenbachia camille*, *Dieffenbachia* 'Exotica Compacta', *Dieffenbachia maculata*, *Dracaena deremensis* 'Janet Craig', *Dracaena deremensis* 'Warneckii', *Dracaena fragrans*, *Dracaena marginata*, *Euphorbia pulcherrima*, *Ficus benjamina*, *Ficus sabre*, *Guzmania* 'Cherry', *Hedera helix*, *Homalomena* sp., *Kalanchoë*, *Liriope spicata*, *Neoregelia* cv., *Nephrolepis exaltata* 'Bostoniensis', *Nephrolepis obliterata*, *Phalaenopsis* sp., *Phoenix roebelenii*, *Rhapis excelsa*, *Rhododendron indicum*, *Sansevieria trifasciata*, *Senecio cruentus*, *Spathiphyllum* 'Clevelandii', *Syngonium podophyllum*, *Tulip* 'Yellow Present'	Formaldehyde, xylene	N/A	47–1,863 μg/h
Wolverton et al. (1989)	*Aglaonema modestum*, *Aglaonema* 'Silver Queen', *Aloe vera*, *Chamaedorea seifrizii*, *Chlorophytum elatum*, *Chrysanthemum morifolium*, *Dracaena deremensis* 'Janet Craig', *Dracaena deremensis* 'Warneckii', *Dracaena marginata*, *Dracaena massangeana*, *Ficus benjamina*, *Gerbera jamesonii*, *Hedera helix*, *Musa oriana*, *Philodendron domesticum*, *Philodendron oxycardium*, *Philodendron selloum*, *Sansevieria laurentii*, *Scindapsus aureus*, *Spathiphyllum* 'Mauna Loa'	Benzene, formaldehyde, trichloroethylene	316–207,535	1,555–107,653 μg in 24 h 9.2–89.8 % in 24 h
Wood et al. (2002)	*Dracaena deremensis* 'Janet Craig', *Howea forsteriana*, *Spathiphyllum wallisii* 'Petite'	Benzene, *n*-hexane	80,000–353,000	367–4,032 $mg/m^3/day/m^2$
Xu et al. (2011)	*Aloe vera*, *Chlorophytum comosum*, *Epipremnum aureum*	Formaldehyde	1,000–11,000	0–2.2 mg/h[a]
Yang et al. (2009)	*Anthurium andraeanum*, *Asparagus densiflorus*, *Aspidistra elatior*, *Calathea roseopicta*, *Chlorophytum comosum*, *Codiaeum variegatum*, *Dieffenbachia seguine*, *Dracaena fragrans*, *Epipremnum aureum*, *Ficus benjamina*, *Ficus elastica*, *Fittonia argyroneura*, *Guzmania* sp., *Hedera helix*, *Hemigraphis alternata*, *Howea belmoreana*, *Hoya carnosa*, *Maranta leuconeura*, *Pelargonium graveolens*, *Peperomia clusiifolia*, *Philodendron scandens* sp. *oxycardium*, *Polyscias fruticosa*, *Sansevieria trifasciata*, *Schefflera arboricola*, *Schefflera elegantissima*, *Spathiphyllum wallisii*, *Syngonium podophyllum*, *Tradescantia pallida*	Benzene, octane, α-pinene, toluene, trichloroethylene	30,900–59,100	0–13.28 $\mu g/m^3/m^2/h$
Yoo et al. (2006)		Benzene, toluene	3,204–3,779	18.8–220.2 $ng/m^3/cm^2/h$

Table 1 (continued)

Reference	Plant species	VOC	VOC concentration ($\mu g/m^3$)	Removal rate or removal efficiency
	Cissus rhombifolia, *Hedera helix*, *Spathiphyllum wallisii*, *Syngonium podophyllum*			
Zhou et al. (2011)	*Agave potatorum*, *Aglaonema commutatum* 'Golden Jewelry', *Aglaonema commutatum* 'White Rajah', *Aglaonema commutatum* 'Red Narrow', *Aglaonema commutatum* 'Silver Queen', *Aglaonema commutatum* 'Treubii', *Alocasia macrorrhiza*, *Aloe aristata*, *Aloe nobilis*, *Asparagus setaceus*, *Chlorophytum comosum*, *Cordyline fruticosa*, *Dieffenbachia amoena* 'Camilla', *Dieffenbachia amoena* 'Green Magic', *Dracaena angustifolia*, *Dracaena deremensis* 'Compacta', *Dracaena fragrans* 'Massangeana', *Dracaena reflexa*, *Dracaena sanderiana*, *Gasteria gracilis*, *Philodendron martianum* 'Congo', *Philodendron selloum*, *Philodendron sodiroi* 'Wendimbe', *Sansevieria trifasciata* 'Hahnii', *Sansevieria trifasciata* 'Laurentii', *Scindapsus aureus*, *Scindapsus pictus* 'Argyraeus', *Spathiphyllum floribundum* 'Clevelandii', *Syngonium podophyllum*, *Zamioculcas zamiifolia*	Formaldehyde	15,000	2.21–4.60 mg/m^3 in 7 days

[a] Values have been extrapolated from graphs

With leaf areas of 6,440, 6,442 and 5,667 cm^2, this corresponds to a removal rate of 20.4–25.3 mg/m^2/day. These results also indicate that there is a large variability in VOC removal both within the same study for various plant species and between two related studies. Therefore, to understand the nature of these removal rates, it is necessary to investigate how the VOCs are removed and how different factors such as light intensity and VOC concentration can affect the efficiency and rates by which VOCs are removed by plants. Based on the reviewed literature, Fig. 1 provides an overview of the pathways of VOC removal by both the aboveground and belowground parts of the plant, and factors that have been investigated in relation to effects on VOC removal by plants. First listed are factors related to the potted plant (i.e. plant species and growing media), next are environmental factors (i.e. temperature and light), and last are chemical factors (i.e. VOC concentration, VOC identity and VOC mixture effects). These pathways and factors will be reviewed in the following sections.

Pathways for VOC removal

Pathways for removal of VOCs by potted plants can largely be divided into four types: (1) removal by the aboveground plant part, (2) removal by the microorganisms residing in the soil, (3) removal by the roots, and (4) removal by the growing media. In the reviewed literature, removal by the roots has not been separated from removal by the growing media and these two pathways are therefore treated in the same section.

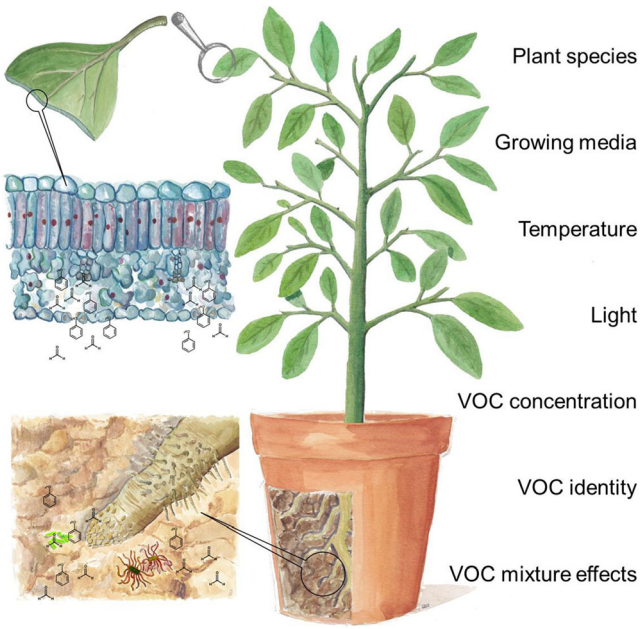

Fig. 1 Overview of VOC removal by plant. *Left*: suggested uptake of formaldehyde and toluene through the cuticle and stomata of the leaves and by microorganisms and roots in the soil. *Right*: factors that can affect plants' VOC removal efficiencies and rates (illustration by Ramón Guitián)

Removal of VOCs by aboveground plant parts

Both the stomata and cuticle are suggested to be pathways for VOC removal by the aboveground plant parts (Fig. 1). Uptake through stomata was shown for formaldehyde where increased removal was linearly related to increased stomatal conductance of *Nerium indicum* (Kondo et al. 1995). The results were obtained by measuring the transpiration rate. However, since wind speed and the boundary layer were kept constant, the increase in transpiration rate was assumed to be equal to an increase in stomatal conductance. Tani et al. (2007) noted that the intercellular concentration of methyl isobutyl ketone was high when the stomatal conductance was high and suggested that uptake was regulated by the stomata. Studies conducted on only the aboveground plant parts document higher removal of formaldehyde, benzene and toluene in light than in darkness. It was therefore concluded that these compounds were taken up through the stomata as stomata are open in light and closed in darkness (Kim et al. 2008; Treesubsuntorn and Thiravetyan 2012; Yoo et al. 2006). Due to the fact that the aboveground parts were still removing VOCs in darkness and a decline in removal was not always observed, other uptake sites were suggested such as cuticular absorption or adhesion (Kim et al. 2008; Treesubsuntorn and Thiravetyan 2012; Yoo et al. 2006). The stomata were not examined in any of the studies and it can, therefore, not be confirmed that the pollutants were taken up through the stomata. Under water stress *Zamioculcas zamiifolia* showed no difference in removal of benzene, toluene, ethylbenzene and xylene under dark and light conditions. Here the stomata were open under dark conditions due to the plant's unregulated crassulacean acid metabolism (CAM) properties (Sriprapat and Thiravetyan 2013). The majority of plants take up and use CO_2 during the day where their stomata are open. CAM plants take up CO_2 during the night and metabolize it during the day, which means they have their stomata open during night time and closed during daytime. The removal of VOCs in darkness can, therefore, not necessarily be ascribed to non-stomatal pathways unless it is confirmed that the stomata are closed. A light-phase metabolic role such as stomata was suggested to be of no importance when it was observed that moving plants from light to dark conditions had no effect or caused a slight increase in removal efficiency and rate of formaldehyde, benzene and *n*-hexane (Godish and Guindon 1989; Orwell et al. 2004; Wood et al. 2002). In these studies, the pots had not been sealed and removal of the VOCs was not restricted to the aerial plant parts. A conclusion about the role of stomata is difficult to make as the removal of the VOCs is possibly influenced by the roots, growing media and microorganisms.

Studies directly examining the role of stomata and cuticle show uptake by both sites. ^{14}C benzene and toluene were mainly taken up through the stomata, but there was still substantial uptake through the cuticle by *Vitis vinifera*, *Malus domestica*, and *Acer campestre* (Ugrekhelidze et al. 1997). The uptake was examined for both the upper and lower side of the leaves by letting them float on water. Thereby it was possible to distinguish between uptake through the cuticle and uptake through both cuticle and stomata, since the stomata are only located on the lower side of the leaves from these plants (Ugrekhelidze et al. 1997). A confounding factor in this study may be the partitioning of the compounds into water and further sorption to the leaf side under water. However, it is hypothesized that this would be minimal and it should, therefore, not affect the results.

Adsorption by crude wax of *Dracaena sanderiana* was estimated to account for 46 % of total benzene uptake (Treesubsuntorn and Thiravetyan 2012). Cuticular absorption by *Z. zamiifolia* accounted for 20 %, 23 %, 25 %, and 26 % of benzene, toluene, ethylbenzene, and xylene uptake, respectively (Sriprapat and Thiravetyan 2013). These percentages were based on the amount of VOC that extracted wax from the plants had adsorbed after 120 h. The studies show that benzene, toluene, ethylbenzene, and xylene can be adsorbed by the wax layer, but the relation between uptake through the stomata and cuticle may not be correct as the uptake by the extracted wax is not a dynamic process as it would be by the plant.

The pathway for VOC uptake by the aboveground plant parts is likely dependent on the properties of the VOCs. A hydrophilic VOC such as formaldehyde will not diffuse easily through the cuticle that consists of lipids whereas a lipophilic VOC such as benzene is more likely to penetrate through the cuticle. The relative importance of the stomatal uptake compared to the cuticular uptake will therefore be dependent on the VOC in question. Indeed, in work with modelling plant uptake of xenobiotics the VOC characteristics that are included are often the 1-octanol/water partition coefficient and the Henry's law constant or the air/water partition coefficient (Bacci et al. 1990; Riederer 1995; Trapp 2007). The ease of entry through the cuticle has been shown to be directly proportional to the molecular size of the compound (Sabljic et al. 1990). These investigations are conducted within an agricultural or outdoor bioremediation context with pollutants such as pesticides or PAHs, and much is based on theoretical calculations. It is necessary to also investigate these factors for the special situation of indoor VOC removal by potted plants.

After entering the leaf, a compound can undergo degradation, storage or excretion, either at site of uptake or after translocation to other parts of the plant. Tani and Hewitt (2009) observed that for eight aldehydes and five ketones, the amount of pollutant taken up was 30–100 times higher than what theoretically could be absorbed by the aqueous phase inside the leaves. This finding indicated metabolism or translocation (Tani and Hewitt 2009). Removal rates

obtained at different concentrations of toluene and *m*-xylene exhibited possible saturation and it was suggested that the VOCs were undergoing enzymatic reactions (Orwell et al. 2006; Porter 1994). This is supported by studies using radioactive labelled VOCs. *Glycine max* cells were exposed to ^{14}C labelled formaldehyde, and the allocation of the ^{14}C indicated that formaldehyde was firstly detoxified by oxidation and subsequently underwent C1 metabolism (Giese et al. 1994). Uptake and transformation of ^{14}C labelled formaldehyde by *Epipremnum aureum* and *Ficus benjamina* indicated that formaldehyde was transformed into CO_2 and built into the plant material via the Calvin cycle (Schmitz et al. 2000). On the other hand, leaves of *Spinacia oleracea* primarily incorporated benzene and toluene into low-molecular weight compounds and to a lesser extend into high-molecular weight compounds (Ugrekhelidze et al. 1997). In the outdoor context, degradation of xenobiotics has been reviewed by Korte et al. (2000).

Degradation to harmless constituents is the optimal goal, but storage or excretion will be necessary if degradation cannot occur. Storage by the plant will remove VOCs from the air but excessive storage may lead to damaging effects on the plant due to pollutants building up to lethal concentrations. Storage of pollutants has not been investigated in relation to indoor VOC removal by plants, but accumulation of benzene was observed in apple and blackberry leaves as well as in the fruits of apple, blackberry and cucumber (Collins et al. 2000). If the VOC is excreted after uptake, the effect on the indoor VOC concentration is limited. However, the pollutant may be excreted by the roots and subsequently degraded by microorganisms in the soil or adsorbed to the soil particles. Uptake by leaves and subsequent excretion by roots has been observed for trichloroethylene and 1,2,3-trichlorobenzene in wheat, tomato and corn (Su and Liang 2013).

Removal of VOCs by microorganisms

Microorganisms residing in the soil of potted plants are suggested to play an essential role in removal of VOCs from indoor air. A bacterial culture derived from the soil of plants exposed to benzene could account for the whole of the VOC removal by the plant/soil system (Orwell et al. 2004; Wood et al. 2002). Bacterial counts in the soil of plants that had been exposed to benzene were unaltered compared to counts before exposure but the bacterial community was changed (Wood et al. 2002). A change in bacterial community as a result of benzene exposure was also observed by Irga et al. (2013). In a different study, bacterial counts were related to removal efficiency of benzene, but this was inconsistent and other unspecified biological factors were therefore suggested to be important (Wolverton et al. 1989). Wolverton and Wolverton (1993) suggested that gram negative bacteria such as *Pseudomonas* were responsible for a higher removal rate obtained by *Spathiphyllum* sp. than by *Kalanchoë* sp. as gram negative bacteria were found in the soil from *Spathiphyllum* sp. but not in the soil from *Kalanchoë* sp. From the soils of *Hoya carnosa* and *Fittonia verschaffeltii* var. *argyroneura*, 12 and 30 bacterial isolates were obtained, respectively. The plants were grown in identical potting mix and exposed continuously to toluene for 2 months (Zhang et al. 2013). From the 42 bacterial isolates, 23 were characterized and shown to have sequence similarity of 97–100 % with eight known bacteria strains of which *Microbacterium aerolatum* strain V-73 and *Paenibacillus tundra* strain Ab10b were the most common (Zhang et al. 2013). Five of the isolates were confirmed for their toluene mineralization ability. The results did, however, not corroborate with previous results of toluene removal efficiency where *H. carnosa* was superior to *F. verschaffeltii* var. *argyroneura* (Zhang et al. 2013).

Removal rates of benzene, toluene, *m*/*p*-xylene, and *o*-xylene were increased if plants were inoculated with bacteria isolated from growing media of a plant with high removal rate (Chun et al. 2010). When leaves of *Azalea indica* were inoculated with *Pseudomonas* TVA8, the time for 95 % removal decreased significantly compared to *A. indica* without inoculum (De Kempeneer et al. 2004). When inoculum was applied to the substrate or to an artificial plant the removal efficiency levelled off and it was therefore suggested that leaf degradation, transport to roots for microbial degradation and increase in phyllosphere microorganisms could be important factors in removal of VOCs (De Kempeneer et al. 2004).

It is clear that microorganisms play a role in a potted plant's ability to remove VOCs. In relation to removal of VOCs from indoor air there are a limited number of studies researching the role of microorganisms. The ability of microorganisms to degrade pollutants has been covered by extensive literature on bioremediation or phytoremediation (Bouwer and Zehnder 1993; Jindrova et al. 2002; McGuinness and Dowling 2009; Wenzel 2009). Several endophytic and rhizospheric bacteria have been identified as capable of assisting plants in removing toxic compounds from soil (McGuinness and Dowling 2009). In addition, monooxygenases and dioxygenases, which are bacterial multicomponent enzymatic systems, are known to be responsible for degradation of benzene, toluene, ethylbenzene and xylene in the environment (Jindrova et al. 2002). Mycorrhizal fungi are equally important as bacteria for the mineralization of pollutants (Bouwer and Zehnder 1993). Arbuscular mychorrhizal fungal hyphae have been found to translocate fluorene and phenanthrene to roots of *Lolium multiflorum* (Gao et al. 2010a) and in a remediation study of petroleum-polluted soil, *Polygonum aviculare* and its root-associated fungal strains were more effective in remediation of the soil than the plant or fungi alone (Mohsenzadeh et al. 2010). Several studies have shown that the action of microorganisms can be enhanced when a plant is present (Wood et al. 2002; Xu et al.

2010, 2013). A hypothesis for the increased activity is that the pollution source may not be adequate to maintain or increase the growth of the microorganisms. The presence of a plant will ensure a steady carbon source in the form of root exudates and the microorganisms will in addition to the root exudates also forage on the pollutants (Guieysse et al. 2008).

Removal of VOCs by growing media and roots

Unused potting soil was able to remove benzene, but the removal rate was generally lower than that of both soil and plant (Irga et al. 2013; Wood et al. 2002). In these studies, the volume of the belowground parts (either soil alone or soil and roots together) was kept the same. In addition, the unused soil experienced exhaustion (Wood et al. 2002). Unused potting soil was also able to remove formaldehyde (Godish and Guindon 1989; Wolverton and Mcdonald 1982; Wolverton and Wolverton 1993) and an unused hydroponic system could remove benzene (Irga et al. 2013). Sterilized potting soil was able to remove formaldehyde in the study by Godish and Guindon (1989), but not in the study by Wolverton and Wolverton (1993). Sterilization of used potting soil still containing plant roots decreased the removal rate of formaldehyde by 90 % compared to soil before sterilization (Kim et al. 2008). Expanded clay and growstone, which are two types of growing media, were able to remove formaldehyde. The efficiency was highest when the material was wet where a total reduction of 62–63 % was obtained in 10 h (Aydogan and Montoya 2011).

It is evident that sterilization has a dramatic effect on the removal capacity of roots and growing media which could indicate that the contribution from the belowground parts is due to microorganisms. The majority of these studies have been carried out with formaldehyde which is water soluble. Hence, if the growing media is wet the uptake capacity is higher than for dry growing media as also seen by Aydogan and Montoya (2011). If formaldehyde is only absorbed by the water there is a risk of reemission if the plant dries out.

Soil particles, both inorganic and organic, can remove pollutants from the air in the process of adsorption. Unless the pollutant is trapped by the soil in the process of aging (Alexander 1995), it will still be available for reemission or uptake by plants and/or microorganisms. Potting soil usually consists of mainly organic material which adsorbs pollutants stronger than mineral soil (Calvet 1989; Gao et al. 2010b). However, as also noted by Wood et al. (2002), the soil will have a limited capacity for adsorption of pollutants. Adsorption of pollutants may either be to the solid phase or the water phase and as for adsorption to any material will be dependent on the VOC (Huang et al. 2006).

The role of the plant roots has not been researched specifically in relation to VOC removal from indoor air, but here knowledge exists from research in phytoremediation (Wenzel 2009). Roots can take up pollutants by themselves (Wild et al. 2005), but can also increase the bioavailability of the pollutants for the microorganisms (Wenzel 2009). Increased bioavailability will be achieved through the excretion of root exudates (Gao et al. 2010b; Wenzel 2009) which is estimated to be 2–4 % of net photosynthetic fixed carbon (Jones et al. 2004). Uptake by roots depends on the root morphology where the lipid content and specific surface area are significant parameters (Zhan et al. 2013). Once taken up by the root, the pollutant can undergo the same processes as in the leaf — i.e. degradation, storage or excretion, either at site or after translocation. A hindrance for translocation from the root to the vegetative parts via the xylem or phloem is the crossing of the Casparian strip (Bromilow and Chamberlain 1995). The importance of the roots in removing VOCs from indoor air is unknown, but it may be substantial as roots often occupy a considerable amount of space in the pot of an ornamental potted plant. However, if the microorganisms rapidly consume the pollutants that diffuse into the soil, the role of the roots may mainly be indirect in the support of the microorganisms via root exudates as a very limited amount of the pollutants may be available for uptake by the roots.

The question often arises whether the aboveground or belowground parts are the most important for VOC removal. The ratio between removal by the aboveground part and the belowground part of whole potted plants have to some extend been investigated. The removal efficiency of formaldehyde and xylene that can be related to the soil was 50.5–67.0 % for *Aglaonema* sp., *Dieffenbachia* sp., *Nephrolepis exaltata* and *Dieffenbachia maculata* (Wolverton and Wolverton 1993). The experiment was carried out by comparing plants with and without the soil covered with sterilized sand. For *Fatsia japonica* and *Ficus benjamina* removal of formaldehyde by aboveground plant parts compared to the root zone was 1:1 during the day and 1:11 during the night (Kim et al. 2008). The difference was due to a lower removal efficiency by the aboveground plant parts at night and a decline in removal by the root zone by day (Kim et al. 2008). In this study, the soil had been covered with a Teflon bag for the examination of the aerial plant parts, and the root zone was investigated by surgically removing the aboveground parts. Xu et al. (2011) investigated the soil by removing the aboveground parts as well as the roots from the soil. For formaldehyde removal by *Chlorophytum comosum*, *Aloe vera* and *Epipremnum aureum* the soil contributed with 45–55 %.

Removal of the aboveground parts will invariably influence the root zone, both through the lack of photosynthates available for root exudation and through the lack of a driving force for the transpiration stream. When comparing the removal efficiency for the root zone, the aboveground parts and the whole plant in the study by Kim et al. (2008), the combined removal efficiency for the root zone and the aboveground parts exceeds that of the whole plant. This could

indicate that removal of the aerial plant parts to investigate the root zone or enclosing the root zone in a Teflon bag is not adequate for investigation of the contribution from the different parts. Despite this, it is clear that both the aboveground and belowground parts contribute to removal of VOCs.

Factors affecting the efficiency and rate of VOC removal by plants

Any factor that can have an effect on the pathways of VOC removal is likely to have an effect on the efficiency or rate by which VOCs are removed by plants. As illustrated in Fig. 1, plant species, growing media, light, temperature, VOC concentration, VOC identity, and VOC mixture effects have been investigated.

Plant species

It is well documented that VOC removal rates depend on plant species (Liu et al. 2007; Orwell et al. 2004; Wolverton and Mcdonald 1982; Yang et al. 2009) (Table 1). Even differences between cultivars have been observed (Kim et al. 2011b; Orwell et al. 2004; Zhou et al. 2011).

Two studies have investigated the relation between taxonomy and VOC removal rate (Kim et al. 2010; Yang et al. 2009). Investigation of 28 plant species from 15 families for their removal of benzene, toluene, octane, trichloroethylene and α-pinene revealed that members of the Araliaceae family had a tendency towards intermediate to high removal rates, whereas members of the Araceae family exhibited lower removal rates. There was though no significant difference between the families. In the study design, six plant species were from the Araliaceae family, four were from the Araceae family, and the last 18 plant species were representing the remaining 13 families (Yang et al. 2009). Kim et al. (2010) studied formaldehyde removal rates by 86 plant species divided into five categories. Ferns exhibited the highest removal rates of formaldehyde followed by herbs. Woody foliage plants, herbaceous foliage plants and Korean native plants were similar to each other, but had lower removal rates than ferns and herbs (Kim et al. 2010). The variation within each group was large and the results did not appear to be significant.

The groupings in the abovementioned studies may have been too broad to explore the differences among plant species. The determining factors for the differences between plant species could be leaf parameters such as stomatal characteristics, wax layer, and hair growth which all influence the diffusion of the VOC into the leaf. On the inside, plant species may exhibit differences in the ability to incorporate or store the VOC. Jin et al. (2013) reported that higher stomatal density and increased catalase activity after exposure to formaldehyde were the main reasons for the higher removal of formaldehyde exhibited by *Melissa officinalis* compared to *Hedera helix*. However, the control plants had not been exposed to the same experimental condition as the test plants. Thus, it is not possible to say if the observed effects are due to exposure to formaldehyde or the experimental conditions.

Belowground, the root growth and the ability to support microbial growth in the soil are likely to differ among plant species and can indirectly be determining factors for differences in VOC removal rates among plant species. Indeed, Zhang et al. (2013) observed that *Fittonia verschaffeltii var. argyroneura* was able to support a more diverse community of toluene degraders than *Hoya carnosa* after 2 months of toluene exposure.

Growing media

The type of growing media used to support plant growth can affect the rate and efficiency of VOC uptake. Formaldehyde and acetone removal efficiency by *Epipremnum aureum* was affected by soil type (Oyabu et al. 2003b). The names of the soil types used were: Ecodo-Hydro; a three-layer structure of clay, humus and Japanese charcoal; and Hydro; however, further specifications were not given. The three-layer structure appeared superior for formaldehyde removal efficiency whereas Ecodo-Hydro and Hydro resulted in lower formaldehyde removal efficiencies. For acetone, the three-layer structure and Ecodo-Hydro appeared superior to Hydro (Oyabu et al. 2003b). Unfortunately, from the data given in this study it is unknown if the effect of soil type was statistically significant. Formaldehyde, toluene, and xylene removal efficiency by *E. aureum* was also affected by type of growing media (Sawada and Oyabu 2008). In this study pot soil, growing water and tap water were used, where growing water was defined as water that had supported plant growth for more than a year. Using pot soil resulted in the highest removal efficiency, but no explanation for this effect was given (Sawada and Oyabu 2008).

Soil was superior to a hydroponic system when measuring benzene and *n*-hexane removal rates by *Howea forsteriana*, *Spathiphyllum wallisii* and *Dracaena deremensis* (Wood et al. 2002). This was also the case for removal of benzene by *Syngonium podophyllum* (Irga et al. 2013). The difference between soil and hydroponics was suggested to be caused by microorganisms as the plants in hydroponics had been washed with sterile water with the result that only rhizosphere bacteria remained (Wood et al. 2002). Plants in hydroponics had been acclimatized for 48 h or more prior to exposure to VOCs (Wood et al. 2002). However, an increase in the length of the acclimatization period may increase the amount of microorganisms in the water, which may increase removal rates. In the study by Irga et al. (2013), plants had been grown in soil or hydroponics for 133 days prior to exposure to benzene, and their bacterial analysis revealed that samples from potting mix before exposure to benzene were different

from those after benzene exposure as well as samples from the hydroponic medium before and after benzene exposure (Irga et al. 2013). However, the test did not show how they were different. In addition, effects of growing media may be caused by differences in the ability of the growing media to adsorb the pollutants as also noted in Removal of VOCs by microorganisms. To make a conclusion on the effect of growing media is difficult as significance levels were only reported by Irga et al. (2013).

Light

Increasing light intensity is found to have a positive effect on VOC removal efficiencies and rates (Baosheng et al. 2009; Kondo et al. 1995; Oyabu et al. 2003a,c; Porter 1994; Sawada and Oyabu 2008; Xu et al. 2011). As example, *Nerium indicum* exhibited a clear increase in formaldehyde removal rate with increasing light intensity (Fig. 2).

In the abovementioned studies, light intensities varied between 0 and 18 μmol/m^2/s, except in the studies by Kondo et al. (1995) and Porter (1994), in which the light intensity ranged between 100–600 and 35–90 μmol/m^2/s, respectively. The effect of light intensity is not always straightforward. An increase in VOC removal efficiency as a response to an increase in light intensity was only seen at a low toluene concentration of 8,669 μg/m^3 (Porter 1994). Conversely, at a high toluene concentration of 43,345 μg/m^3, an increase in light intensity resulted in a decrease in VOC removal efficiency from 12.62 % to 5.11% for a 3-h period (Porter 1994). The author suggested that this decrease in VOC removal efficiency was related to toxicity or limitation in the metabolic capacity of the plant (Porter 1994). At light levels lower than 9 μmol/m^2/s, removal efficiency of formaldehyde was unaffected as response to increasing light levels (Baosheng et al. 2009).

Light has in many cases a positive effect on VOC removal by plants. This observation can be expected if VOCs are taken up through the stomata since stomatal conductance increases with increasing light intensity until saturation (Yera et al. 1986). For VOCs that also have a good entry through the cuticle, the effect of increased light intensity may be less obvious as the entry through the cuticle will be unaffected by light. However, it is still expected that VOC removal will increase with increased stomatal conductance because larger openings into the plant will lead to increased uptake. In a few studies there was no effect of light when moving plants from light condition to dark condition (Aydogan and Montoya 2011; Godish and Guindon 1989; Orwell et al. 2004; Wood et al. 2002). This lack of response to light was assumed to be related to the action of microorganisms being the main route for VOC removal (Orwell et al. 2004; Wood et al. 2002). In these studies, the plant parts were suggested to play a limited role in removal of VOCs, but to be important in maintaining the microflora (Orwell et al. 2004; Wood et al. 2002). Removal of VOCs by plant parts versus microorganisms was not separated in these studies. Therefore, it cannot be ruled out that the plants were also involved in the removal of VOCs. There are no apparent differences in the type of VOC, light intensity or plant species used in the studies observing positive effects of light and the studies observing no effects of light. This may indicate that other influencing factors can override the effect of light. In addition, there is also the potential that some VOCs such as formaldehyde can be photochemically degraded without any action by the plants (Horowitz and Calvert 1978), which may complicate the analysis of the effects of light on VOC removal by plants.

The effect of light may be limited in indoor environments where light levels are typically around 9–14 μmol/m^2/s (Akashi and Boyce 2006; Nicol et al. 2006). These light levels are, for many plants, low for photosynthetic activity. Light levels in indoor environments are usually measured on a horizontal plane, but as plants intercept light in many planes, i.e. their leaves bend in different directions, the experienced light level for the plants may be higher. Thoughtful placement of plants where light levels are highest may potentially increase the plants' ability to remove VOCs, both through the direct effect of more open stomata but also through the indirect effect on microorganisms caused by increased root exudation due to increased photosynthesis.

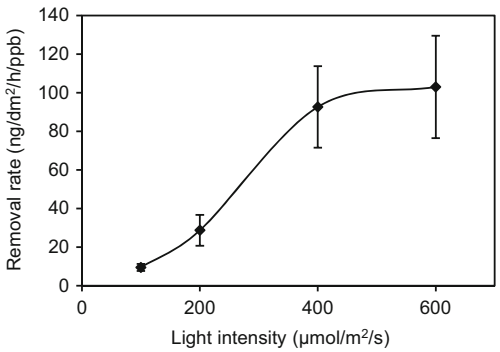

Fig. 2 Effect of light intensity on formaldehyde removal rate by *Nerium indicum*. Adapted from Kondo et al. (1995); bars are mean±SD, n=4

Temperature

The effects of increased temperature on removal efficiencies are various (Baosheng et al. 2009; Sawada et al. 2007; Sawada and Oyabu 2008). *Phoenix roebelenii* was exposed to formaldehyde at 21–26 °C, and the removal efficiency was increased with increasing temperature (Baosheng et al. 2009). Exposure to formaldehyde at 21–27 °C resulted in no change in removal efficiency with increasing temperature for wild-type and transformed tobacco plants (*Nicotiana tabacum*) (Sawada et al. 2007). Depending on the growing media, *Epipremnum aureum* exposed to formaldehyde at 12–25 °C showed both decreased and constant removal efficiency with increasing temperature as well as an optimum removal

efficiency at 21 °C (Sawada and Oyabu 2008). The authors did not state whether the effect of temperature on VOC removal efficiency was statistically significant for any of the three plant species. The tin oxide gas sensor that was used in these studies was reported to be affected by temperature (Baosheng et al. 2009), and it is unknown how this has affected the obtained results.

Increasing temperature is likely to have an effect on plants' efficiency and rate of removing VOCs as it will increase the permeability of the cuticle (Baur and Schönherr 1995). Hence, the diffusion rate of the VOCs into the plant may increase. Increasing temperature will also affect microbial growth in the soil (Madigan et al. 2009) and possibly the microorganisms' consumption of the VOCs.

VOC concentration

In a study by Porter (1994), an increase in toluene concentration led to an increase in VOC removal rate by *Dieffenbachia amoena* 'Tropic Snow', but only up to ca. 200 mg/m^3. Above this concentration, there was no longer any effect of increasing concentration (Porter 1994). The effect of increasing concentration was only observed at low light intensity of 35 μmol/m^2/s, while at high light intensity of 90 μmol/m^2/s the relationship between removal rate and toluene concentration became unclear (Porter 1994). The author suggested that at least under low light conditions the uptake of toluene was metabolically controlled. At a concentration range of 43–300 μg/m^3 formaldehyde, the removal rate by *Nerium indicum* increased linearly with increasing initial concentration (Kondo et al. 2005). For *Chlorophytum comosum*, *Alow vera* and *Epipremnum aureum*, removal rates for formaldehyde also increased at concentration ranges of 1,000–11,000, 1,000–8,000 and 1,000–6,000 μg/m^3, respectively (Xu et al. 2011). The VOC removal rate increased as a function of VOC concentration, whereas the removal efficiency mainly decreased with increasing concentration (Fig. 3) (Orwell et al. 2006). In this study, the VOC removal rate and efficiency by *Dracaena deremensis* 'Janet Craig' and *Spathiphyllum* 'Sweet Chico' were investigated at 764–439,844 μg/m^3 of toluene and *m*-xylene (Orwell et al. 2006).

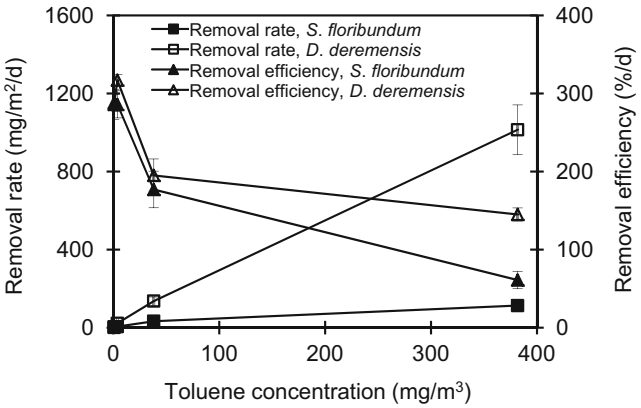

Fig. 3 Toluene removal rate and removal efficiency by *Spathiphyllum floribundum* and *Dracaena deremensis* at four toluene concentrations. Adapted from Orwell et al. (2006); bars are mean±SE, n=4

Acetone removal efficiency by *E. aureum* was unaffected by an increase in concentration from 2394 to 19,153 μg/m^3 (Oyabu et al. 2003b). Toluene and xylene removal efficiencies by *E. aureum* and *Spathiphyllum* were also unaffected by increasing concentration from 3,805 to 8,767 μg/m^3 (Oyabu et al. 2005), and formaldehyde removal efficiency by golden pothos (*E. aureum*) was unaffected with increasing concentration from 6,184 to 61,842 μg/m^3 and from 6,200 to 49,600 μg/m^3 (Oyabu et al. 2001, 2003a). Contrary to this, removal efficiency by *E. aureum* increased slightly with increasing formaldehyde concentration from 6,190 to 24,758 μg/m^3 and from 6,200 to 9,920 μg/m^3 (Oyabu et al. 2003b, 2005). This was also observed for *Spathiphyllum* at formaldehyde concentrations of 6,200–9,920 μg/m^3 (Oyabu et al. 2005). For rubber plant (*Ficus elastica*) and Boston fern (*Nephrolepis exaltata*), the removal efficiencies increased linearly with increasing formaldehyde concentration from 6,200 to 49,600 μg/m^3, whereas snake plant (*Sansevieria trifasciata*) had an optimum removal efficiency at 24,800 μg/m^3 (Oyabu et al. 2003a). Removal efficiencies by wild-type and transformed tobacco plants (*Nicotiana tabacum*) decreased with increasing formaldehyde concentration from 9,755 to 24,387 μg/m^3 (Sawada et al. 2007). Furthermore, the removal efficiency of gasoline components by *E. aureum* decreased with increasing injection volumes of 0.01–0.05 ml (Oyabu et al. 2003c).

In summary, removal rates are found to increase with increasing concentration whereas the effect on removal efficiency is less clear. Whether the plant, the microorganisms or both are responsible for this effect is unclear. Similar results have though been seen for bacteria where the removal rate increased with increasing concentration of four different pollutants and the removal efficiency either increased or decreased depending on the pollutant (Boethling and Alexander 1979). A decrease in removal efficiency indicates that at the tested VOC concentrations the capacity of the plant/soil system is being reached. This can be expected, also when considering plant uptake of CO_2 (Mortensen and Ulsaker 1985) and bacterial degradation of organic compounds (Boethling and Alexander 1979).

VOC identity

A noticeable number of pollutants with different properties are found to be taken up by indoor plants (Table 1). Investigations into the effect of molecular weight of the VOCs show that removal efficiencies decrease as the molecular weight increases (Baosheng et al. 2009; Oyabu et al. 2001, 2003b, 2005; Sawada and Oyabu 2008). Formaldehyde, ethyl alcohol, acetone, benzene, toluene, styrene, xylene and trichloroethylene were measured in these studies. Seven of the VOCs were analysed by Oyabu et al. (2001), six by

Baosheng et al. (2009), five by Sawada and Oyabu (2008), three by Oyabu et al. (2005) and two by Oyabu et al. (2003b). It was suggested that the decrease in removal efficiency as a function of molecular weight was caused by increased diffusion resistance of the VOCs into the plant (Oyabu et al. 2001). The tin oxide gas sensor that was used in these studies is affected by the molecular weight of the VOCs (Oyabu et al. 2004), and it is unclear how this has affected the results.

Removal of aldehydes and ketones, which represent two chemical classes, revealed that aldehydes tended to be taken up more easily than ketones and that the uptake increased with increasing water solubility of the compound (Tani and Hewitt 2009). Acetone which was only taken up temporarily and benzaldehyde, an aromatic compound, were exceptions to this tendency (Tani and Hewitt 2009). Eight aldehydes and six ketones were investigated by Tani and Hewitt (2009) and they suggested that the differences in uptake may be related to the ease by which the compound is scavenged inside the leaf which was investigated by calculating the concentration of the compounds in the intercellular air space of the leaf. This may be supported by the fact that VOCs are incorporated into the plant material in different ways (Giese et al. 1994; Schmitz et al. 2000; Ugrekhelidze et al. 1997) (see also Removal of VOCs by aboveground plant parts).

The relationship between removal and VOC identity may be further explored by looking at parameters such as molecular size, 1-octanol/water coefficient and Henry's law constant (Bacci et al. 1990; Riederer 1990; Sabljic et al. 1990; Trapp and Matthies 1995). Uptake of pollutants has earlier been noted to be independent of functional group or molecular weight (Bromilow and Chamberlain 1995), but for degradation studies, functional groups may be a relevant factor (Korte et al. 2000).

VOC mixture effects

Removal of VOCs in mixtures has been investigated in a few studies (Chun et al. 2010; Cornejo et al. 1999; Orwell et al. 2006; Oyabu et al. 2003c; Porter 1994; Sriprapat and Thiravetyan 2013; Yoo et al. 2006). These mixtures were mainly binary. However, Chun et al. (2010) measured removal of a mixture of benzene, toluene, *m*/*p*-xylene, and *o*-xylene, Sriprapat and Thiravetyan (2013) investigated removal of benzene, ethylbenzene, toluene and xylene in mixture, and Oyabu et al. (2003c) measured removal of total gasoline.

Trichloroethylene had an antagonistic effect on benzene and pentane removal rates by *Ficus elastica*, and benzene was selectively removed over toluene by *Kalanchoë blossfeldiana* (Cornejo et al. 1999). In the experiment with *F. elastica*, the concentration of the VOCs is unknown, whereas *K. blossfeldiana* was exposed to 51,805 μg/m^3 benzene and 7,609 μg/m^3 toluene (Cornejo et al. 1999). Exposure to a mixture of 1,890 μg/m^3 toluene and 1,602 μg/m^3 benzene resulted in removal rates of toluene being higher than those of benzene by *Hedera helix*, *Spathiphyllum wallisii*, *Syngonium podophyllum* and *Cissus rhombifolia* (Yoo et al. 2006). This difference in removal rates was observed during both day and night, except for *S. wallisii* during the night. Benzene and toluene in mixture were removed with the same efficiency by *Dieffenbachia amoena* at individual concentrations of ca. 8,700 μg/m^3 (Porter 1994). The fact that benzene was selectively removed over toluene in the study by Cornejo et al. (1999) which was not observed by Yoo et al. (2006) was suggested to be caused by the use of different plant species. The fact that the initial benzene concentration was much higher than the toluene concentration in the work of Cornejo et al. (1999) may also explain the antagonistic effect, simply due to competitive uptake of benzene over toluene.

Toluene had a synergistic effect on removal rate of *m*-xylene by *Dracaena deremensis* 'Janet Craig', but *m*-xylene had no effect on removal rate of toluene compared to exposure to a single VOC (Orwell et al. 2006). However, this only occurred at concentrations of 764–4398 μg/m^3 and not at concentrations of 38,176–439,844 μg/m^3 (Orwell et al. 2006). The synergistic effect of toluene on *m*-xylene removal rate was suggested to be caused by bacterial adaptation and possible induction of an enzyme, which had been observed by Yeom et al. (1997), who investigated microbial adaptation in the degradation of benzene, toluene and xylene.

When *H. helix*, *S. wallisii*, *S. podophyllum* and *C. rhombifolia* were exposed to a mixture of benzene and toluene, the removal rates for each VOC were lower than when the plants were exposed to only one of the VOCs (Yoo et al. 2006). In the mixture, the concentrations of the individual VOCs were 1,602–1,890 μg/m^3 whereas the concentration was 3,204–3,779 μg/m^3 for single exposure. Exposure to a mixture of toluene and benzene decreased the removal efficiencies by *D. amoena* by ca. 50 % compared to removal efficiencies when the VOCs were alone (Porter 1994). The concentrations of the single exposures were not stated. The decrease in removal rate and efficiency was suggested to be due to competitive uptake (Porter 1994) or increased deleterious effects on the plants compared to exposure to a single VOC (Yoo et al. 2006). Removal rates decrease with decreasing concentration (Orwell et al. 2006). Therefore, the observation of decreased removal rates for VOCs in mixture may not be surprising since the individual VOC concentration was halved. For a mixture of toluene and *m*-xylene, removal rates were unaffected or increased compared to single exposure (Orwell et al. 2006). In this study, the individual VOC concentration was the same in mixture and in single exposure experiments.

Removal of VOCs in more complex mixtures has also been investigated. *Pachira aquatica*, *F. elastica* and *S. podophyllum* were able to remove a mixture of benzene, toluene, *m*/*p*-xylene, and *o*-xylene with individual concentrations in the mixture of 1,602, 11,337, 1,089 and

1,089 μg/m^3, respectively (Chun et al. 2010). Benzene was removed faster than toluene, ethylbenzene, and xylene in that order by *Zamioculcas zamiifolia* with individual VOC concentrations of 62,392–84,806 μg/m^3 (Sriprapat and Thiravetyan 2013). *E. aureum* was able to remove volatile reducible gasoline components when exposed to 0.05 ml liquid gasoline in a 300-l chamber (Oyabu et al. 2003c). The constituents of the gasoline mixture were not further specified.

Most of the tested binary mixtures consisted of volatile aromatics, which may have similar degradation pathways. Removal of VOCs in mixtures which are chemically dissimilar may show different results. Nonetheless, the findings indicate that a plant's removal rate or efficiency for a single VOC cannot be transferred to a situation where VOCs are present in a mixture (Yoo et al. 2006), which will be the case in real-life settings.

VOC removal in real-life settings

Despite the growing interest in plants' ability to remove volatiles from indoor air, only few studies have been carried out in real-life offices and homes. A reduction of 50 % in total VOC concentration from an initial concentration of ca. 700 μg/m^3 was observed in offices with three or six specimens of *Dracaena deremensis* 'Janet Craig' compared to offices without plants (Wood et al. 2006). There was no difference between placing three or six plants in the offices. The study was conducted in 18 naturally ventilated and 18 air-conditioned offices of 30–50 m^3, and samples were taken every week for 9 weeks. The result was, however, only significant if samples taken when total VOC concentration in reference office was below 100 ppb were excluded from the data analysis. If separating the naturally ventilated offices from the air-conditioned offices, total VOC concentration was reduced by 75 % in naturally ventilated offices from an initial concentration of ca. 1,000 μg/m^3, but remained unchanged in air-conditioned offices (Wood et al. 2006). The lack of removal of VOCs by plants at low total VOC concentration was suggested to be due to a threshold value for VOC removal by plants. However, no such value was established in the study. The total VOC concentration in air-conditioned reference offices when samples below 100 ppb were excluded was only ca. 145 ppb, and the low concentration could be the reason why no effect of plants was observed (Wood et al. 2006).

In a second investigation by Wood et al. (2006), a significant reduction of ca. 70 % in total VOC concentration from an initial concentration of ca. 765 μg/m^{3}was achieved in air-conditioned offices with five table-sized *Spathiphyllum* 'Sweet Chico' and one *D. deremensis* 'Janet Craig'. Samples below 100 ppb were again excluded (Wood et al. 2006). In contrast, the total VOC concentration increased in the naturally ventilated offices possibly because the table-sized *Spathiphyllum* 'Sweet Chico' had started flowering and were emitting VOCs of their own (Wood et al. 2006). As only total VOC concentration was measured, these results did not take changes in the relative concentrations of individual VOCs into account.

To achieve a reduction in formaldehyde concentration of 11 % from an initial concentration of 856 ppb, it was necessary to place a mixture of 20 plants in offices of ca. 20 m^3 (Dingle et al. 2000). There was no significant reduction in formaldehyde concentration with 0–15 plants. The lack of decline in formaldehyde concentration with 0–15 plants was suggested to be caused by a high emission rate of formaldehyde from the building materials. With a high emission rate, a high removal rate had to be obtained before an actual reduction in formaldehyde concentration could be measured (Dingle et al. 2000). The experiment was carried out by continuously placing five different plants in the offices every second day, thus the plants may have had too little time to acclimate to the situation and reach full capacity for formaldehyde removal.

Formaldehyde and toluene concentrations in offices in a newly constructed building decreased from 80.8 to 66.4 μg/m^3 and from 275 to 106 μg/m^3, respectively, due to a combination of ventilation and introduction of plants. The combination of plant placement and ventilation also resulted in a reduction in benzene concentration from 7.20 to 1.96 μg/m^3 in offices in aged building (Kim et al. 2011a). The introduction of plants resulted in a reduction of formaldehyde from 23.2 to 16.5 μg/m^3 in the period of no ventilation and from 28.8 to 18.6 μg/m^3 in the period of ventilation in offices in aged buildings (Kim et al. 2011a). There were no changes in ethylbenzene and xylene concentrations as a result of introducing plants, regardless of ventilation and the age of the buildings (Kim et al. 2011a). In this study, two offices of more than 100 m^2 were selected in either six new or six aged office buildings. After selection, 22–25 plants of six species were placed in half of the offices. It is, unfortunately, not possible from the statistical analysis carried out in the study to evaluate if the abovementioned results are significant.

In a study investigating the effects of plants in homes over 2 years, formaldehyde concentrations were seen to decrease as an effect of plant placement from 72.0 to 33.7 μg/m^3 in a period of no ventilation and from 70.6 to 10.7 μg/m^3 in a period of ventilation in the first year. In the second year, the concentrations were reduced from 85.1 to 44.7 μg/m^3 and from 54.0 to 11.9 μg/m^3, respectively due to plant placement (Lim et al. 2009). Xylene concentrations also decreased in homes with plants compared to homes without plants from 12.3 to 2.4 μg/m^3 and from 10.7 to 1.0 μg/m^3, respectively but only in the first year. In the second year, the xylene concentration was too low to show any tendencies (Lim et al. 2009). Toluene and ethylbenzene concentrations were unaffected by plant placement regardless of ventilation state. In addition, ventilation decreased the concentration of all four VOCs (Lim

et al. 2009). The experiment was carried out in 82 homes of varying sizes where 7–8 plants of different species were introduced to 42 of the homes. Measurements were taken in 2 successive years, but the number of plants and plant species were different from year to year. The level of statistical significance was not given and it is, therefore, difficult to evaluate the importance of the findings.

Generally, increasing the amount of plant material or light intensity decreased the concentrations of benzene, toluene, ethylbenzene, xylene and formaldehyde from various initial concentrations (Song et al. 2007). In this study, two newly built laboratory chambers of ca. 30 m^3 were used, where one was used as control and one was supplied with plants. The number of plants introduced is unknown, but it was stated that the plants occupied either 5 % or 10 % of the laboratory space. The use of large laboratory chambers may be in closer resemblance to a large-scale laboratory experiment than an office study and it is difficult to say to which extent the results are valid in offices. In addition, the level of significance was not given.

Oyabu et al. (2005) analysed total VOC concentration in a relaxation space with a volume of 100.5 m^3 before and after introduction of plants. Nine pots of different sizes containing various plant species were installed and the total VOC concentration decreased by 74 % (Oyabu et al. 2005). The total VOC concentration was measured three times during 2 days before introduction of the plants and twice during 2 days after the plants had been introduced. The total VOC concentration before and after introduction of plants is unknown.

Concentrations of formaldehyde, benzene, ethylbenzene, toluene and xylene were seen to be unaffected, decrease or increase during the sampling period regardless of plant placement (Kim et al. 2013). Four classrooms at two schools were filled with one large and one small plant of various species per 6 m^2, and one classroom at each school functioned as control. Measurements were carried out three times a week for 3 weeks prior to plant placement and again after 3 months of intervention (Kim et al. 2013). Unfortunately, it is not possible from the statistical analysis to conclude if plants had an effect or not on the pollutants that were reduced.

Placement of six potted plants (*D. deremensis*, *D. marginata* and *Spathiphyllum*) in a classroom of 52.5 m^2 effectively decreased total VOC concentration by approximately 73 % from an initial concentration of 933 $\mu g/m^3$ (Pegas et al. 2012). This did not include carbonyls which were reduced by 40 % from an initial concentration of 52.9 $\mu g/m^3$ (Pegas et al. 2012). The compounds that were reduced included, among others, benzene, ethylbenzene, toluene, xylenes and formaldehyde. Measurements were carried out weekly for 9 weeks where the first 3 weeks were without plants and the remaining 6 weeks were with plants (Pegas et al. 2012).

The studies investigating plants' ability to remove VOCs from indoor occupational settings show that plants to some extent are able to reduce the concentration of VOCs. However, high VOC emission rates from building materials and emission of VOCs from the plants themselves can affect the positive effects that plants can have on the total VOC concentration. Ventilation rate can also influence VOC concentrations in indoor settings (Salonen et al. 2009), but the ventilation rate was only reported by Pegas et al. (2012). This can raise the question whether the obtained results are caused by introduction of plants or ventilation. In two of the field studies the effects of plants together with ventilation was analysed (Kim et al. 2011a; Lim et al. 2009). However, ventilation was characterized as windows being opened in the summertime and no ventilation as windows being closed in the wintertime. Summer and winter periods can influence VOC concentrations (Reiser et al. 2002; Wolkoff et al. 1991). Therefore, the distinction between ventilation and no ventilation should not be made when time of year is an influencing factor. As noted by Pegas et al. (2012), possible confounding factors should be included in the statistical analyses.

In the study by Wood et al. (2006), positive effects of plants were only significant at high total VOC concentrations. It was suggested that the lack of VOC removal at low concentrations was due to a too small stimulation of the plant/microcosm for VOC removal to commence (Wood et al. 2006). At low total VOC concentration, the ventilation rate may have been increased. In this case, the residence time a molecule is in vicinity of a plant is decreased and the uptake by the plant may be limited. Excluding samples, as seen in the work of Wood et al. (2006), may conceal knowledge related to the real potential of VOC removal by plants especially at low VOC concentrations. If VOC concentrations are to be decreased to below odour thresholds as suggested by Wolkoff et al. (1997) it may be necessary to see the potential of VOC removal at very low concentrations.

Plant modifications for enhanced VOC removal

To increase the VOC removal rate, *Nicotiana tabacum* plants were genetically modified with the mammalian cytochrome P450 2E1, which is known to play an important role in the metabolism of a number of VOCs of low molecular weight (James et al. 2008). For benzene, bromodichloromethane, carbon tetrachloride, chloroform, toluene, trichloroethylene and vinyl chloride the strategy was effective as the transgenic plant removed significantly more VOC than the control plant. 1,1,1-Trichloroethane and perchloroethylene were not removed by either the control or the transgenic plant (James et al. 2008).

In another study, tobacco plants (*N. tabacum*) were genetically modified to express genes for two key enzymes in the monophosphate pathway from bacteria. These enzymes are important in the degradation of formaldehyde (Sawada et al.

2007). The transgenic plants were 20 % more efficient than wild-type plants in removing formaldehyde (Sawada et al. 2007). The selectivity towards formaldehyde was investigated by exposing the plants to toluene, xylene and styrene. For these three VOCs there was no difference in removal efficiencies between the wild-type and transgenic tobacco plants (Sawada et al. 2007).

Two studies have illustrated that it is possible to increase both removal rate and removal efficiency of VOCs by genetically modifying the plants (James et al. 2008; Sawada et al. 2007). The question remains whether this approach will be of value in real settings or remains restricted to the scientific context. James et al. (2008) suggested that their modified plant could be valuable in cleaning up environments that are polluted by a single VOC or even where VOCs are in mixture.

Supplementary comments and future research needs

Studies conducted in laboratories have generally been carried out by placing a plant in a closed chamber, introducing a VOC, and then recording the VOC removal as a function of time. The length of these experiments has varied from a few hours to several days. The VOCs have been introduced by injection of a liquid or gaseous standard into the chamber and in some cases a fan has been installed to aid equilibrium (e.g. Kim et al. 2008; Wood et al. 2002). Hence, the VOC source has often been discontinuous, and air exchange has been absent. Continuous emission of VOCs and/or air exchange has been ensured in a few studies (Godish and Guindon 1989; Kondo et al. 1995; Liu et al. 2007; Tani et al. 2007; Tani and Hewitt 2009; Xu et al. 2011).

When plants are placed in sealed chambers with no air exchange, relative humidity will increase and the CO_2 concentration will decrease due to transpiration and photosynthetic activity of the plant. This is in contrast to real-life settings, where air exchange often varies (Missia et al. 2010). In addition, relative humidity is mainly below 60 % and CO_2 concentration is above ambient (Berardi et al. 1991; Wargocki et al. 2004). The increase in relative humidity and water condensation on chamber surfaces was only reported by Aydogan and Montoya (2011). Water condensation on chamber walls may act as an adsorbent for VOCs, and this can lead to erroneous conclusions regarding plant uptake of the VOCs. In particular, hydrophilic compounds such as formaldehyde will be affected by this. High relative humidity and low CO_2 concentration may further affect stomatal aperture which will not be seen in real-life situations. Furthermore, the VOC source was often non-continuous, which also is unlike real life, where VOCs from, e.g. building materials are continuously emitted (Yu and Crump 1998).

It has been noted that the efficiency and rate by which VOCs are removed increase upon repeated exposure (De Kempeneer et al. 2004; Kim et al. 2011b, 2012; Orwell et al. 2004, 2006; Wolverton et al. 1989; Wolverton and Wolverton 1993; Wood et al. 2002). This increase was suggested to be caused by biochemical pathways being induced in bacteria as well as in the plant itself (Orwell et al. 2004). Another explanation can be bacterial adaptation and/or multiplication (De Kempeneer et al. 2004). Changes in gene expression were also suggested as a causal factor since increased removal efficiency as a result of stimulation was rapid (Kim et al. 2012). If plants were re-exposed to a VOC after a period of no exposure, the effect of stimulation could not be upheld. For *Begonia maculate*, the effect of stimulation was gone after 1 day, whereas for *Ardisia japonica* it had disappeared after 7 days (Kim et al. 2012).

Removal efficiency measured at different time intervals during an experimental run with a single injection of a VOC exhibited a decrease in efficiency with time (De Kempeneer et al. 2004; Kim et al. 2008, 2010; Lim et al. 2009; Wolverton and Mcdonald 1982; Yang et al. 2009). This is likely to be ascribed to depletion of the VOC in the chamber and thereby a slower rate of diffusion into the plant (Kim et al. 2008). This indicates that removal rates and removal efficiencies based on few hours will be higher than those based on e.g. a day. Furthermore, lower removal efficiencies and rates will be obtained if the effect of repeated exposure is not taken into account.

For better real-life simulation, factors such as VOC concentration and light intensity should also be considered. Laboratory studies have been carried out at light intensities of 5.45–600 $\mu mol/m^2/s$ with many studies exceeding the 9–14 $\mu mol/m^2/s$ usually experienced in offices (Akashi and Boyce 2006; Nicol et al. 2006). VOC concentrations used in laboratory studies are often above 1000 $\mu g/m^3$ (Table 1). This is substantially higher than VOC concentrations found in indoor environments which are typically less than 100 $\mu g/m^3$ (Zabiegala 2006). Both light intensity and VOC concentration have an effect on the removal of VOCs, and it will be highly relevant to keep these factors at realistic conditions. Regarding VOC concentration, the limitation may lie in the available techniques. For most part of the studies, samples have been taken manually with a gas-tight microsyringe and injected directly into a gas chromatograph (GC) with flame ionization detection (FID) (e.g. Wood et al. 2002). This technique limits the concentration at which the experiments can be carried out depending on the sensitivity of the instrument. Sampling on adsorbent tubes allows for pre-concentration of the compound and lower VOC concentrations can be used in experiments. Alternatively, a proton transfer reaction mass spectrometer can be used which offers real time quantification of VOC uptake at low concentrations (Tani et al. 2007; Tani and Hewitt 2009).

The subject of indoor VOC removal by plants combines plant biology with the field of indoor environment. This

combination can give challenges in reporting findings in a relevant manner. Optimal application of plants for removal of indoor VOCs requires the integration of VOC removal rates with VOC emission rates. This necessitates an agreement of how rates are reported. A number of different units have been used throughout the laboratory studies, e.g. % or μg/h (Table 1). Emission rates for building materials are often measured in mass per area per time, e.g. $\mu g/m^2/h$ (Wolkoff 1995; Yu and Crump 1998). Therefore, we suggest that this unit should also be used when measuring VOC removal rates by plants. Leaf area is an excellent measure for size of plants and is also used in photosynthetic measurements (Flood et al. 2011). It can be measured by a leaf area meter (Dela Cruz et al. 2014) or for a larger canopy, a non-destructive stereological estimation can be carried out (Wulfsohn et al. 2010). Other units such as pot size can indicate variable plant sizes and are, therefore, less useful.

To be able to transfer removal rates from laboratory experiments to real-life settings, the abovementioned factors should be taken into account. For a large part of the studies, this is not the case. Laboratory studies are important to investigate the underlying mechanisms of and factors influencing plants' ability to remove VOCs. Until there is a greater understanding of how plants remove VOCs, removal rates obtained in laboratory studies, even under proper real-life simulation, are only valid for the specific potted plant (including soil) and VOC investigated.

More than 30 years of research has been conducted on plants' ability to remove VOCs, but there is still knowledge to be obtained. A few ideas are presented here. Since removal of VOCs is dependent on plant species, it would be relevant to investigate if there are components of the plant that can explain removal rates. These components could be cuticle characteristics such as lipid content and speciation, stomatal conductance, net photosynthesis, and enzyme activity. Belowground, root characteristics as well as characteristics of the soil would be relevant to investigate. These could include root exudation patterns, specific root length and soil parameters such as organic matter quantity and quality which may influence removal of VOCs e.g. by trapping pollutants, but may also be important for the growth of microorganisms. In addition, characteristics of the VOCs, such as molecular size, 1-octanol/water coefficient, and Henry's law constant may be relevant to include. Preferably, a multi-component analysis should be carried out with various plant species and VOCs.

Research into environmental factors potentially affecting removal rates is also relevant. A few factors have been investigated, but others may also be relevant such as the CO_2 concentration, air velocity and exchange, soil water content, soil nutritional status, and soil surface area. Not only is it necessary to reveal how these factors influence removal rates but also why, as this will give a better opportunity to design pollutant removal interventions in real-life settings. In parallel to laboratory studies, more studies conducted in real life are also necessary. This will give an evaluation of the usefulness of plants as VOC removers, but it may also help identify additional factors that could be relevant to study under laboratory conditions.

Conclusion

This review aimed at providing an overview of indoor VOC removal by plants. Pathways for VOC removal and factors affecting the removal rates and efficiencies were examined. The mechanisms of how VOCs are removed by potted plants were recognized to be related to the plant, the soil and the microorganisms in the soil. VOC removal efficiency and rate can be influenced by the plant species, the growing media of the plant, light intensity, temperature, VOC concentration, VOC identity, VOCs in mixtures and genetic transformation of the plants. The reason why and how these factors influence VOC removal is largely unknown, but several hypotheses were stated. The concept of VOC removal by plants is of value in indoor occupational settings. Studies conducted in indoor environments show mixed results and VOC emission rates, ventilation rate and VOC emission by the plants themselves were potential influencing factors. A universal answer to the question: "Can ornamental potted plants remove VOCs from indoor air?" cannot be given yet. While the plant's ability to take up VOCs is well documented in laboratory studies, the effect of plants on indoor air in complex environments like offices requires further investigations to clarify the full capacity of plants in real-life settings. It is evident from this review that future research is needed to fully understand indoor VOC removal by plants.

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