Introduction

In industrialized countries people spend 80 - 90% of their time indoors (Klepeis et al., 2001; Schweizer et al., 2006). Therefore, the health and well-being of human is primary influenced by psychological variables and indoor air quality (IAQ) (Bauer et al., 1992; Ryan and Morrow, 1992; Tham, 2016). Several studies have shown that a relationship exists between the quality of indoor environmental design and the well-being and health of human (Evans and McCoy, 1998; Hongisto et al., 2016; Ryan and Morrow, 1992). For decades there has also been evidence that IAQ, especially in regard to volatile pollutants, impacts human health (Brooks et al., 1991; Jones, 1999; Tham, 2016). Pollutants are emitted by technical office equipment, human activities as well as furniture and carpets. Furthermore, the use of synthetic building materials has increased. Although these materials often provide more comfort and lower maintenance costs, they can emit a high amount of pollutants (Jones, 1999; Yu and Kim, 2010). The most common indoor pollutants are ozone (Destaillats et al., 2008; Jones, 1999), particulate matter (Destaillats et al., 2008; Wensing et al., 2008), and volatile organic compounds (VOC) (Berrios et al., 2005; Destaillats et al., 2008; Katsoyiannis et al., 2012; Que et al., 2013).

VOC's belong to the most important chemicals occurring in indoor airs. They are characterized as organic chemicals with a boiling point between 50°C and 260°C. More than 350 VOC's have already been identified indoors, including aromatic compounds (e.g. toluene and xylene), terpenes (e.g. limonene and α-pinene), alcohols (e.g. 2-ethylhexanol and butanol), and carbonyl compounds (e.g. formaldehyde and acetaldehyde) (Salthammer and Bahadir, 2009; Sarigiannis et al., 2011). Major sources of VOC's are building materials and technical equipment (Berrios et al., 2005; Brooks et al., 1991; Destaillats et al., 2008; Jones, 1999; Wolkoff and Nielsen, 2001). Board materials like particle board, plywood, and lumber emit up to 900 µg/m³ total VOC, mostly toluene and several terpenes (Que et al., 2013). In comparison, a running PC was found to emit up to 270 µg toluene, 81.9 µg styrene, 237 µg xylene, and 188 µg ethylbenzene per hour (Berrios et al., 2005). Measurements of different photocopy devices during the copying process revealed emission rates of up to 7500 µg ozone, 29000 µg xylene, 2000 µg toluene, 14000 µg 2-ethylhexanol, and 9600 µg styrene per hour (Leovic et al., 1998, 1996). More recent studies report lower emission rates for PCs and printers. Nonetheless, total chemical emissions of up to 740 µg/h for PCs and 5000 to 8400 µg/h for copy devices are still of concern (Kowalska et al., 2015; Maddalena et al., 2011). Other VOC sources are related to human activities, like cooking or the use of products

for cleaning and personal care. Besides the emission of primary VOC's from indoor sources, indoor gas-phase reactions lead to the formation of secondary VOC's (Luengas et al., 2015). For example, 2-ethylhexanol is a derivate of di-2-ethylhexyl phthalate (DEHP), which is a commonly used plasticizer incorporated in electrical cables, wall covering, flooring, and others. The alkaline hydrolysis of DEHP is likely a major source of 2-ethylhexanol in indoor air (Azuma et al., 2016; Nalli et al., 2006; Reiser et al., 2002). Concentrations up to 130 $\mu g/m^3$ of 2-ethylhexanol were recognized, for example, in Japanese houses (Azuma et al., 2016).

The contamination of indoor air by VOC and other pollutants is (among other factors) related to different disease symptoms of people who spend a lot of time in buildings, mainly those with mechanical heating, ventilation, and air-conditioning systems. These symptoms include headache, lethargy, dry skin, and mucous membrane symptoms related to the eyes, nose, and throat, and are summarized as sick building syndrome (SBS) or building-related illness (Burge, 2004). Studies have shown that more than 30% of office workers in Germany suffer from SBS (Bischof et al., 2004; Brasche et al., 1999). Although VOC's do not necessarily cause obvious symptoms, a chronic exposure can lead to reduced concentration and effectivity, or other health problems like asthma and cardiovascular diseases (Brasche et al., 1999; Burge, 2004; Jones, 1999; Mendell et al., 2002; Redlich et al., 1997). Further, an exposure to low concentrations of VOC's was associated with an increased risk of cancer (Vaughan et al., 1986; Wallace, 1991; Wolkoff and Nielsen, 2001).

To remove sources of pollution or to increase the ventilation rate is technically and economically difficult to achieve. The easiest way to clean the indoor air is natural ventilation. However, this is often not possible or desired, due to reasons like unfavorable weather conditions, outdoor pollution, safety standards, climate regulation, or noise pollution. Further, due to energy-saving measures, buildings have become more and more airtight, often with a minimum of air exchange, which leads to a higher concentration of pollutants indoors than outdoors (Jones, 1999; Wolkoff and Nielsen, 2001). Thus, several treatment technologies have been developed for improving IAQ. Among them are technologies based on mechanical and electrical filtration, photolysis, adsorption, and ozonation. Even though these technologies work well for particle filtration, there is no fully-satisfying method for VOC removal (Guieysse et al., 2008; Luengas et al., 2015; Vizhemehr et al., 2015). The results of several investigations demonstrated that the filter capacity of different air cleaners is partially insufficient (especially for low-molecular weight compounds like formaldehyde and

dichloromethane) or the devices release pollutants themselves, e.g. ozone, formaldehyde, and acetaldehyde (Chen et al., 2005; Hodgson et al., 2007; Luengas et al., 2015; Tseng et al., 2005; Vizhemehr et al., 2015; Yu et al., 2011).

Beside the well-established technologies for improvement of IAQ, new developments have been introduced in recent years. Among them, innovations in air cleaning, leveraging on smart technologies and sensing systems, and regulations for the evaluation of emissions from building products (Daeumling, 2016; Tham, 2016). These recently developed strategies together with responses to climate change and energy conservation have led to a change in the indoor chemical environment. For example, heavy metal toxicants (e.g. cadmium and mercury) and carcinogens (e.g. formaldehyde and benzene) could be reduced, however, reproductive toxicants (e.g. phthalates and polychlorinated biphenyls (PCBs)) and endocrine disruptors (e.g. brominated flame-retardants and bisphenol-A) have increased (Rudel and Perovich, 2009; Weschler, 2009). The deterioration of IAQ could not be alleviated effectively and therefore, the interest in IAQ is still growing at a public, a political, and a scientific level. Considerations for its enhancement to mitigate health complains, improve quality of life and the work environment with consequential benefits to well-being and performance are mandatory (Knöppel and Wolkoff, 2013; Tham, 2016).

However, beside IAQ, different psychological variables are also important in regard to human health, especially in workplace environments (O´Leary, 1990; Ryan and Morrow, 1992). Environmental dimensions in building design, like stimulation (e.g. odor, color, and visual exposure), coherence (e.g. landmark and floorplan complexity), affordance, control (e.g. boundaries and privacy), and restoration (e.g. minimal distraction and fascination), have the potential to affect human health (Evans and McCoy, 1998). The quality of the physical environment, e.g. thermal conditions, visual and acoustic design, and the interior design are strongly related to environmental satisfaction (Hongisto et al., 2016). Thus, in addition to improved air cleaning strategies, a comfortable and satisfying indoor environment should be created to improve occupants' environmental satisfaction (as well as job satisfaction), and accompanying health.

Plants are long-standing known to assimilate and metabolize toxic compounds from the air, soil or water. Acting as an important global sink for environmental chemicals, they can be considered as "green liver" (Paterson et al., 1990; Sandermann, 1992; Schulte-Hostede et al., 1987; Terry and Banuelos, 2000). Based on this fact, research has been directed toward the capability of plants to filter toxic compounds out of indoor air. In recent decades, a large

number of chamber experiments were conducted to evaluate the capability of ornamental plants to filter indoor pollutants, mainly VOC. First reports were published by Wolverton and co-workers as part of a NASA study (Wolverton and Wolverton, 1993 a; Wolverton et al., 1984). This was followed by a series of similar experiments, performed by other researchers worldwide. Also several field studies were conducted to examine the effects of ornamental plants on IAQ.

However, in most experiments it is not clear, whether the plant and/or the substrate with the containing microorganisms adsorbed VOC (or other air pollutants). Further, the environmental conditions relevant for plant growth and for the plant physiological status, such as humidity and CO_2 content, were often not controlled leading to non-reproducible results. Generally, less is known about the influence of plant physiology on air pollutant removal as well as about phytotoxic effects of such pollutants, which in return would affect the plant's pollutant removal efficiency. Moreover, due to a substantial heterogeneity in experimental setups (e.g. methods and test designs), the results on VOC removal by plants are quite mixed. This applies to field studies, where setup and parameters are typically less controllable, as well as to chamber experiments. Thus, there remains a need for an efficient and uniform method to determine the filter capability of pollutants by ornamental plants using test chambers.

Interestingly, despite the fact that VOC concentration in field studies was often unaffected (or even higher) in the presence of plants (Dingle et al., 2000; Kim et al., 2013, 2011; Smith and Pitt, 2011), many field studies could prove a positive effect of plants on human health. This could on one hand imply a placebo effect. On the other hand, plants might be capable to promote human well-being independently of a potential VOC removal. For instance, plants can improve human health by creating an environment that is perceived more comfortable, fascinating, and favorable (Evensen et al., 2013; Larsen et al., 1998). Several studies have shown that plants in the workplace environment can reduce health complains (Fjeld et al., 1998), or increase the level of mood, (Larsen et al., 1998), workplace satisfaction (Nieuwenhuis et al., 2014), and well-being (Lohr and Pearson-Mims, 2000).

In summery, many issues regarding a potential VOC removal by plants are still unresolved or emerged by the highly variable published studies. Therefore, there is a need for a test chamber design that is less prone to errors and ensures reproducible results in regard to the VOC removal efficiency of plants. Furthermore, knowledge concerning the correlation between VOC exposure and plant physiology is required to understand which parameters can affect the

air pollutant removal efficiency of plants. Finally, attaining information about the overall effect of plants on human well-being can further help to give appropriate recommendations for indoor greening and thus to improve human health and well-being. In order to obtain in-depth knowledge according these issues, the current doctoral thesis was divided in the following three parts:

Chapter I	**Chapter II**	**Chapter III**
Laboratory studies *- Examination of an experimental chamber to test the VOC removal efficiency of plants* *- Influencing factors on results of chamber experiments* Hörmann et al. (2017): Suitability of test chambers for analyzing air pollutant removal by plants and assessing potential indoor air purification. Water, Air, & Soil Pollution 228: 402	Laboratory studies *- Evaluation of the pollutant removal efficiency of selected plants* *- Putative interrelation of VOC exposure and plant physiology* Hörmann et al. (2017): Assessment of filtration efficiency and physiological responses of selected plant species to indoor air pollutants (toluene and 2-ethylhexanol) under chamber conditions. Environmental Science and Pollution Research	Field study in offices *- Examination of the VOC removal efficiency of Spathiphyllum wallisii in a real-life setting* *- Analysis of people-plant relationship in regard to a possible placebo effect* Hörmann et al. (submitted): Human well-being through plants - a placebo effect? Environmental Psychology

Chapter I - Chamber experiments to determine the pollutant removal capability of indoor plants

Experiments concerning the VOC removal capability of plants are usually examined in chamber experiments. To obtain repeatable results, test chambers should ensure an accurate VOC measurement and the control over environmental conditions that are important for plant physiology. However, such chambers are not commercially available, and the results of different investigations vary greatly and are not comparable. Therefore, the first chapter covers the following issues:

- Are so called Bioboxes (special test chambers that were developed for the examination of plant physiological responses to their environment under controlled conditions) suitable for determining the VOC uptake by plants?
- What are the major pitfalls in the experimental set up?
- What causes the high heterogeneity of results regarding VOC uptake reported in literature and which parameter have an impact on results?
- Which precautions should be taken to extrapolate the results from chamber studies to real environment?
- Finally, recommendations for chamber experiments concerning the VOC removal by plants are given.

Hörmann, V.; Brenske, K.-R. & Ulrichs, C. (2017): Suitability of test chambers for analyzing air pollutant removal by plants and assessing potential indoor air purification. Water, Air, & Soil Pollution 288:402

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Suitability of Test Chambers for Analyzing Air Pollutant Removal by Plants and Assessing Potential Indoor Air Purification

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Abstract A unique test chamber system, which enables experiments with plants under highly controlled environmental conditions, was used to examine the pollutant removal efficiency of plants. For this purpose, the removal of two different volatile organic compounds (VOC) (toluene, 2-ethylhexanol) from the air by aerial plant parts of two common indoor plant species (*Dieffenbachia maculata* and *Spathiphyllum wallisii*) was monitored. While the control over environmental conditions (temperature, relative humidity, CO_2 content, and light condition) worked very well in all experiments, control experiments with the empty chamber revealed high losses of VOC, especially 2-ethylhexanol, over the test duration of 48 h. Nonetheless, compared to the empty chamber, a significantly stronger and more rapid decline in the toluene as well as in the 2-ethylhexanol concentrations was observed when plants were present in the chamber. Interestingly, almost the same VOC removal as by aerial plant parts could be achieved by potting soil without plants. A comparative literature survey revealed substantial heterogeneity in previous results concerning the VOC removal efficiency of plants. This can be mainly attributed to a high diversity in experimental setup. The experimental setup used in the current study offers an excellent opportunity to examine also plant physiological responses to pollutant exposure (or other stressors) under highly controlled conditions. For the analysis of VOC removal under typical indoor conditions, to obtain data for the assessment of realistic VOC removal efficiencies by plants in rooms and offices, a guideline would be helpful to achieve more coherent findings in this field of research.

Keywords Ornamental plants · Indoor air quality · Air purification · Volatile organic compounds (VOC) · Toluene · 2-Ethylhexanol

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1 Introduction

People today spend 80–90% of their time indoors; thus, awareness toward indoor air quality has become increasingly important (Sarigiannis et al. 2011; Schweizer et al. 2006). Of certain interest are pollutants like volatile organic compounds (VOC) that might occur at high concentrations indoors (Jones 1999; Yu and Kim 2010). VOC are emitted by technical equipment as well as by furniture and carpets (Berrios et al. 2005; Que et al. 2013). Another source of VOC is related to human activities (Rösch et al. 2014) and indoor gas phase reactions which lead to the formation of secondary VOC (Salthammer and Bahadir 2009). Benzene, toluene, xylenes, styrene, and the group of terpenes are the

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most important VOC (Sarigiannis et al. 2011). Another compound of rising interest is 2-ethylhexanol which is formed by hydrolyses of di-2-ethylhexyl phthalate (DEHP), a major plasticizer incorporated in electrical cables, wall covering, flooring, and others (Azuma et al. 2016; Nalli et al. 2006; Reiser et al. 2002).

The contamination of indoor air by VOC (among other factors) is linked to disease symptoms including headache, lethargy, dry skin, and mucous membrane symptoms related to the eyes, nose, and throat. These symptoms are summarized as "sick building syndrome" (Burge 2004). Studies have shown that more than 30% of office workers in Germany suffer from the sick building syndrome (Bischof and Bullinger 1998; Brasche et al. 1999). Other authors associate a long-term exposure to low concentrations of VOC with an increased risk of cancer (Vaughan et al. 1986; Wallace 1991; Wolkoff and Nielsen 2001).

Several actions for abatement of indoor pollutants have been introduced. Among them are innovations in air cleaning, leveraging on smart technologies and sensing systems, and regulations for the evaluation of emissions from building products (Daeumling 2016; Tham 2016). These actions have led to a change in the indoor chemical environment. Even with air purification technology, heavy metal toxicants and carcinogens could be reduced; however, reproductive toxicants and endocrine disruptors have increased (Rudel and Perovich 2009; Weschler 2009). While technologies for particle filtration work well, there is no fully satisfying method for VOC removal (Chen et al. 2005; Guieysse et al. 2008; Luengas et al. 2015; Vizhemehr et al. 2015).

Plants are known to assimilate and metabolize toxic compounds from the air, soil, or water. Several enzymatic driven actions, like functionalization, transformation, and compartmentation, are included in the detoxification process. Xenobiotics may than be stored in vacuoles (soluble compounds) or cell walls (insoluble compounds) or further metabolized up to a deep oxidation. Acting as an important global sink for environmental chemicals, plants can be considered as "green liver" (Kvesitadze et al. 2009; Paterson et al. 1990; Sandermann 1992; Schulte-Hostede et al. 1987; Terry and Banuelos 2000). Based on this fact, research has been directed toward the capability of plants to filter toxic compounds out of indoor air. In recent decades, a large number of chamber experiments were conducted to evaluate the capability of ornamental plants to filter indoor pollutants, mainly VOC. First reports were published by authors taking part in a NASA study (Wolverton and Wolverton 1993; Wolverton et al. 1984). This was followed by a series of similar experiments, investigated by other researchers worldwide. However, if and to what extent plants really have an impact on indoor air quality is still under discussion in the scientific community (Dela Cruz et al. 2014; Llewellyn and Dixon 2011; Schmitz et al. 2000). The reports of different investigations show a broad variability in results. This gives rise to the questions of what causes this variability and what can we learn from these results considering the air purification capability of plants indoors.

Therefore, the aim of this study was to identify major challenges that have to be overcome in test chamber experiments considering the air purification capability of plants. Beside the impact of the test chamber design, the influence of different treatments and environmental conditions were taken into account. In order to identify major difficulties that may occur, we conducted a set of selected chamber experiments. The suitability of the test chambers and which conclusions can be drawn are discussed. The feature of our test chamber, in comparison to many other studies, was the possibility to control and record environmental conditions (including relative humidity and CO_2 content). The plant species *Dieffenbachia maculata* and *Spathiphyllum wallisii* were chosen because they are commonly used in interiorscapes, are widely distributed, and were already tested against their filter capability in several other studies. Toluene is a VOC which is frequently detected indoors (Sarigiannis et al. 2011) and has also been tested by other authors in similar experiments (Wood et al. 2006; Yang et al. 2009; Yoo et al. 2006). The alcohol 2-ethylhexanol is a (potential) indoor pollutant of rising interest (Azuma et al. 2016; Nalli et al. 2006; Reiser et al. 2002) and was not yet tested against removal by plants. Both VOC are chemically different, e.g., a high vapor pressure (29.1 hPa at 20 °C), no polar functional groups, and an aromatic structure for toluene versus low vapor pressure (0.48 hPa at 20 °C), a polar hydroxyl group, and an aliphatic acyclic structure for 2-ethylhexanol. The behavior and fate of these VOC with their different chemical properties was examined in our test chamber with and without plants to get an impression of the chamber's suitability regarding air purification experiments. For this, high VOC concentrations were used that are not representative of usual indoor air pollution levels. Furthermore, a literature survey was

conducted to demonstrate the high heterogeneity of results of chamber experiments on VOC removal by plants, examining different aspects like light conditions or VOC concentration. It is discussed to what extent the experimental setup, including test chamber design, treatments, and environmental conditions, may affect results. Further, suggestions for general guidelines for VOC removal experiments are given.

2 Material and Methods

2.1 Test Chambers

Two individual gas-tight chambers measuring 80 × 60 × 50 cm (height, width, depth) were purchased from the company GMS (Gaswechsel-Messsysteme GmbH, Berlin, Germany). Each of these so-called Bioboxes (Fig. 1) with a total volume of 240 L consists of two parts: a metal base (15 × 60 × 50 cm) and a Plexiglas hood (65 × 60 × 50 cm) on top. The base contains sensors for temperature, relative humidity, and CO_2 and a heat exchanger. The base of each Biobox is further equipped with stainless steel fittings to allow injection of VOC and to take air samples. In addition, fans were installed in the base to provide a complete mixing of the VOC-loaded air within the chamber and to overcome the boundary layer resistance of the leaves. The hood that has a volume of 195 L is connected to the base via a gas-tight Neoprene gasket. It has an opening at the front that allows the loading of plants into the system. This opening can be closed by attaching a panel, also with a gas-tight Neoprene gasket. A metal panel (50 × 50 cm) separates the base from the hood. Plants (or pots with soil) were placed on top of the metal panel. Left and right of the panel, a gap facilitates the air movement between hood and base.

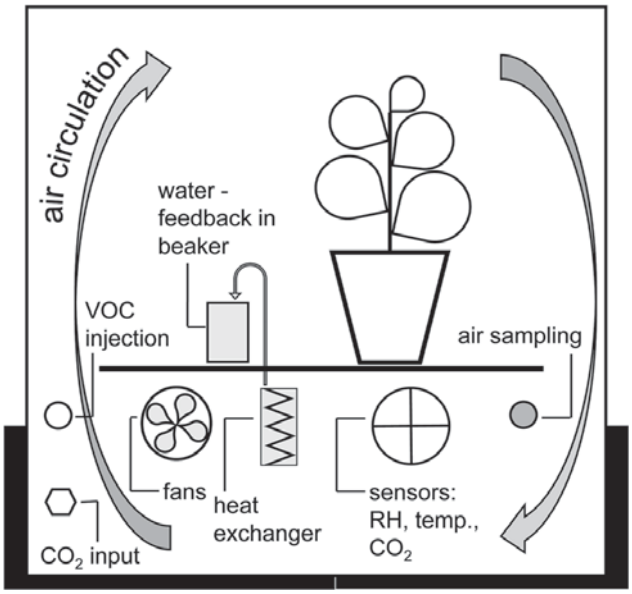

Fig. 1 Schematic illustration of the Bioboxes used in this study. RH, relative humidity; temp., temperature

Each Biobox is placed in a plant growth chamber (Adaptis A 1000, Co. Conviron, Winnipeg, Canada) which controls light intensity, light duration, and temperature. The Biobox sensors pass their signals on to a computer which controls the air humidity and the CO_2 concentration. During the experiments, the air humidity was kept constant by lowering the surface temperature of the heat exchanger so that surplus water condensed. The condensed water was fed via a tube to a beaker inside the Biobox. The CO_2 content was measured continuously by infrared spectroscopy. If the concentration dropped below the set point, CO_2 was automatically reinjected into the system via a tube from an external CO_2 gas cylinder.

Both Bioboxes were used in parallel for all experiments/treatments, including the empty chamber controls.

2.2 VOC Injection and Air Sampling

VOC used in this study were toluene (≥ 99.5% toluene for synthesis, Co. Carl Roth GmbH & Co. KG, Karlsruhe, Germany), of which 5.5 μL were injected (≈ 20 mg m^{-3}; 5.3 ppm) and 2-ethylhexanol (99% 2-ethyl-1-hexanol, Co. Alfa Aesar, Karlsruhe, Germany), of which 4.2 μL were injected (≈ 14.6 mg m^{-3}; 2.9 ppm). A 10-μL syringe with built-in Chaney Adapter (Model 701 NCH SYR, Cemented NDL, 26s ga, Co. Hamilton, Bonaduz, Switzerland) was used for all VOC injections through the left-side port in the Biobox base. This equipment ensured that the defined volume of a certain VOC could be injected very precisely in every replicate.

The right-side fitting in the base of the Biobox was used to take the air samples. Therefore, a sorption tube (C1-CXXX-5003, Tenax TA. C6-C30. Inert-coated., Co. Markes, Frankfurt, Germany) spiked with internal standards (100 ng of each, cyclooctane and cyclododecane) was connected to a gas-tight syringe (Borosilicate glass barrel 3.3, 100 mL, Co. Lehrmittel- und Verlagsgesellschaft mbH, Hofheim-Diedenbergen, Germany) and inserted into the Biobox via the fitting. A defined volume of air (50 mL for experiments with

toluene and 100 mL for experiments with 2-ethylhexanol) was drawn through the tube with a flow rate of 100 mL/min. Until analysis, the sorption tubes were stored in gas-tight aluminum bags at room temperature.

2.3 Test Plants and Culture

Well-developed plants of *Dieffenbachia maculata* "Compacta" (Lodd. et al.) G. Don and *Spathiphyllum wallisii* "Daniel" (Regel) (pots with 12 cm diameter, see Fig. 2) were purchased from a wholesale market. Prior to the experiments, the plants were cultivated in a growth chamber (Adaptis A 1000, Co. Conviron) for at least 3 days and up to 3 weeks with 15 h light per day (100 ± 10 μmol m^{-2} s^{-1}; MQ-200 Quantum Separate Sensor, Apogee Instruments, Inc., USA), temperature of 22/20 °C (day/night), and a constant relative humidity of 60–70%. Plants were watered regularly with tap water as needed.

2.4 Experimental Protocol

Three plants of either *D. maculata* or *S. wallisii* or three pots without plants filled with unused potting soil only (potting soil + clay + FE, Co Gramoflor, Vechta, Germany) were tested per Biobox (Fig. 2) under continuous light. All experiments were replicated four times ($n = 4$) using another set of plants or potting soil. For the experiments with potting soil only, the pots were wrapped in aluminum foil before filling with soil, to avoid sorption of VOC on plastic pots. In experiments with plants, the pots and the substrate surface were entirely covered with aluminum foil before placing the plants into the Biobox to ensure that removal of VOC can be attributed to aerial plant parts and soil effects are negligible within the experimental time span. Prior to VOC exposure, the plants were watered to saturation and allowed to drain for 1 h. During that time plants were placed in the Biobox under experimental conditions to get acclimatized. The potting soil was supplied with 100 mL water directly prior VOC exposure.

The climate conditions were set as follows: CO_2 = 500 ppm, RH = 70%, temperature = 22 °C, light = 180 ± 10 μmol m^{-2} s^{-1} (all parameters related within the Biobox). The duration of the experiment is an important factor. In published studies, the exposure time in chamber experiments varied between 2 h (Liu et al. 2007) and several days (Treesubsuntorn and Thiravetyan 2012). It is described that plants may need some time for the induction of VOC removal (at least 24 h) (Orwell et al. 2006; Wood et al. 2002) and that the VOC removal may vary diurnally (Liu et al. 2007). Thus, we decided to run our chamber experiments on the VOC removal by aerial plant parts (and by potting soil) for 48 h. Over this time, plants would have enough time for the induction of VOC removal and the natural VOC decline would have decreased due to saturation of surfaces while the plant would continue to remove VOC. At the beginning of each experiment, toluene or 2-ethylhexanol was injected and allowed to evaporate and equilibrate in the chamber. Thus, the first air samples were taken after 6 min for toluene and after 1 h for 2-ethylhexanol. The following air samples were taken after 5, 24, 29, and 48 h for both VOC. Tests on adsorption in empty chambers were conducted to assess potential effects by sorption on chamber surfaces.

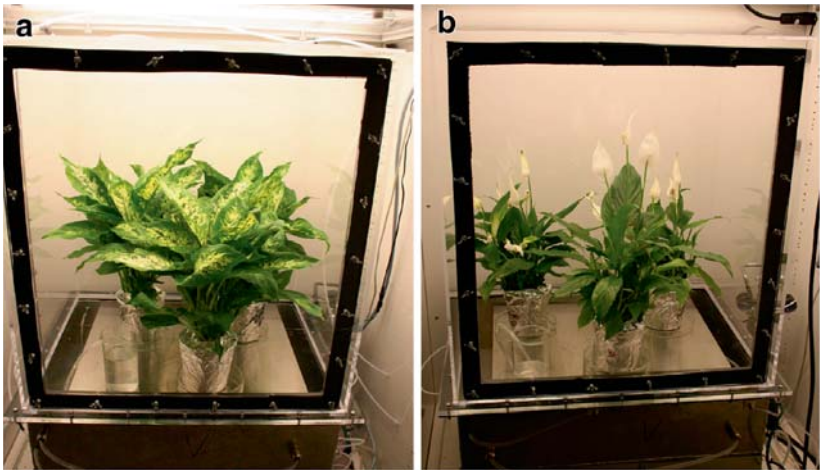

Fig. 2 Biobox equipped with *Dieffenbachia maculata* (**a**) and *Spathiphyllum wallisii* (**b**)