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RESEARCH ARTICLE

Assessment of volatile organic compound removal by indoor plants—a novel experimental setup

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Abstract Indoor plants can remove volatile organic compounds (VOCs) from the air. The majority of knowledge comes from laboratory studies where results cannot directly be transferred to real-life settings. The aim of this study was to develop an experimental test system to assess VOC removal by indoor plants which allows for an improved real-life simulation. Parameters such as relative humidity, air exchange rate and VOC concentration are controlled and can be varied to simulate different real-life settings. For example, toluene diffusion through a needle gave concentrations in the range of 0.10–2.35 μg/L with deviations from theoretical values of 3.2–10.5 %. Overall, the system proved to be functional for the assessment of VOC removal by indoor plants with *Hedera helix* reaching a toluene removal rate of up to 66.5 μg/m^2/h. The mode of toluene exposure (semi-dynamic or dynamic) had a significant influence on the removal rate obtained by *H. helix*.

Keywords Toluene · *Hedera helix* · VOC · Indoor air quality · Dynamic- and semi-dynamic conditions · Removal rate

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Introduction

Volatile organic compounds (VOCs) are ubiquitous in indoor air with sources being, e.g. building materials and human activities such as cooking and cleaning (Wolkoff 1995). The presence of VOCs in indoor air can affect human health, e.g. benzene can cause blood dyscrasias and formaldehyde can cause sensory irritation and nasopharyngeal cancer (World Health Organization 2010).

Indoor potted plants are capable of removing VOCs from air (e.g. Wood et al. 2006) and are in this way a potential green solution for improvement of indoor air quality. A reduction of 75 % in total VOC concentration was achieved with three specimens of *Dracaena deremensis* 'Janet Craig' in naturally ventilated offices of 30–50 m^3 if total VOC concentration in control offices was above 100 ppb (Wood et al. 2006).

Most knowledge on plants' ability to remove VOCs from indoor air is retrieved from studies conducted in laboratories. These studies have been carried out by placing plants in closed chambers, injecting one or multiple VOCs into the chamber and recording the decrease in VOC concentration over time (e.g. Wood et al. 2002). Air exchange has often been omitted from the chambers, and an increase in relative humidity to above ambient and a decrease in CO_2 concentration to below ambient due to gas exchange by the plant are likely to have taken place. This is in contrast to real-life situations in office environments where VOC emission is continuous (Yu and Crump 1998), air exchange can vary (Missia et al. 2010), relative humidity is often below 60 % and CO_2 concentration is above ambient concentration (Berardi et al. 1991; Wargocki et al. 2004). In a few studies, air exchange and continuous emission of a specific VOC have been ensured (Godish and Guindon 1989; Kondo et al. 1995; Liu et al. 2007; Xu et al. 2011).

The setup with closed chambers further gives problems with calculations of removal rates. The VOC concentration in the chamber will decrease over time due to uptake by the plant, and

this will lead to a decline in the removal rate over time (e.g. Kim et al. 2008). This means that the calculated removal rate will depend on the length of the experiment. On the other hand, removal rates increase upon repeated exposure (e.g. Orwell et al. 2004) which means that reported removal rates based on first-time exposure may be lower than the real potential of the plant. If continuous VOC emission is ensured and the plants are allowed to adapt to the situation, the experimental settings will be in closer resemblance to real-life settings and the calculated removal rates will give an improved estimation of what can be achieved in, e.g. office settings.

To our knowledge, an experimental test system that solves these challenges does not exist. The aim of this study was therefore to develop a robust and flexible experimental test system for the investigation of potted plants' ability to affect the concentration of VOCs in indoor air. Physical and chemical parameters that potentially could have an influence on removal rates and efficiencies should be stable and controllable. Parameters that vary in real-life settings should likewise be controllable. These parameters include air exchange rate, light intensity, temperature, relative humidity, CO_2 concentration, VOC concentration, and VOC composition. The experimental test system was optimized and validated with toluene as VOC and *Hedera helix* as plant species.

Materials and methods

Experimental test system

Four glass chambers (28.8 cm width × 33.8 cm depth × 59.1 cm height, 57.5 L) (Cichlide Centret Aps, Vallensbæk Strand, Denmark) were set up in a climate chamber with temperature control (model VEPHQ 5/2000, Heraeus Vötsch GmbH, Balingen, Germany). The front glass plate of each chamber functioned as the opening into each chamber and was held in place with clamps and further sealed with rubber foam and gaffer tape (Fig. 1). An air inlet and outlet enabled aeration and another inlet allowed for watering via a 15-cm Teflon tubing (i.d. 6.0 mm, VWR International, LLC, West Chester, PA, USA) extending inside the chamber.

Air was supplied from a central compressor (TREK LINE 2.2, Sullair Europe, Montbrison, France) and cleaned by a compressed air filter (Oil-X Evolution, Domnick Hunter, Parker Hannifin Manufacturing Limited, Birtley, England). The air flow was adjusted by a pressure regulator (Gloor 5650, Gloor Bros Ltd., Burgdorf, Switzerland) and measured by a mass flow meter (Sierra top-trak model 822, Sierra Instruments, Monterey, CA, USA). The flow meter was further connected to a datalogger (CR10X, Campbell Scientific, Logan, UT, USA) for constant logging of the air flow. Before entering the chambers, the air was directed through a specially designed glass mixing chamber of 6 L (Fig. 1b) where a VOC source was placed. The VOC source was a liquid VOC added to a 4-mL amber vial and allowed to diffuse through a needle placed through the lid of the vial (Fig. 1c). A similar setup for VOC exposure has previously been reported (Jia et al. 2007). The controllability of the VOC exposure was validated at four needle lengths, needle areas, air flow rates, and temperatures.

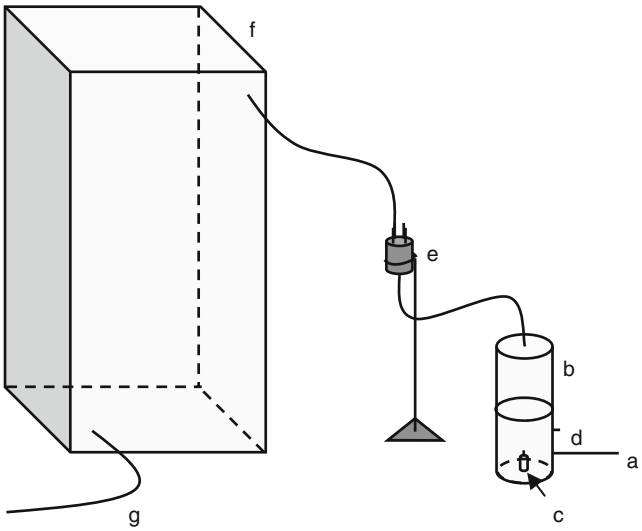

Fig. 1 Schematic view of the experimental test system: Glass chamber connected to mixing chamber. *a* Air inlet. *b* Mixing chamber. *c* VOC source. *d* CO_2 inlet. *e* Distributor. *f* Glass chamber. *g* Outlet to the sampling area

Addition of CO_2 (99.9 %, Yara Praxair A/S, Fredericia, Denmark) to the mixing chamber was possible with the flow rate controlled and measured by a mass flow controller and meter (model 5850TR, Brooks Instrument, Hatfield, PA, USA) (Fig. 1d) and logged by the datalogger. CO_2 concentration in the outlet air was analysed with a CIRAS-CS single channel CO_2/H_2O analyser (PP Systems, Amesbury, MA, USA).

From the mixing chamber, the air was directed to a specially made stainless steel distributor for equal distribution of the air to the four glass chambers (Fig. 1e, f). From the chambers, the air was directed out of the climate chamber (Fig. 1g) to the sampling area. Tubing from the mixing chamber to the glass chambers and from the glass chambers to the sampling area was Tygon SE-200 (i.d. 6.4 mm, VWR International, LLC, West Chester, PA, USA). Tubing from the inlet air pressure regulator to the mixing chamber was silicone (i.d. 6.0 mm, VWR International, LLC, West Chester, PA, USA).

In the climate chamber, light was supplied by Osram Powerstar HQI-E 250/D PRO bulbs (OSRAM GmbH, München, Germany). The intensity was adjustable within the range of 0–300 μmol/m^2/s by switching a variable number of lamps on/off and additionally by covering the lights with white cloth (Lutrasil P23 Freudenberg & Co., Weinheim, Germany). The photosynthetic active radiation was measured with a LI-250 light meter with a quantum sensor (LI-COR. Inc., Lincoln, NE, USA) and expressed in micromole per

square meter per second. Relative humidity in the glass chambers with plants was controlled using a drying agent. Anhydrous $MgSO_4$ (dried for 4 h at 200 °C prior to use) was tested in the amounts of 300, 800, and 1,200 g spread out in aluminium trays. $MgSO_4$ (300 g) was spread out in one large aluminium tray (size 720 cm^2) in the bottom of the chambers, and 800 and 1,200 g MgSO4 were divided between one large and five small aluminium trays (total size 1,070 cm^2). The five small trays were placed on a grate together with the plant at ca. 8 cm height. Temperature and relative humidity inside the glass chambers were measured with Tinytag Ultra 2 TGU-4500 dataloggers (Gemini Data Loggers (UK) Ltd, West Sussex, UK).

Sampling and analysis

The outlet air was sampled on small activated coconut charcoal tubes (ORBO™ 32, (20/40), 100/50 mg, Supelco, Bellafonte, PA, USA), which were connected to AirChek2000 pumps (SKC Inc., Eighty Four, PA, USA). Flow rates of the pumps were between 0 and 3,250 mL/min±5 %. Immediately after sampling, the tubes were capped, and if analysis was not carried out on the same day, the tubes were stored in airtight bags at −18 °C.

Toluene adsorbed to the activated charcoal was quantified using a slightly modified version of the NIOSH method 1501 (NIOSH 2003). Briefly, the tubes were opened and the glass wool plug and the activated charcoal from the adsorbing section were transferred to a 4-mL amber glass vial. Two milliliters of carbon disulfide (CS_2) (puriss, p.a., Sigma-Aldrich, St. Louis, MO, USA) was added, and the vials were ultrasonicated for 30 min. The solution was transferred with glass pipettes to another 4-mL amber glass vial for storage and to a 1-mL clear gas chromatograph (GC) vial for analysis.

Samples were analysed using a GC with flame ionization detection (FID) (model 6890, Agilent Technologies, Santa Clara, CA, USA) with a DB-WAX column of 30 m× 0.320 mm inner diameter and with a film thickness of 0.50 μm (Agilent Technologies, Santa Clara, CA, USA). The oven temperature programme was 40 °C for 4 min and ramped to 240 °C at 25 °C/min. Samples of 2 μL were injected in splitless mode and hydrogen was used as carrier gas at a flow rate of 3.0 mL/min.

Operating procedure

The test system was operational in two modes: semi-dynamic and dynamic conditions. In the semi-dynamic condition, the air flow with the VOC was stopped for 8 h by capping the inlet and outlet of the chambers. For sampling, clean air was introduced to the chambers thus exchanging the air and collecting residual VOCs from the chamber. The chamber air was exchanged at least three times during the sampling. In the dynamic condition, the air flow with the VOC was maintained during the entire experiment. Hence, sampling was carried out while maintaining the air flow with the VOC through the chambers.

Validation of the experimental test system

Validation of the experimental test system was carried out by analysing toluene removal by the potted plant English ivy (*H. helix* 'Gitte') (supplied by Multigreen.dk A/S, Odense, Denmark). One plant was placed in each of two chambers and the remaining two chambers functioned as control chambers without plants. The plants were 12 weeks old when supplied with seven plantlets in 11-cm pots, which is a plant size commonly brought into the Danish market. Prior to the experiment, the plants were acclimatized to 20 °C, 49 μmol/m^2/s light intensity and 12/12 h day/night for 2–4 weeks in a similar climate chamber as described Experimental test system. To reach a light intensity of 49 μmol/m^2/s, three light bulbs were turned on and the lights were covered with three layers of white cloth. Plants received 46 mL of tap water each day with no addition of nutrients. During the validation experiments, light conditions, temperature and watering were similar to those under acclimatization. These parameter settings were chosen to simulate a window pane in an office. Relative humidity was controlled by 800 g $MgSO_4$ placed as described above.

Air flow through the mixing chamber was kept at 4.37± 0.04 L/min which gave an air exchange rate in the glass chambers of 1.14/h. Toluene (anhydrous, 99.8 %, Sigma-Aldrich, St. Louis, MO, USA) was added to the 4-mL amber vial in the mixing chamber and diffused through a 40-mm-long 16-gauge needle. Plants were exposed to toluene for at least 4 days before the first samples were taken. Samples were collected over 4 days where days 1 and 3 were under dynamic conditions and days 2 and 4 were under semi-dynamic conditions with an exposure time of 8 h. The experiment was repeated twice giving a total of four biological replicates. At the end of an experiment, the leaf area of the plants was measured with a LI-3100 area meter (LI-COR. Inc., Lincoln, NE, USA).

For statistical analysis, toluene concentrations in control chambers were compared to toluene concentrations in chambers with plants separately for the two conditions. Statistical analysis was carried out in R (www.r-project.org) using mixed linear models with repeated measurements.

Results and discussion

The developed experimental test system can be divided into five categories for which there are different considerations to be made: system setup; VOC exposure; control of relative humidity; control of CO_2 concentration; and sampling and chemical analysis.

System setup

The experimental test system was built from as inert materials as possible to limit adsorption of VOCs to the system surfaces. This is a practice used in many previous studies (e.g. Wood et al. 2002; Yoo et al. 2006; Kim et al. 2008). To seal the glass chambers, some silicone and rubber were used which may act as adsorption sites. Loss of toluene to the glass chambers was evaluated twice under dynamic conditions by measuring the toluene concentration in the air before and after the glass chambers at concentrations of 0.35 and 1.00 μg/L. Air was sampled in duplicate or triplicate for all chambers. The average loss to the glass chambers was 8.9±0.2 %, which was constant over time. As the main usage of the system will be in dynamic mode, a constant loss of toluene over time will only lead to the measured pollution load being 8.9 % lower than expected. The removal by the plants is measured against empty control chambers, and the loss of toluene to the glass chambers should therefore not influence the removal rates obtained for the plants. With a change of VOC composition, the average loss may be changed and should therefore be measured again.

When using the semi-dynamic procedure, the steady state will be changed once the air flow is stopped, and there may be some re-emission from the adsorption sites in the glass chamber to the air. The semi-dynamic procedure is in addition more sensitive to any leakages from the glass chambers as this will have a direct influence on the calculated removal rates. In the dynamic procedure, the VOC concentration at steady state is measured and leakages will not have any influence on this.

VOC exposure

The VOC exposure in the experimental test system was based on simple diffusion through a needle. This means that the VOC exposure can be calculated from Fick's first law (Erbil and Avci 2002):

$$\frac{M}{t} = \frac{D \times A \times (C_0 - C)}{Ld} \tag{1}$$

$$C_0 = \frac{P_v \times \mathrm{mw}}{R \times T} \tag{2}$$

$$P_v = P_T \times \ln\left(\frac{P_T}{P_T - P_{vs}}\right) \tag{3}$$

$$C_a = \frac{M}{t \times F} \tag{4}$$

where M is total mass evaporated (μg), t is time (min), D is diffusion coefficient (m^2/s), A is diffusion area (m^2), C_0 is VOC concentration in the vial headspace ($\mu g/m^3$), C is VOC concentration in the mixing chamber ($\mu g/m^3$), Ld is diffusion length (m), P_v is actual vapour pressure (Pa), mw is molecular weight of the VOC (μg/mol), R is the gas constant (m^3 Pa/K/mol), T is temperature (K), P_T is total pressure of the ambient atmosphere (Pa), P_{vs} is saturation vapour pressure (Pa), C_a is VOC concentration in the air leaving the mixing chamber (μg/L) and F is the air flow through the mixing chamber (L/min).

The parameters A and Ld are the dimensions of the needle inserted into the lid of the amber glass vial. Since the VOC is constantly removed by the air flow in the mixing chamber, C is expected to be very small compared to C_0 and is therefore ignored. The D, P_{vs} and mw of the VOC of interest can be found in chemical tables (e.g. Lugg 1968; Mackay et al. 1982).

A parameter sensitivity analysis was made to evaluate which parameters have a large influence on the VOC concentration (Fig. 2). Four parameters, needle length, needle area, air flow rate and temperature, are considered central for the control of the VOC concentration and are therefore included in the parameter sensitivity analysis.

For the temperature simulation, further two formulas are needed that are specific for toluene

$$D = \left(8.075 \times 10^{-8}\right) \times T(^{\circ}\mathrm{C}) + 6.051 \times 10^{-6} \tag{5}$$

(Erbil and Avci 2002)

$$\ln(P_{vs}) = 19.275 - \frac{4,748.4}{T} \tag{6}$$

(Perry and Chilton 1973)

The analysis was made for toluene, and as base for the simulations, needle length was 0.04 m, needle area 1.12×10^{-6} m^2, air flow rate 4.26 L/min and temperature 21.8 °C.

Needle area and length have a direct effect on the VOC concentration in the air leaving the mixing chamber. Increasing the needle length will decrease the VOC concentration hyperbolically while increasing the needle area will have a positive linear influence on the VOC concentration (Fig. 2a, b). As the effect of needle length is hyperbolic, precise control of VOC concentration may be difficult with very short needles. Theoretically, the needle area is a more robust parameter to use for control of the VOC concentration as the effect of this is linear. However, the dimensions of the needle area are more or less restricted by the commercially available sizes.

The air flow rate also has a direct effect on the VOC concentration in the air leaving the mixing chamber. As with needle length, the effect of the air flow rate is hyperbolic, meaning that the relative effect of a change in air flow rate is highest at low air flow rates (Fig. 2c). This means that it is vital to keep a very constant air flow rate especially at low air flow rates.

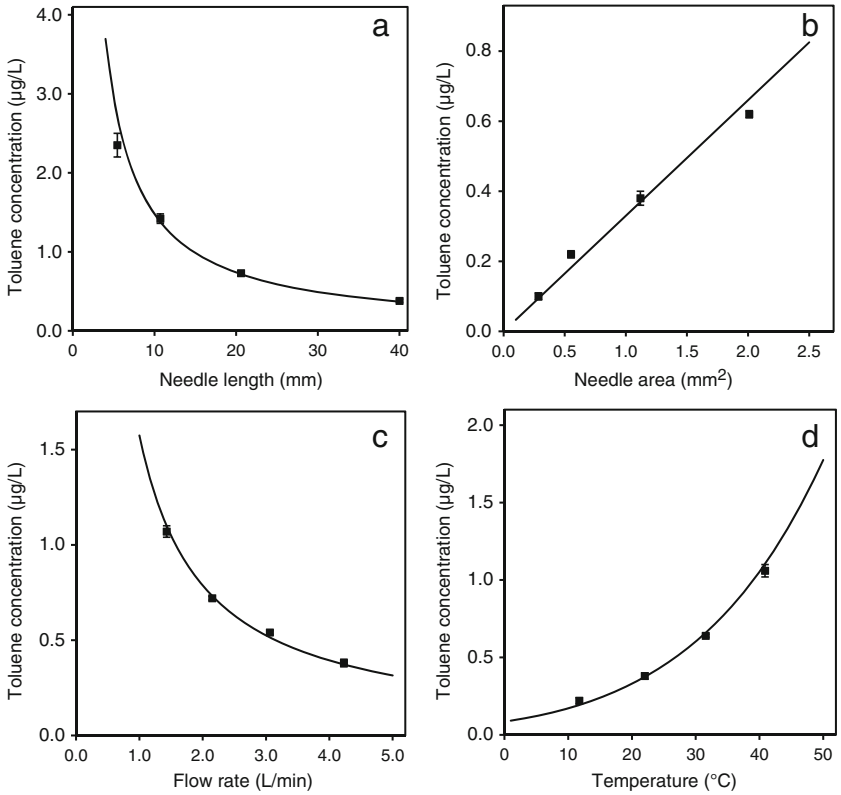

Fig. 2 Parameter sensitivity analysis: *Lines* are simulation of toluene concentration depending on **a** needle length, **b** needle area, **c** air flow rate and **d** temperature. *Points* are experimental validation, $n=4\pm SD$

Temperature has an indirect effect on the VOC concentration in the air leaving the mixing chamber through its effect on the VOC concentration in the vial headspace. As seen in Fig. 2d, the VOC concentration in the air leaving the mixing chamber increases hyperbolically with increasing temperature.

Adjustment of the VOC concentration by changing the temperature or air flow rate can potentially lead to unwanted effects on the test plants, and it is therefore recommended to use needle length and/or needle area to change the VOC concentration. Note also that if it is desired to investigate the effects of temperature or air flow rate on plants' removal rates, it is necessary to adjust the VOC concentration accordingly.

The experimental values were deviating from the theoretical values with only 3.2–10.5 %. The experimental control of the VOC concentration is therefore considered satisfactory. There are, however, some limitations to the control of the VOC concentration. The minimum needle length was 5.45 mm as shorter needle was not securely fitted through the lid of the vial. Minimum needle area was also restricted by what was possible to push through the vial lid. In this test system, the minimum air flow rate was 1.4 L/min as this is restricted by the pressure regulator. This can, though, be changed by changing the pressure regulator. The lower limit of 1.4 L/min which will give an air exchange rate in the chambers of 0.36/h is, however, sufficient to simulate real-life conditions. The temperature for the sensitivity analysis was held within the range of 10–40 °C. For real-life simulations, a much narrower range of, e.g. 18–25 °C is more realistic. However, to fully test the system, the wider range of 10–40 °C was chosen.

The VOC concentration will also depend on the VOC in question. Figure 3 shows how the VOC concentration changes with vapour pressure of the VOC. This is not a straightforward relationship as the VOC concentration is dependent on the vapour pressure, the diffusion coefficient and the molecular weight of the VOC. However, high vapour pressure will generally result in a high VOC concentration.

In this system, the VOC can easily be changed to another VOC or to a mixture of VOCs by changing the liquid contaminant source in the mixing chamber. A mixture of VOCs can be produced by placing a number of vials each containing a single VOC in the mixing chamber and adjusting the concentration of each as mentioned for toluene. Alternatively, a single vial containing a mixture of VOCs can be introduced to the mixing chamber. In this way, the concentration of each VOC in the air will depend on their concentration in the liquid mixture. By changing the concentration of a VOC in the liquid mixture, the concentration of that VOC in the air is changed.

A drawback of the exposure system is the creation of pseudoreplicates as only one mixing chamber supplies polluted air to the four glass chambers. Ideally, each chamber should

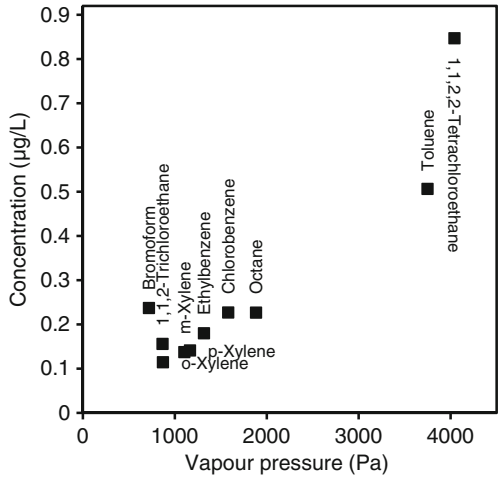

Fig. 3 Dependency of vapour pressure on VOC concentration at 20 °C. Diffusion coefficients are retrieved from Lugg (1968) and vapour pressure from Mackay et al. (1982)

be supplied by its own mixing chamber. This was, however, done to create similar conditions for all four glass chambers as the effect of the biological replicates, i.e. the plants, is the main interest. In addition, repetition in time can increase the number of replicates.

CO_2

Control of the CO_2 concentration was implemented as CO_2 has an influence on the photosynthetic activity of the plants. A change in photosynthetic activity may influence VOC removal rates and efficiencies by increasing the stomatal conductance and thereby ease the entry of the VOC into the plant. Indirectly, an increase in photosynthetic activity may also influence the microbial activity in the soil as the plants produce more root exudates (e.g. Canadell et al. 1996). This can increase the microbial activity in the soil (Zak et al. 1993). Furthermore, the CO_2 concentration in office environments is often above ambient (Berardi et al. 1991; Wargocki et al. 2004), and with control of the CO_2 concentration, it will be possible to simulate this condition.

The lowest CO_2 concentration in the glass chambers was the ambient CO_2 concentration of 388±39 ppm. An increase in CO_2 concentration from this point was controllable. Figure 4 shows that an increase in CO_2 supply is linearly related to an increase in CO_2 concentration. The slope of the relationship between CO_2 supply and CO_2 concentration is dependent on the air flow rate through the mixing chamber. The relationship in Fig. 4 is measured at an air flow rate of 4.30±0.20 L/min. An increase in the air flow rate will lead to a decrease in CO_2 concentration and vice versa.

The relationship between CO_2 supply and CO_2 concentration was measured in three turns. The increase in CO_2 concentration was calculated on the basis of measurements of the CO_2 concentration in the air leaving the glass chambers. This was subtracted with the ambient CO_2 concentration measured before or after the addition of CO_2. This means that the increase in CO_2 concentration can be influenced by fluctuations in the ambient CO_2 concentration.

Relative humidity

Condensation of water on the glass chamber walls due to transpiration by the plant is a potential source of error as VOCs are soluble in water. The effect of condensation depends mainly on the water solubility of the individual VOCs. Even if the effect of VOC absorption by water is low, a high humidity may have an effect on the plants' stomatal conductance (Turner 1991) and thereby on the VOC removal rate.

Relative humidity was adjusted using drying agents. The quality criteria for the drying agent were (1) no absorption of the VOCs, (2) high capacity for uptake of water and (3) high uptake rate to continuously keep down the humidity. Three candidates were considered, Na_2SO_4, $CaSO_4$ and $MgSO_4$, which are generally useful and will likely not absorb VOCs. Na_2SO_4 has a high capacity and a low uptake rate, $CaSO_4$ has a low capacity and a high uptake rate and $MgSO_4$ has a high capacity and a high uptake rate (Ault 1998).

Preliminary tests showed that the capacity of $CaSO_4$ and the uptake rate of Na_2SO_4 were too low as they were not able to prevent condensation of water on the surfaces under the current experimental conditions. $MgSO_4$ was able to prevent condensation and was therefore chosen for further testing (Fig. 5).

Without a drying agent, the relative humidity always increased to 100 % when plants were present in the glass chambers and condensed water was dripping from the walls. A decrease in relative humidity to 89.7±2.4 % was achieved with 300 g $MgSO_4$ covering an area of 720 cm^2, whereas 800 or 1,200 g $MgSO_4$ spread over an area of 1,070 cm^2 lowered the relative humidity to 84.3±2.9 % (Fig. 5). The average leaf area was 0.24 m^2, air exchange rate was 4.26 L/min and light intensity was 45 µmol/m^2/s. For analysis of toluene uptake by the $MgSO_4$, approximately 1 g of $MgSO_4$ was dissolved in 2 mL CS_2 and measured by GC-FID. No detectable levels were found, and it was concluded that toluene is not adsorbed to $MgSO_4$.

The relative humidity in the glass chambers depends mainly on the transpiration rate, total leaf area and air exchange rate. An increase in relative humidity is expected with increasing transpiration rate and leaf area. On the contrary, an increase in air exchange rate will lead to a decrease in relative humidity as the supply air has a relative humidity of less than 10 %. Increasing the amount of the drying agent ($MgSO_4$) can to some degree compensate for an increase in relative humidity. However, there seems to be no further reduction in relative humidity with an increase in $MgSO_4$ from 800 to 1,200 g (see Fig. 5). A possible explanation for this is that the surface area

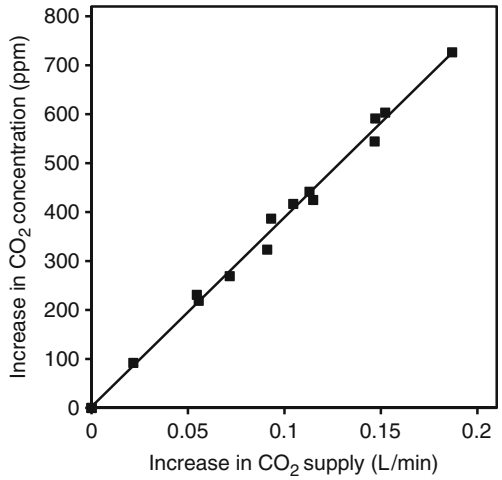

Fig. 4 Increase in CO_2 concentration is controlled with an increase in CO_2 supply

rather than the thickness of the drying agent is the controlling factor. A further increase in surface area of the $MgSO_4$ was, however, not possible due to the size of the glass chambers. Larger glass chambers could minimize problems with high relative air humidity as surface area of the drying agent can be increased, but the increased air volume will also be able to contain more water. Alternatively, an external device can be fitted containing $MgSO_4$ through which the air can be circulated and in this way remove the water from the chamber. This increases the air circulation in the chamber creating a situation that potentially could be unrealistic compared to a real-life situation.

Sampling and analysis

For VOC sampling, it is possible to use a variety of adsorptive material (Dettmer and Engewald 2002; Ras et al. 2009). The activated charcoal tubes used in this study have the advantages

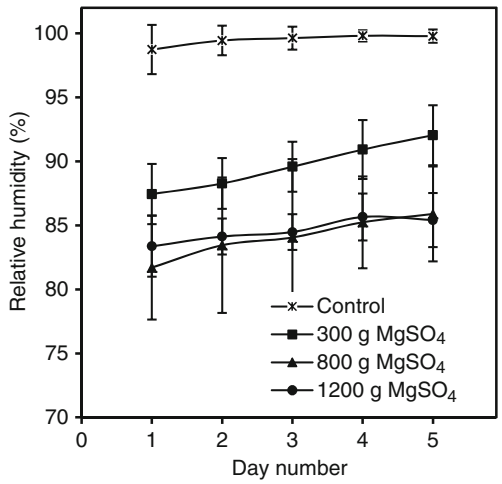

Fig. 5 Adjustment of relative humidity over 5 days with various amounts of $MgSO_4$, n=2±SD, except control where n=6±SD

that they are cheap and disposable. They do, however, have to be manually opened for sampling, meaning that they will differ in resistance as the opening sizes will not be equal. The AirChek2000 pumps used in this study are designed to keep a certain flow rate regardless of the resistance put in front of it, but in practice, some deviation from this was observed. Therefore, the flow rate through the tubes was measured before and after sampling. This means that the tubes were exposed to ambient air for a short period of time which can cause pollution of the tubes. This pollution will, however, be insignificant if the sampling time is long. Alternatively, reusable adsorbent tubes can be used which are defined in size and flow rate measurements can be carried out with a tube set aside for this.

The limit of detection and the limit of quantification for toluene on the GC-FID used in this study were 0.96 and 3.2 μg/L, respectively. The low sensitivity can be compensated for by increasing the sampling time and rate. Compared to taking a sample with a gas-tight microsyringe and injecting it directly into the GC as done in previous studies (e.g. Wood et al. 2002), the sampling on adsorbent tubes allows for preconcentration of the analyte and lower VOC concentrations can be used in experiments. Alternatively, reusable tubes that can be thermally desorbed allow for all sampled analyte to be transferred to the GC, and the sensitivity may be increased 1,000-fold. This requires a thermal desorption unit to be installed on the GC. The sensitivity can be further increased by using mass spectrometry or time-of-flight mass spectrometry. For more information on sampling and analysis of VOCs, the reader is referred to Kumar and Viden (2007), Demeestere et al. (2008) and Ramirez et al. (2010).

Validation

The test system was validated by investigating toluene removal by *H. helix* 'Gitte' under dynamic and semi-dynamic conditions. Experimental conditions are given in Table 1. Under dynamic conditions, the plants achieved a removal rate of 66.5 μg/m^2/h, whereas the removal rate was 28.7 μg/m^2/h under semi-dynamic conditions. Both rates were significant at $p<0.05$. The semi-dynamic condition will allow for a comparison with earlier studies conducted in closed chambers, while the dynamic condition is an improved simulation of real-life settings.

Removal rates under dynamic conditions are higher than under semi-dynamic conditions. This shows how the experimental conditions easily can affect calculated removal rates. A likely explanation for this effect is the concentration profile over time in the chambers. Under the semi-dynamic conditions, the concentration of the VOC will decline over time as the plants remove it as seen by, e.g. De Kempeneer et al. (2004). This creates an overall lower exposure than under dynamic conditions and thereby a lower removal rate. Since

Table 1 Experimental conditions for toluene removal by *H. helix*

	Repetition 1	Repetition 2
Temperature—day	21.3±0.2 °C	N/A
Temperature—night	19.8±0.1 °C	N/A
Relative humidity—day	74.4±5.7 %	N/A
Relative humidity—night	55.9±2.4 %	N/A
CO_2 concentration—day	359±18 ppm	343±20 ppm
CO_2 concentration—night	448±16 ppm	452±11 ppm
Light intensity—day	45.4±3.9 μmol/m^2/s	45.4±3.9 μmol/m^2/s
Leaf area	0.064±0.008 m^2	0.080±0.029 m^2
Toluene concentration	0.35±0.05 μg/L	0.43±0.03 μg/L

the dynamic condition is closest to real-life settings, 66.5 μg/m^2/h is the removal rate that can be expected in, e.g. offices with parameters such as air exchange rate and light intensity similar to the experimental conditions in this study.

Toluene removal rates by *Spathiphyllum* 'Sweet Chico' and *Dracaena deremensis* 'Janet Craig' have been reported to be 44.6 and 166.7 μg/m^2/h, respectively, with an initial concentration of 0.81 μg/L (Orwell et al. 2006). These removal rates can be compared to the removal rate found under semi-dynamic conditions, but as seen by, e.g. Kim et al. (2010), removal rates are plant species specific and can be influenced by factors such as light intensity and VOC concentration. In conclusion, the experimental test system proved successful for the assessment of air contaminant removal by indoor plants.

Concluding remarks

The design of the experimental test system was both robust and flexible for the investigation of air contaminant removal by indoor plants. The approach with simple diffusion of a VOC through a needle proved satisfactory as the VOC exposure was controllable within 3.2–10.5 %. This approach further allows for easily changing the VOC which has not been possible in earlier studies. Control of the relative humidity with a drying agent reduced problems with water condensation on chamber surfaces, and control of the CO_2 supply was sufficient to control the CO_2 concentration albeit this is influenced by changes in the ambient CO_2 concentration.

Compared to the static method used in previous studies (e.g. Orwell et al. 2006), the semi-dynamic setup has the advantage that the plants are continuously exposed to a VOC until the air flow is stopped. This will take into account that removal rates increase upon repeated exposure (Wood et al. 2002) and ensure that the VOC is well mixed in the glass chamber. The dynamic setup has furthermore the advantage that it is a closer simulation of a real-life setting, and results produced using this method will be more easily transferrable to, e.g. office settings.

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