Air purification by house plants

A literature survey

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Wageningen Plant Research
Wageningen, September 2017

Report WPR-695

WAGENINGEN
UNIVERSITY & RESEARCH

Referaat
Binnen het project 'Plantkampioen luchtzuivering', een publiek-private samenwerking, is een literatuurstudie uitgevoerd naar de meest recente bevindingen over de mogelijkheid van planten om lucht binnenshuis te zuiveren. Er is gezocht in wetenschappelijke publicaties, vakbladen en tuinbouwrapporten. Het algemene beeld is dat planten in zekere mate Vluchtige Organische Stof (VOS) kunnen opnemen zonder zelf schade te ondervinden. De opnamemechanismen verschillen tussen typen VOS. Hydrofiele VOS zoals formaldehyde worden vrij goed door het blad verwerkt, terwijl lipofiele componenten via andere routes worden opgenomen. Verschillen tussen plantensoorten houden verband met de hoeveelheid blad, de huidmondjesopening, de waslaag en de beharing. Naast de groene plantendelen spelen ook de wortels, de micro-organismen en het substraat een rol in de luchtzuivering. Het onderzoek in plantkamers leverde vooral resultaten over de kortdurende opnamen door planten, maar over de lange-termijn effecten en de onderliggende mechanismen is nog weinig bekend. Het onderzoek naar opschaling van lab- naar praktijksituaties is nog weinig ontwikkeld. Enkele goede studies laten veelbelovende resultaten zien, maar veel onderzoek is matig onderbouwd. Meer onderzoek is nodig om de labproeven te kunnen extrapoleren naar de praktijk.

Abstract
Within the project 'Plant champion air purification', a public-private cooperation, a literate survey was carried out to explore recent findings on the possibilities of plants to purify indoor contaminated air. Literature was searched in academic journals, on the internet and within reports recently carried out for the horticultural sector. Here this knowledge is shortly described. Plants generally have the capacity to assimilate hydrophilic Volatile Organic Compounds (VOCs) like formaldehyde without harm. Lipophilic VOCs are less well assimilated and follow different uptake pathways. Differences between plant species can sometimes be related to amount of leaves, wax layer composition, stomatal conductance or hairs. Apart from the green plant parts, the roots, the micro-organisms and rooting medium have a role in air purification. The research in plant chambers mainly generated knowledge on short term uptake of volatiles, but the uptake mechanisms and the long-term performances of plants are only partly understood. The research on upscaling of lab results to air purification in rooms within buildings is still in its infancy. A few good studies have been done and show promising results, but most research was statistically poor. More research is needed to extrapolate the findings from lab research to practice.

Reportinfo

Report WPR-695
Project number: 3742241400

This project/research has been made possible by the contribution of 'TKI Tuinbouw en Uitgangsmaterialen', Royal FLoraHolland, Air so Pure, KP Holland, VBG, iVerde and of Stimuflori.

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Summary

In the past 30-40 years a wide spectrum of plant species has been scientifically examined for their capacity to purify air. Many plants can to a certain extent clean the air by uptake of Volatile Organic Compounds (VOC) and fine particles. The hydrophilic VOC like aldehydes are assimilated in leaves and the real-life concentrations hardly cause harm to the plant. Lipophilic VOC like benzenes are less well assimilated and follow other uptake pathways then hydrophilic VOC. Differences between plant species can sometimes be related to amount of leaves, composition of the wax layer, stomatal conductance or hairs. Apart from the green plant parts, the roots and rooting medium have an important role in air purification by adhesion to carbon and assimilation by microbes. The research in plant chambers mainly generated knowledge on short term removal of volatiles, but the uptake mechanisms and the long-term performances of plants are only partly understood. The research on upscaling of lab results to air purification in rooms within buildings is still in its infancy. A few good studies have been done and show promising results, but most research was statistically poor. More research is needed to extrapolate the findings from lab research to practice.

1 Introduction

In the eighties of the 20th century, people experienced bad indoor air qualities in their offices which was named the 'sick building syndrome'. In the meantime, experiments were performed by NASA to accommodate stand-alone life support systems, for life in space, with the support of plants and their rhizosphere to consume CO_2, produce O_2 and abate air quality (Wolverton et al., 1984). The experiments were using quite advanced technologies for those days, with inert materials, completely sealed cabinets, heating and illumination (Fig. 1). Their studies on air purification by plants were one of the first, and many studies have been carried out since.

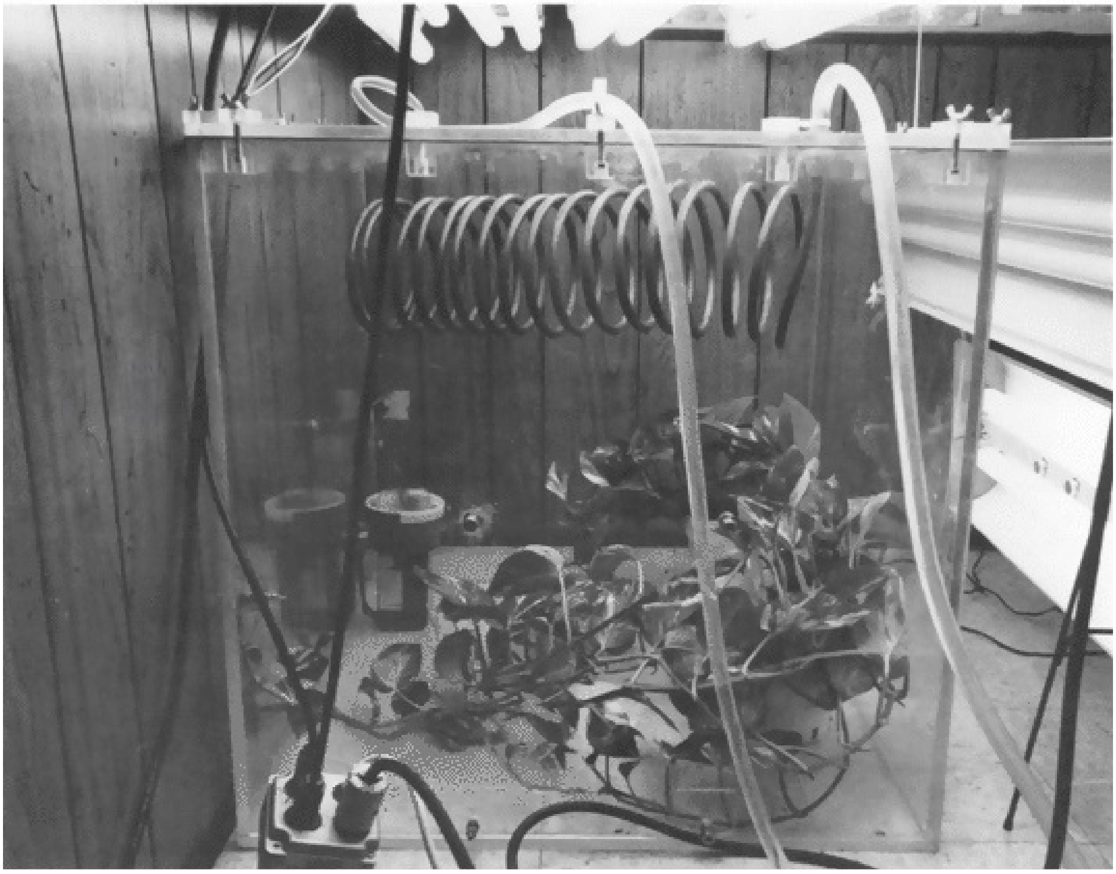

Figure 1. *Plexiglas test chamber containing golden pothos (Scindapsus aureus), demonstrating the techniques used in the studies of Wolverton et al. (1984).*

Nowadays, technologies have been improved considerably, e.g. having analytical equipment with much higher detection levels, more inert tubing, more accurate dosing techniques.
Apart from the technical aspects, much more insight is gained in the plant's mechanisms on growth, assimilation, detoxification and stress resistance. The developments in science thus motivate us to evaluate the findings of the last three decades, and reconsider the current insights in the plant's ability to purify air, and to suggest new research with the most up-to-date technologies.
This literature survey tries to collect the existing knowledge of the last 20-30 years, indicate possible knowledge gaps and misinterpretations, and suggest new research.

2 Uptake by aerial parts

The uptake of volatile organic compounds (VOC) can take place through a number of routes. Although not all routes may be known today, the most obvious ones are absorption to the leaves, uptake through the leaf stomata and incorporation in substrate and roots. The uptake is generally observed as a depletion of the VOC from the air in the examined cabinet or growth chamber. This observation thus does not indicate though which route uptake has been established. These routes are discussed in more detail in §2.2.
In the uptake studies, one of the pioneers in this research was Dr. Wolverton, who did extensive growth chamber trials in the eighties of the 20th century (e.g. Wolverton et al., 1984). His research was carried out at NASA, since the aim was to use plants to purify air in enclosed environments as to be used in space. He studied plant uptake in large perspex cabinets (Fig. 1) and later changed to plant-microcosmos systems (Fig. 2.1) to explicitly take into account the role of the rooting substrate. Wolverton ranked the plant species in their capacity to remove one of three contaminants: formaldehyde, benzene, trichloroethylene.

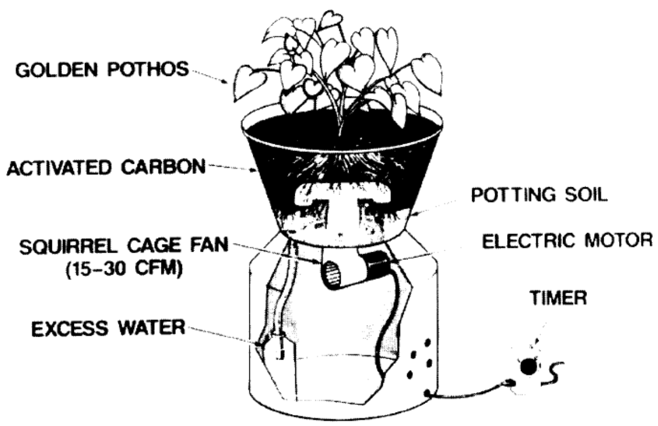

Figure 2.1 *The often used plant-microcosmos system (illustration from Wolverton et al., 1989).*

Most uptake studies were done in growth cabinets, and results are reported in the following paragraphs. Only seldom uptake was studied using a vertical plant wall, and with the exception below, we will not further deal with plant walls in this report:
In a plant wall system in Norrköping, Sweden, the uptake of VOCs by *Nephrolepis exaltata* Bostoniensis was studied. The system correctly showed a higher CO_2 assimilation at higher light levels and/or fan controlled ventilation rate, and assimilation of formaldehyde was equally increased. Yet, half of the plants were visibly damaged when exposed to formaldehyde levels of 1.55 ppm during 24 hours. Apart from formaldehyde, the experiment showed that plants can remove acetone and methyl acetate, being evaporated from glue.

2.1 Differences between plant species and compounds

Differences in uptake of volatiles between plant species can often be related to amount of leaves, stomatal conductance or hairs. At the start of the science on VOC uptake by plants, these differences were not systematically researched. The initial studies were very empirical, more like a blind shot using as many plant species as possible.
The first major studies on the performance of different plant species in capturing VOCs were carried out by Wolverton et al. (1984, 1989). They used sealed cabinets of perspex (Fig. 1) and determined the uptake of VOCs by plant and soil separately by measuring the concentration decrease of a single addition of one VOC over 24 hours. The Top10 of plant species for three respective VOCs are listed in Table 1. The best performing plant species are not used indoors as ornamental (banana, gerbera, chrysanthemum, hedera). The main ornamental species that were given further attention in much research were *Spatiphyllum, Draceana, Chlorophytum* and *Sansviera*. So, following the 1984 studies, similar plant-microcosmos systems (Fig. 2.1) were used with the species *Dracaena* and *Spathiphyllum* (Wolverton et al. 1989; Wood et al., 2006) since they showed the best performance in removing toluene and benzene from the air. Since Wolverton, plant chamber experiments were continued in many countries, among which quite a few in Asia.

Table 1 *Top 10 air purifyers according to Wolverton et al. (1984), based on uptake per unit leaf area.*

Rank	Formaldehyde		Benzene		Trichloroethylene	
1	Banana	Musa oriana	Gerbera daisy	Gerbera jamesonii	Gerbera daisy	Gerbera jamesonii
2	Mother-in-law tongue	Sansevieria laurentii	Pot mum	Chrysanthemum morifolium	English ivy	Hedera helix
3	English ivy	Hedera helix	English ivy	Hedera helix	Marginata	Dracaena marganita
4	Bamboo palm	Chamaedorea seifrizii	Mother-in-law tongue	Sansevieria	Peace Liliy	Spatiphyllum "Mauna Loa"
5	Heart Leaf philodendron	Philodendron oxycardium	Warneckei	Dracaena deremensis "Warneckei"	Mother-in-law tongue	Sansevieria
6	Elephant ear philodendron	Philodendron domesticum	Peace Lily	Spatiphyllum "Mauna Loa"	Warneckei	Dracaena deremensis "Warneckei"
7	Green spider plant	Chlorophytum elatum	Chinese evergreen	Aglonema "Silver Queen"	Bamboo palm	Chamaedorea seifrizii
8	Golden pothos	Scindapsus aureus	Marginata	Dracaena marganita	Mass cane	Dracaena massangeana
9	Janet craig	Dracaena deremensis “Janet Craig”	Bamboo palm	Chamaedorea seifrizii	Janet craig	Dracaena deremensis "Janet Craig"
10	Marginata	Dracaena marginita	Janet craig	Dracaena deremensis "Janet Craig"	Gerbera daisy	Gerbera jamesonii

More recent research on the differences between plant species was done by Han and Lee (2002) who evaluated different orchid species for the potential to remove aerial pollutants within buildings. Laboratory tests were carried out to evaluate 4 species of orchid. *Cymbidium rubrigemmum* was useful in removing a wide range of pollutant gases including 2.66 mg of carbon dioxide, 155 mg of nitrous oxide, 87 mg of formaldehyde and 230 mg cm^{-2} min^{-1} of benzene. Ammonia was also removed, especially by *Cymbidium viresence*. *Cymbidium sinense* was useful for its ability to remove more trichloroethylene than comparable species. Gases that became trapped in soil particles were most effectively removed, probably due to large microbial populations associated with the rhizosphere. The ability to absorb gases strongly related to the physiological status of the plant, i.e. high photosynthetic and stomatal conductance rates increasing the effectiveness of pollutant removal by the plant. This is in agreement with other research on the effect of light intensity on removal of formaldehyde (see §2.2)

At a concentration range of 43–300 μg m^{-3} formaldehyde, the removal rate by *Nerium indicum* increased linearly with increasing initial concentration. 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).

Dela Cruz et al. (2014) shows 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). 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. However, there was 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 between 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.

The potential for indoor ultrafine particle reduction of 11 commercial ornamental plants under laboratory conditions showed that all but one (*Dracaena deremensis* compacta,) on average reduced 5.5% of the existing ultrafine particles (<100 nm diameter) within 3 hours (Stapleton and Ruiz-Rudolph, 2016). The experiment was done in chambers of 114 liter with an air exchange rate of 4.67 per hour, which is very high compared to realistic indoor environment. For the case of *Juniperus chinensis* they showed that particle absorption was linearly related to leaf area.

2.2 Mechanisms of uptake and incorporation

The plant can have a number of pathways to withdraw volatiles from the air. The most obvious pathway is the mechanical process of deposition on plant parts like leaves or flowers. A second mechanism is the absorption in the cuticle, at the upper side of the leaf. A third mechanism is the uptake of volatiles through the stomata, only if the volatiles are small enough to pass the stomatal cavity. When the volatiles are absorbed by the plant tissue within this cavity, a concentration gradient is occurring and the volatiles are subsequently drawn in the leaf by diffusion. Purely based on dissolving in the water phase of leaf cytoplasm, the aldehydes are only poorly absorbed from the air: stomatal uptake is a factor 30-100 higher when the aldehydes are subsequently assimilated or transported within the plant, and as such build the concentration gradient mentioned above (Tani and Hewitt, 2009).

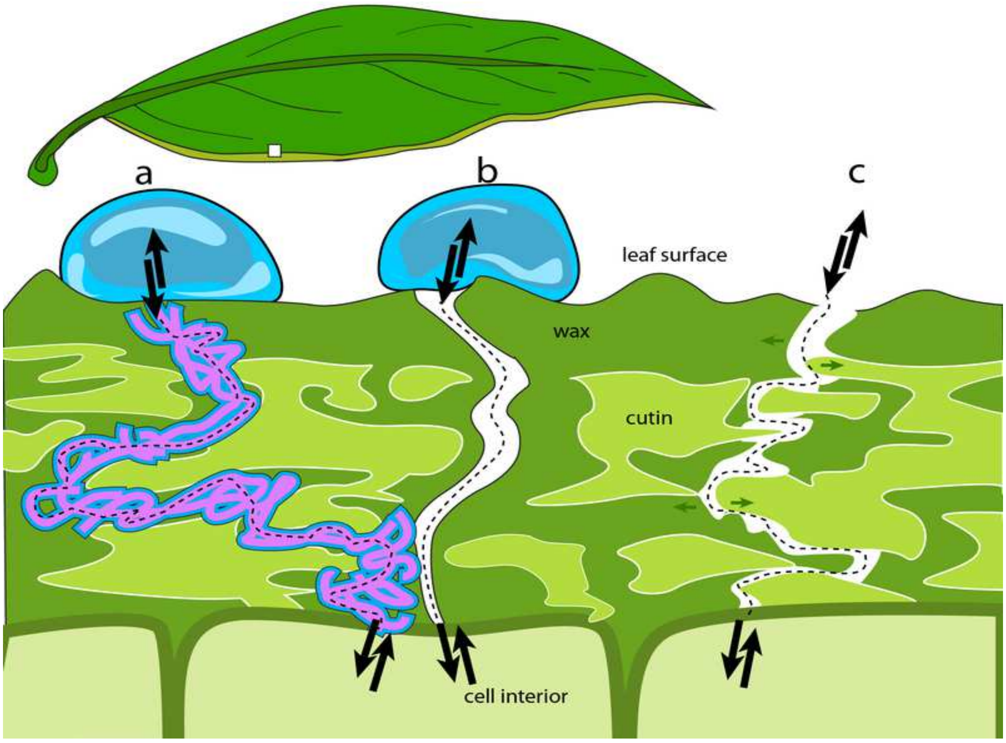

Figure 2.2. *On top of the leaf the cuticule, consisting of cutin and wax, forms a smart barrier by selective permeability for lipophilic as well as hydrophilic molecules.*

Lipophilic VOCs are less well assimilated by plants than hydrophilic VOCs. Their uptake may follow the route via soil and microorganisms, although this is often confused with plant uptake when the total of plant plus substrate is under examination. On average 10^7 micro-organisms reside on 1 cm^2 leaf, mostly within the wax layer and who feed from leaf exudates (Lindow and Brandl, 2003). The uptake by the microbiome on the leaf is much less then stomatal uptake under optimal plant growth conditions, but at suboptimal conditions like very low light levels indoors, this contribution will be significant.
The formaldehyde assimilation is achieved by the glutathion-depending formaldehyde dehydrogenase (Giese,1994). This pathway is present in most plants and suffices to assimilate formaldehyde concentrations up to 8 ppm. The research of Giese used C14-labeled formaldehyde which was traced back in all compartments of the cell (proteins, cytoplasm, cell membrane, etc.). Most enriched compounds were serine and phosphatidylcholine. Giese exposed *Glycine max* cells to 14C labelled formaldehyde, and the allocation of the 14C indicated that formaldehyde was firstly detoxified by oxidation and subsequently underwent C1 metabolism (Giese et al. 1994). This was confirmed by research on uptake and transformation of 14C labelled formaldehyde by *Epipremnum aureum* and *Ficus benjamina*, where formaldehyde was transformed into CO_2 and built into the plant material via the Calvin cycle (Schmitz et al. 2000).

Contrary to the research of Giese and Schmitz, Chen et al. (2010) argue that plants by default are not able to assimilate formaldehyde. They claim that if trials seem to show formaldehyde depletion, it will probably be caused by micro-organisms that live symbiotically with plants, as already predicted but not proven earlier by Wolverton and Wolverton (1993). These micro-organisms have enzymes that can assimilate formaldehyde following the Calvin-Bensson metabolic pathway. Chen at al. have

proofed this by incorporation of this enzyme by genetic modification of Arabidopsis. Practical applications of such GMO plants would be societally unwanted, thus favoring systems that contain useful micro-organisms.
Sawada et al. (2007) did similar GMO work like Chen et al. on tobacco where they implemented a new metabolic pathway for monophosphate assimilation: the plants assimilated 20% more VOCs than the reference, non-GMO plants.
The standpoint that plants lack a mechanism to assimilate formaldehyde, much experimental evidence in recent years does show that many plant species do have this possibility with the important notice that formaldehyde is first oxidized to CO_2 to be used in the C1 pathways.

Assimilation of formaldehyde increases with light intensity (Fig. 2.2), showing that formaldehyde may partly serve as a substitute of CO_2 as electron acceptor.

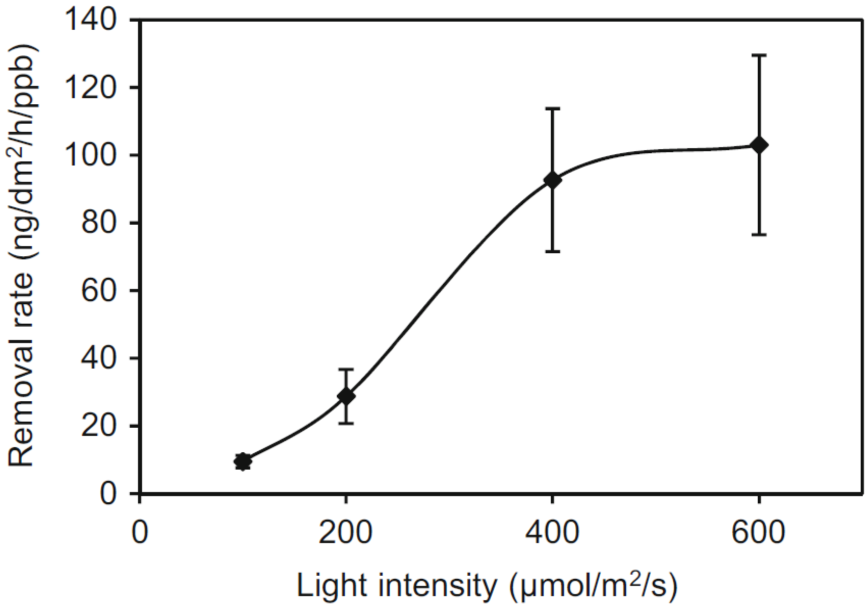

Figure 2.3. *Effect of light intensity on formaldehyde removal rate by Nerium indicum. Adapted from Kondo et al. (1995) by Dela Cruz (2014); bars are mean ±SD, n=4.*

Despite all the observations that formaldehyde is removed from the air by plant activity as promoted by light intensity, formaldehyde is also broken down photo chemically by light itself (Horowitz and Calvert 1978).

For benzene and toluene a substantial hypostomatous uptake through the cuticle by *Vitis vinifera, Malus domestica,* and *Acer campestre* was observed, where degradation occurred by aromatic ring cleavage and incorporation in nonvolatile organic acids (Ugrekhelidze et al. 1997). 46% of absorbed benzene was detected in the wax of the cuticle of *Dracaena sanderiana* as exposed to benzene for 120 hours (Treesubsuntorn and Thiravetyan, 2012). Yet no relationship between cuticle and stomatal uptake could be established, which would require a dynamic uptake study that is hard to perform.
Toluene was found to be strongly absorbed in the cuticle wax and preferably at high hexadecanoic contents, while ethylbenzene was also stored in the wax layer but also affected the photosynthetic apparatus negatively (Sriprapat et al., 2014). Their study showed that among twelve plant species *Sansevieria trifasciata* removed the most toluene while *Chlorophytum comosum* removed most of the benzene.
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, in review by Dela Cruz et al, 2014). Subsequent degradation by micro-organisms has been found. 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).

Plants on hydroculture are also able to assimilate benzene despite the lack of an organic substrate. This was shown by Irga et al. (2013) who found benzene degrading bacteria on the roots of plants on hydroculture, while the potted plants had similar benzene degrading micro-organisms but a much richer microbial community in the soil.

At offering a combination of different VOC components (eg. mixtures of toluene and benzene) no interaction in uptake was found, and uptake of each VOC was proportional to its concentration.

Genetic modification to improve VOC assimilation of benzene and toluene has been realized by incorporation of mammalian cytochrome P450 2E1. This construct indeed increased uptake of a series of VOCs amongst which benzene (James et al., 2008).

Mechanisms of formaldehyde uptake were studied on *Spatiphyllum* in a growth chamber by van der Meulen & van Duijn (2014). Uptake of formaldehyde were increased when stomatal opening was increased by blue light, decreased when the plant hormone abscisic acid (ABA) was applied for closing of the stomata to prevent transpiration losses. Uptake also decreased when plants were dehydrated. The results show that the stomatal opening is a strong regulating factor of formaldehyde uptake. Control trials without plants showed that uptake in soil and roots was very minor. Tests on the effect of high humidity (>99%) in the growth chamber on formaldehyde depletion were unfortunately lacking, although formaldehyde can quickly dissolve in water, condensation droplets and even foggy air.

3 Uptake of aerial contaminants in belowground parts

Since plants in an indoor environment often come with the associated substrate, the role of this substrate cannot be ignored. Moreover, the claimed air purification effects of plants are often assumed to be partly or completely accounted for by the processes taking place belowground. Already in the eighties Wolverton tested a plant-soil system, and claimed that this setup had evolved from wastewater treatment studies. The rationale of the approach was to move large volumes of contaminated air through an activated carbon bed where smoke, organic chemicals, pathogenic microorganisms (if present), and possibly radon are absorbed by the carbon filter. Plant roots and their associated microorganisms then destroy the pathogenic viruses, bacteria, and the organic chemicals, eventually converting all of these air pollutants into new plant tissue (Wolverton et al., 1989).

3.1 Role of substrate properties

With regards to uptake of air contaminants in rooting substrate of plants, the three most influential physical factors are water, carbon and porosity. Hydrophilic VOCs like formaldehyde quickly dissolve in water and are converted to formalin. Lipophilic VOCs will easily absorb to the carbon residing in organic matter which has long carbohydrate chains with multiple ion exchange sites and hydrogen bond possibilities. A high porosity will lead to higher flow and exchange rates with outside air, thus promoting reactions of VOC with the substrate. Activated carbon combines both properties 'carbon' and 'porosity' and has proven to absorb many contaminants (see also §3.2). A comparative study between uptake of formaldehyde by soil and roots with and without a *Spatiphyllum* plant indicated that the aboveground part is responsible for most (>80% on basis of their depletion curves) of the formaldehyde removal (van der Meulen & van Duijn, 2014). There were no replicate measurements and it was not known whether soil water content and microbial biomass were representative for the default house plant situation. Apart from the physical factors, biological factors are important. Apart from the micro-organisms in soil (see §3.2) plant roots either assimilate the gases or produce exudates to feed the micro-organisms. The role of the rhizosphere was shown by research of Han and Lee (2002), where gases that became trapped in soil particles were most effectively removed, probably due to large microbial populations that were fed by roots in the rhizosphere.

3.2 Role of micro-organisms

During is NASA studies Wolverton already discovered that microbes associated with the root systems of houseplants naturally consume toxins from the air (Wolverton et al., 1984). The byproducts of this process become a feeding substrate for the microbes and the host plant. Wolverton also examined the effect of activated carbon, an extremely porous material which attracts pollutants in the air through "molecular attraction", or Van der Waals forces. When the activated carbon was mixed with the growing media, the amount of pollutants removed from the air drastically increased. The toxins that absorb on the carbon are subsequently consumed by the microbes. These findings twenty years later resulted in a commercially available plant system, see 3.3.

3.3 Practical applications

The company U.S. Health Equipment Company claims that with their Plant Air Purifier® the contaminants in the air are removed while blowing the air through the substrate of their plant systems. The company cooperates with the former authority of the studies on air purifying plants, B.C. Wolverton. As reported above, the soil aggregates are able to absorb volatiles, and the residing micro-organisms are capable of assimilating VOCs within their metabolism.

4 Air purification by plants under practical circumstances

4.1 Introduction

Based on the successful results on air purification in plant chamber experiments, scientists made the step to air purification in living rooms, class rooms and offices. Solid research was done in Portuguese class rooms (Pegas et al., 2012), which showed that the presence of plants decreased the concentration of CO_2 as well as contaminants like PM10 and VOCs. Below the research findings will be reported for a number of situations, i.e. classrooms, households, offices and, shortly, outdoors.

4.2 Findings

Studies in classrooms

In Portugal, a class room was monitored for concentrations of VOC, CO_2, PM10 following placement of six plants (Pegas et al., 2012). The monitoring took 9 weeks, starting with the control situation during 3 weeks, followed by a 6-week period with plants. The plants had significant effects on air quality: they found a 30% reduction in PM10, a threefold reduction in VOC concentrations and a twofold reduction in CO_2 levels. The number of plants per class room was relatively low: only 6, since each plant than covered a recommendable area of 9.25 m^2. The three species used were *Dracaena deremensis* (striped dracaena or Janet Craig), *Dracaena marginata* (rededge dracaena, Madagascar dragon tree, or Marginata), and *Spathiphyllum* (Mauna Loa or peace lily). These species were selected because previous test-chamber studies (Orwell et al., 2004; Tarran et al., 2002; Wolverton et al., 1989; Wood et al., 2002; 2006) showed these plants were found to be reliably effective in removing benzene, toluene, ethylbenzene, and xylenes (BTEX). Although the Pegas study was only monitoring one class room, his statistics were adequate since (1) outdoor and indoor air quality were simultaneously measured frequently, (2) the time series of control and plant treatment were long enough to show a consistent temporal pattern. Moreover, both total VOC sensors as analytical methods to detect the individual VOCs were used, so they concluded, interestingly, that plants decreased toluene concentrations (7.62 ± 1.73 μg m^{-3} ambient vs. 4.09 ± 0.66 μg m^{-3} with plants), decreased m+p-xylene and o-xylene concentrations by 80%, and ethylbenzene from 1.09 ± 0.21 μg m^{-3} to 0.84 ± 0.03 μg m^{-3}, a decrease by 15%. The mentioned VOCs were all higher then outdoors, where VOCs like acetone, methanol, and 1,1,1-trichloroethane were more abundant.

Project "Planten in de klas" (Duijn et al., 2011). This project was carried out by Fytagoras and finance by growers cooperation "Air so Pure". Results showed that plants decreased the following contaminants during a 2 months trial in class rooms: (1) bad smells, (2) CO_2 and – possibly – VOCs (not measured), (3) 7% less health problems. Students scored better on the tests (+35% at plants that received sufficient PAR, 20% at PAR levels < 15 μmol m^{-2} s^{-1}). Results have not been statistically tested; it is likely that results that differ 5-10% maximally are not significant, in view of the small test sample and the generally occurring high variability among student populations (12 classes within a total of 4 schools, of which 6 classes were with, and the other 6 without plants). Of course it is disappointing that no VOCs were measured.

Studies in houses and offices

In Japan, quite some research on air purification by plants in households were carried out. Lim (2009) observed a decrease in formaldehyde and xylene levels in houses, yet toluene and ethylbenzene were not. The 2-year study involved 82 households. Kim et al. (2011) observed a decrease of all 4 contaminants mentioned above within working offices due to plant presence as well as ventilation rates. These effects were observed both in old and new buildings, but the results were not statistically tested. The omission of statistical tests is often occurring in this scientific discipline, thus not allowing any conclusions of the effect of plants on indoor air quality. One important exception is the study of Pegas et al.(2012) who did use scientifically sound statistics; moreover, in his results he accounted for the effect of ventilation rate, and thus proofed that plants do have a significantly positive effect on the air quality in school classes (see above).

Results from the Japanese research of depletion of VOC from indoors, as cited from Dela Cruz et al. (2014):
"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 m2 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 from10.7 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 The Netherlands the company Ballieux Organic Architects claimed that the placement of plants in offices improved air quality by removing VOCs, but no scientific report has yet been presented.

The Dutch company Fytagoras claims that 350 g fresh leaf mass per person is advisable to keep the air clean; their other estimate is that 3 average-sized plants that can purify air in a moderate way are sufficient in rooms of 75 m3 to decrease formaldehyde concentrations by half in a period of 4 hours. These estimates are loosely based on their and Wolverton's work and would be very helpful in recommendations if they were solid, but the estimates have a large uncertainty. Yet, we have to keep in mind that a substantial decrease in formaldehyde concentration of 47 to 70% in 24 hours was found by Wolverton et al. (1989). Results from active sampling in office environments suggested that achieving 11% reduction in formaldehyde levels in a real-life situation would require the equivalent of 1 plant m^{-3} or 2.4 plants m^{-2} (Dingle et al., 2000), which is much more than the Fytagoras estimate.

Studies outdoors

In a research collaboration between AMS Institute (Amsterdam Institute for Advanced Metropolitan Solutions) and WUR, the possible removal of fine particles smaller than 2.5 μm diameter (PM2.5) by plants was studied in 2016. A rather hairy cultivar of the Honeysuckle (kamperfolie) plant, called 'Green Junkie' by plant breeder MyEarth because of its expected addiction to particle adsorption, was selected with the hypothesis that the hairs would scavenge many fine particles. In the wind tunnel treatment, positioned along a street in Amsterdam, the plant did not significantly decrease PM2.5 amounts (pers. comm. B. Heusinkveld, WUR).

Darlington et al. (2002) discuss the use of plants and their substrate to remove VOC from air in buildings instead of installing huge bio-infiltration units that require much organic matter and may as well produce certain organic volatiles. Plants can assimilate VOCs but do not solely rely on them as a carbon source by photosynthesizing as well.

4.3 Outlook

In order to extrapolate the lab findings to practice, lab tests should be carried out at more realistic conditions. This can be illustrated by a paragraph from the extensive review paper of Dela Cruz et al. (2014):
"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 μmol m^{-2} s^{-1} with many studies exceeding the 9–14 μmol m^{-2} s^{-1} usually experienced in offices (Akashi and Boyce 2006; Nicol et al. 2006). VOC concentrations used in laboratory studies are often above 1000 μg m^{-3}. This is substantially higher than VOC concentrations found in indoor environments which are typically less than 100 μg m^{-3} (Zabiegala 2006)."
Furthermore, the measurements in real-life situations should be considering air replacement, emission from office objects and other co-factors in a statistically decently designed measurement scheme. Only a carefully chosen set-up can determine the effect of the plant factor.

5 Conclusions

Literature
The scientific literature on air purifying plant properties does not clearly show a specific plant species that performs best. According to Kim et al. (2011a, b) the aralia family (*Araliaceae*), or ivy family, is the best, although statistically not strongly showing, in uptake of lipophilic VOCs like benzene. Interestingly, English ivy is also high on the lists of Wolverton et al. (1989) for formaldehyde and benzene removal per unit leaf area. Since some house plants typically have a high leaf area to compensate for lower uptake per cm^2, plant species like *Dracaena* and *Spatiphyllum* are performing best. There are quite some technical challenges in correctly measuring the plant's uptake capacity. Many experiments do not distinguish between uptake above- and below-ground, do not mention the applied air circulation rates or light intensity, thus making it difficult to interprete the results. The general view however is that plants are able to purify the indoor air to some extent with regard to VOC, fine particles and, of course, CO_2.

Recommendations
The fate of aerial contaminants in plants as well as the plant's performance in the long run are two of the major gaps in knowledge. New techniques arise, e.g. by radioactive labeling of VOC or by gene expression of genes involved in the assimilation pathway, that may generate answers.
One of the biggest challenges is to scientifically proof to what extent plants are able to clean the air in life-like situations in practice. Only a few studies have statistically proven that certain VOCs are withdrawn by plants during observation periods up to three months, but are still too limited to generate advise on how many plants of which species are needed in a particular situation.

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