Air Cleaning Performance of Two Species of Potted Plants and Different Substrates

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Abstract

Potted plants have been reported to uptake VOCs and help 'cleaning' the air. This paper presents the results of a laboratory study in which two species of plants (Peace Lily and Boston Fern) and three kinds of substrates (expanded clay, soil and activated carbon) were tested and monitored on their capacity to deplete formaldehyde and CO_2 in a glass chamber. Formaldehyde and CO_2 were selected as indicators to evaluate the bio-filtration efficacy of 28 different test conditions; relative humidity (RH) and temperature (T) were monitored during the experiments. To evaluate the efficacy of every test the Clean Air Delivery Rate (CADR) was calculated. Overall, soil had the best performance in removing formaldehyde (~ 0.07–0.16 m^3/h), while plants, in particular, were more effective in reducing CO_2 concentrations (Peace lily 0.01m^3/h) (Boston fern 0.02-0.03m^3/h). On average, plants (~ 0.03 m^3/h) were as effective as dry expanded clay (0.02–0.04 m^3/h) in depleting formaldehyde from the chamber. Regarding air cleaning performance, Boston ferns presented the best performance among the plant species, and the best performing substrate was the soil.

1 Introduction

Studies have shown that poor Indoor Air Quality (IAQ) affects human health in a long-term exposure (WHO, 2010). In the INDEX project (Kotzias et al. 2005) several chemicals, their concentration levels and their toxicity information were analysed and evaluated in indoor environments. It was concluded that Volatile Organic Compounds (VOCs), such as benzene, toluene and xylene, together with aldehydes should be considered as priority pollutants regarding their health effects. Several studies related with IAQ have indicated that VOCs are emitted by indoor sources such as building materials, furnishings and cleaning products (Bluyssen et al. 1997; Bluyssen et al. 1996; Brown et al. 1994; Campagnolo et al. 2017; Sofuoglu et al. 2011). In 1998, Yu and Crump published a review on VOC-emissions from newly built houses (Yu and Crump 1998). They stated that building material emissions are the sources of VOCs in the indoor environment, especially most during the first six months after construction. Among the indoor pollutants, VOCs are ubiquitous and have harmful effects on human health such as asthma, wheezing, allergic rhinitis, and eczema.

VOCs are frequently classified according to their boiling point (Bluyssen 2009): very volatile organic compounds (VVOCs), such as formaldehyde; VOCs, such as solvents and terpenes; Semi VOCs (SVOCs), such as pesticides; and Particulate Organic Matter (POM), such as biocides. Regarding IAQ, VOCs and VVOCs are the pollutants most frequently found indoors (Wolkoff 2003). Some of them are toxic and carcinogenic, such as formaldehyde; and in general, exposure to formaldehyde is higher indoors than outdoors (IARC 2006; Nielsen and Wolkoff 2010; Salthammer et al. 2010). Formaldehyde (CH_2O) is a highly reactive aldehyde. It is a ubiquitous pollutant and it is a component of different chemical and industrial products (Salthammer et al. 2010). Because of its occurrence indoors and the evident impact on human health, the study presented focused on the reduction of indoor formaldehyde concentrations.

1.1 Sources of formaldehyde

Formaldehyde is released directly into the indoor air from various types of sources. People are exposed to environmental formaldehyde from adhesives, lubricants, wall coverings, rubber, water-based paints, cosmetics, electronic equipment, and glued wood-based products. For instance, formaldehyde is known to be emitted considerably by chipboard, MDF, plywood and other wood-based products containing resins (Bluyssen et al. 1996; Campagnolo et al. 2017). Next to these building materials, formaldehyde is a component of tobacco smoke and of combustion gases from heating stoves and gas appliances. It is used as a disinfectant and as a preservative in biological laboratories. It is also used in the fabric and clothing industry.

Major sources of formaldehyde in non-smoking environments are building materials and consumer products. This applies to new materials and products and can last several months, especially in conditions with high relative humidity (RH) and high indoor temperatures (Haghighat and De Bellis 1998; Knoeppel 1990; Salthammer et al. 2010). Formaldehyde is also one of the main components for resins, which are contained in various products, mainly in wood products. Furthermore, it should be noted that secondary formation of formaldehyde occurs in air through the oxidation of VOCs. However, the influence of these secondary chemical processes to the ambient and indoor concentrations has still not been fully measured (Kaden 2010).

1.2 Health effects of formaldehyde

In general, humans are mainly exposed to formaldehyde through inhalation. Since formaldehyde is soluble in water, it is rapidly absorbed in the respiratory and gastrointestinal tracts and metabolized (WHO 2010). Predominant symptoms of formaldehyde exposure in humans are irritation of the eyes, nose and throat, discomfort, sneezing, coughing, nausea, among others (WHO 2000). The lowest concentration may cause sensory irritation of the eyes with humans, increasing eye blink frequency and conjunctival redness (WHO 2010).

1.3 Formaldehyde guidelines and regulations

In the Netherlands, several formaldehyde measurement studies have been executed specially in homes and at schools, where there were complaints which might have been caused by formaldehyde. Several complaints were connected with a concentration above 120 µg/m^3. In Dutch schools the highest concentration measured was 2.5 mg/m^3. In homes, the highest concentrations found were between 0.75 and 1 mg/m^3 (Knoeppel 1990). In 2011, Van Gemert reported that the odour thresholds for formaldehyde can fluctuate from 0.03 to 2.2 mg/m^3 (Van Gemert 2011).

WHO 2010 reported that the lowest concentration to cause sensory irritation of the eyes in humans is 0.38 mg/m^3 for four hours. Besides, a formaldehyde concentration of 0.6 mg/m^3 increases eye blink frequency and conjunctival redness. Regarding the perception of odour of formaldehyde, some individuals reported sensory irritation, and formaldehyde may be perceived at concentrations below 0.1 mg/m^3. However, this is not considered to be an adverse health effect (Kaden 2010; WHO 2000, 2010).

1.4 Effects of plants on formaldehyde removal

It has been well established that potted-plants can help to phytoremediate a diverse range of indoor air pollutants. In particular, a substantial body of literature has demonstrated the ability of the potted-plant system to remove VOCs from the indoor air. These findings have largely originated from laboratory-scale chamber experiments, with several studies drawing different conclusions regarding the primary VOC removal mechanism, and removal efficacies (Armijos Moya et al. 2019; Dela Cruz et al. 2014; Irga et al. 2018; Soreanu et al. 2013). The process of VOC depletion found in most studies is through the microbial activity in the substrate and rhizosphere, where bacteria absorb the VOCs and metabolise them as a nutrient source (Armijos Moya et al. 2019; Aydogan and Montoya 2011; Irga et al. 2018; Wolverton et al. 1989).

In 2011, Aydogan and Montoya tested the formaldehyde removal efficiency of the root area and aerial parts independently and found that while the aerial parts of plants were capable of VOC removal, removal by the root area occurred at a substantially faster rate (Aydogan and Montoya 2011). Other research has identified the potential for the microorganisms existing on and in leaves to remove VOCs (Khaksar 2016; Sandhu et al. 2007). However, most recent research has acknowledged that the mechanisms of removal are mainly located in the substrate, rather than the plant itself (Kim et al. 2008; Orwell et al. 2004; Wood et al. 2002).

Based on the studies mentioned, it is valid to assume that plants together with is substrate can have a positive removal effect on the concentration of formaldehyde in indoor environments. However, the extent to which different plants remove formaldehyde is not well known yet. This paper presents the results of a study on the uptake of formaldehyde and CO_2 from selected potted plants and substrates, with the objective of using the outcome of these experiments to select the best performing plant and substrate for the construction of an indoor plant-based system (biowall).

2 Materials And Methods

2.1 Experimental setup

The setup, schematically presented in Fig. 1, consisted mainly of a dynamic chamber. The dynamic chamber was made out of glass with an inner diameter of 28 cm, height of 60 cm and volume (V) of 0.033 m^3. The glass chamber had three air entrances that were sealed during the tests. The gas stream of 300 ppb concentration of formaldehyde was released in the chamber by heating the formaldehyde solution.

The actual formaldehyde concentration was determined by a formaldehyde sensor (DART-sensor 11 mm, calibrated, ppb-level, lower detection limit of < 30 ppb, response time (T90) < 30 s, resolution 10 ppb). Two axial fans were placed into the glass chamber to distribute the air evenly within the chamber. The sensor performed a measurement every minute. During the tests a LED growing

lamp was activated (1500 $\mu molm^{-2}s^{-1}$ – 1900 $\mu molm^{-2}s^{-1}$), and the temperature, relative humidity and CO_2 levels were also monitored. CO_2 levels were monitored with VAISALA CO_2 probe GMP252 (ppm-level). Furthermore, the glass container was sealed with a solvent free, plastic, self-adhesive sealant, kneading material, based on synthetic rubber during the tests.

2.2 Chemicals

The formaldehyde solution used for these experiments was: Solution Sigma F8775, 25 ml (36.5–38% formaldehyde in H_2O). The formaldehyde solution was mixed with demi-water in order to generate 300 ppb within the chamber. The mixture was executed by technicians in the laboratories of the University of Wageningen, as follows:

- 10 µl formaldehyde + 90 µl demi-water = 100 µl (final mixture)
- 10 µl of the final mixture generated 300 ppb of formaldehyde, within the chamber.

It is important to report that the formaldehyde solution contained 10–15% of methanol, as stabiliser to prevent polymerisation. The DART-sensor is also sensitive to methanol. So, by introducing formaldehyde, a small amount of methanol was introduced as well. The response of the DART-sensor to this amount of methanol therefore also needed to be tested.

2.3 Preparation of the substrates

Three different growth media were chosen for the test: soil, activated carbon and expanded clay. The selected potting soil was composed by peat, green compost, lime and fertilizers. The selection of the substrates was based on previous studies and because they are common substrates available on the market (Aydogan and Montoya 2011; Wolverton et al. 1989). For every type of substrate six tests were executed, three with a dry substrate and three with a wet substrate. The substrates were placed each in a plastic container with a capacity of 1.1 litres (0.0011 m^3) with 0.14 m diameter in the upper part, which was the exposed area of the substrate.

2.4 Preparation of the plant samples

Two different plant species were tested: Spathiphyllum Wallisii Regel (Common name: Peace Lily) and Nephrolepis exaltata L. (Common name: Boston Fern) (Fig. 2*)*. Three plants of every species were chosen for the tests and they were selected with similar characteristics of age and size (Peace lily: 0.35m height; Boston fern: 0.30 m height). The plants were selected based on information gathered by previous studies, which demonstrated that the capability of these species in uptake of some VOCs was good (Liu et al. 2007; Wolverton and Wolverton 1993; Wood et al. 2002). And they were also chosen because they can be used in Living Wall Systems (LWSs) and/or green walls, besides, they are commonly used for indoor decoration. The plants were bought in a house-plant shop in the Netherlands and were re-potted 25 days prior the experiments, to minimize the stress of the plant, in a 14 cm diameter plastic pot of 1.1 litre (0.0011 m^3) of expanded clay growth medium. The expanded clay was selected as a growth medium for the tests because it is the most common substrate used indoors and it is most suitable to be used in indoor living wall systems. All the plants went through a 30 min acclimatization and adaptation process in the laboratory where they were exposed to similar conditions, in order to minimize the stress of the plants prior the execution of the tests.

2.5 Procedure

Two zero-measurement evaluations were performed to establish the conditions of the set-up in the glass container in which the depletion of the formaldehyde took place: one at the beginning of the test series and one at the end. Similarly, two extra zero-measurement evaluations were performed with a plastic container that had the same characteristics of the containers that were used during every test.

The measurements were executed for 1-1.5 hours until the formaldehyde was depleted or stabilized in the chamber. Gas concentrations were measured in ppb in the case of formaldehyde and in ppm in the case of CO_2. For further analysis the concentrations of these gases were expressed as micrograms per cubic meter ($\mu g/m^3$) and milligrams per cubic meter, respectively. For each test, ~ 368.48 $\mu g/m^3$ (~ 300 ppb) of formaldehyde was released in the chamber to generate every time exactly the same condition.

Each set of experiments was conducted three times, in order to evaluate consistently each condition tested (Tables 1 and 2). For each test, the glass container was wiped with a wet paper towel after each measurement. The plastic container with the substrate or

plant sample was placed in the centre of the glass chamber. Depending on the height of the plant a stainless-steel base was placed at the bottom (stainless steel is an inert material).

A small plate connected to a heat source was placed in the lower hole and 10 µl of formaldehyde solution was placed on the plate with a pipette. After a drop of formaldehyde solution was placed on the plate, the hole was closed, and the heat source was activated in order to realise the solution in the air. This was the beginning of the test. During the tests with the Boston ferns, it was necessary to inject some CO_2 when the level was lower than ~ 410 ppm (~ 738 mg/m^3) which is the global atmospheric CO_2 concentration (average outdoor concentration) (IPCC, 2014; NASA, 2019) and is sufficient for the plants to grow although some studies have shown that the optimal CO_2 concentration is around 900 ppm (Zheng et al. 2018).

To calculate the amount of formaldehyde depleted inside of the chamber the following formula was used (Irga et al. 2017):

$$-\lambda = \frac{\ln\left(\frac{N(t)}{N(0)}\right)}{t} \qquad [1]$$

With: λ = Decay rate [h^{-1}]
N(t) = Amount of pollutant after time t [µg/m^3] or [mg/m^3]

N(0) = Initial amount of pollutant at t = 0h [µg/m^3] or [mg/m^3]

To calculate the rates of contaminant reduction in the test chamber the Clean Air Delivery Rate (CADR) was calculated (ANSI/AHAM-AC-1-2013, 2015; EPA., 2008):

$$CADR = (\lambda e - \lambda n - \lambda p)V \qquad [2]$$

With: λe = Total decay rate [h^{-1}]
λn = Natural decay rate which is the reduction of the contaminant due to natural phenomena in the test chamber [h^{-1}]

λp = Decay rate when the plastic pot was placed in the chamber [h^{-1}]

V = Volume of the chamber [m^3], 0.033 [m^3]

To calculate the removal efficiency of the different test conditions the following formula was used (Irga et al. 2017):

$$\eta = \left(\frac{N(0) - N(t)}{N(0)}\right) * 100 \qquad [3]$$

With: η = Efficiency [%]
N(t) = Amount of pollutant after time t [µg/m^3] or [mg/m^3]

N(0) = Initial amount of pollutant at t = 0h [µg/m^3] or [mg/m^3]

A portable leaf area meter was used to scan and calculate the leave area of the plant species. Since the three plants of every species had similar characteristics, one plant of every species was selected to be measured (Fig. 3).

Conversions for chemicals in air were made assuming an air pressure of 1 atmosphere and an air temperature of 25 degrees Celsius. The conversion factor was based on the molecular weight of the chemical and is different for each chemical in this case the molecular weight of formaldehyde is 30.031 g/mol and of the carbon dioxide (CO_2) is 44.01 g/mol:

Concentration [mg/m^3] = 0.0409 x concentration [ppm] x molecular weight [g/mol]

Concentration [ppm] = 24.45 x concentration [mg/m^3] ÷ molecular weight [g/mol]

Concentration [µg/m^3] = 0.0409 x concentration [ppb] x molecular weight [g/mol]

Concentration [ppb] = 24.45 x concentration [µg/m^3] ÷ molecular weight [g/mol]

To stablish the statistical significance of the results, several Independent T-Tests were executed and the mean values and standard errors (± S.E.) were included. Finally, the one-way analysis of variance (ANOVA) was chosen to determine whether there are any statistically significant differences between the means of the tested variables. Additionally, a Pos-Hoc test was also required to confirm where the differences occurred. Based on the nature of this data set, Tukey HSD and the Student-Newman-Keuls were performed to execute a multiple comparison among the groups and to determine homogeneous sets.

3 Results

Figures 4 to 7 show the measured formaldehyde concentrations for the different test configurations. Figures 8 presents the measured CO_2 concentrations when the selected potted plants were included. Figures 9 presents the measured formaldehyde and CO_2 concentrations when the Boston ferns were included. In general, three measurements were executed for every test condition and the figures present the mean values including standard errors (± SE). In Tables 1 and 2, the CADRs of respectively formaldehyde and CO_2 depletion inside of the chamber for the different tests is presented. The CADRs were calculated using equations 1 and 2. Tables 3 and 4 present the statistical analysis of the CADR caused by the selected growth media and selected plants.

During the zero measurements of the setup, the sensor indicated the presence of around 30.7 µg/m^3 (25 ppb) of formaldehyde in the system. It is believed that this value was due to the calibration process. The zero measurement tests indicated that the formaldehyde decreased slowly in the chamber (Figs. 3–6), which could be the natural decay of the gas or because it was partially adsorbed by the setup. When the plastic container was placed inside of the chamber the reduction slightly increased, which shows that the formaldehyde was adsorbed by the container. These two values have to be taken in account when analysing the real effect of the substrates and plants regarding formaldehyde depletion (Table 1). Therefore, to calculate the CADR and establish the real air-cleansing-impact of every test condition, the natural decay of the chamber ($\lambda n = 0.11\ h^{-1}$) and the decay rate of the plastic container ($\lambda p = 0.15\ h^{-}1$) were subtracted from the total decay rate (Tables 1 and 2).

Figure 4 presents the depletion of formaldehyde when expanded clay was tested, under dry and wet conditions, indicating that wet expanded clay was more effective on depleting formaldehyde than under dry conditions. Among all the conditions tested, soil was the most effective element to reduce formaldehyde in the chamber, especially under wet conditions (Fig. 5). Figure 6 shows that activated carbon under dry conditions was more efficient than under wet conditions in reducing formaldehyde in the chamber.

Regarding formaldehyde depletion, potted plants (0.03 m^3/h) were as effective as dry activated carbon (0.03–0.04 m^3/h), less effective in general than soil (0.07–0.16 m^3/h), less effective than wet expanded clay (0.04–0.16 m^3/h) and as effective as dry expanded clay (0.02–0.04 m^3/h) (Table 1). The selected plants (Boston Fern and Peace Lily) present similar performance regarding formaldehyde removal (Fig. 7).

With regards to CO_2 levels, potted plants seemed to be the only test condition that reduced CO_2, of which Boston fern was the most effective (Table 2). While in the case of activated carbon and soil, the levels of CO_2 seemed to increase in the chamber.

Table 1 shows that under dry conditions inside of the chamber, the selected soil adsorbed formaldehyde faster than the other substrates, while the performance of the dry expanded clay was the lowest. The wet soil and expanded clay performed better than the dry conditions tested. Furthermore, Table 1 shows that the selected plants together with the substrate did not perform as well as the wet substrates, but, in general, they performed better than the dry substrates with the exception of the dry soil. Regarding leaf area, the selected plants had similar characteristics in size and number of leaves, therefore, for every species one plant was selected and all its leaves were measured. Consequently, it was considered that the area of the other two plants of the selected species were in the same area range. In general, the peace lilies (approx. 0.14 m^2) had more leaf area than the Boston ferns (approx. 0.11 m^2). Table 3 presents the statistical analysis of the CADR of formaldehyde depletion caused by the selected growth media. It shows that soil has a better performance than the other samples. Regarding the data set of formaldehyde depletion, and once it was established the statistically significant differences between the means of the tested variables (P = 0.00) with ANOVA, the differences between the variables were analyzed in Tables 4 and 5. Table 4 presents the statistical difference among the variables. It shows that mainly wet soil has statistical differences with the other analyzed variables. Table 5 indicates three homogeneous subsets among

the variables in terms of formaldehyde depletion. Within a subset there is no significance different while between subsets there is a significant difference. It is clear that Group 3 (wet soil, dry soil, wet expanded clay) is significantly different from Group 1 (wet activated carbon, dry activated carbon, dry expanded clay, peace lily, Boston fern).

Table 1
CADR of formaldehyde depletion inside of the chamber.

Test N.	Test Condition		RH*	T*	Time	N(0)	N(t)	λe	λn	λp	CADR	η
			(%)	(°C)	(h)	($\mu g/m^3$)	($\mu g/m^3$)	$(h)^{-1}$	$(h)^{-1}$	$(h)^{-1}$	(m^3/h)	(%)
1	Zero measurement 1	(ZM_1)	53	24	2.38	481.48			0.09			
2	Zero measurement 2	(ZM_2)	59	24	1.52	524.47			0.13			
3	Zero measurement_Pot 1	(ZMP_1)	43	24	2.10	498.68				0.16		
4	Zero measurement_Pot 2	(ZMP_2)	58	24	1.52	515.87				0.14		
5	Dry Expanded Clay 1	(EC_D_1)	85	25	1.55	363.57	98.26	0.84			0.02	73
6	Dry Expanded Clay 2	(EC_D_2)	83	24	1.13	335.32	70.01	1.38			0.04	79
7	Dry Expanded Clay 3	(EC_D_3)	57	24	1.60	431.12	116.69	0.82			0.02	73
8	Wet Expanded Clay 1	(EC_W_1)	93	26	1.10	308.30	1.23	5.02			0.16	100
9	Wet Expanded Clay 2	(EC_W_2)	92	25	1.10	368.48	22.11	2.56			0.08	94
10	Wet Expanded Clay 3	(EC_W_3)	95	24	1.65	174.41	17.20	1.40			0.04	90
11	Dry Soil 1	(S_D_1)	92	24	1.27	389.36	2.46	4.00			0.12	99
12	Dry Soil 2	(S_D_2)	93	24	1.50	336.55	4.91	2.82			0.08	99
13	Dry Soil 3	(S_D_3)	93	25	1.43	447.09	13.51	2.44			0.07	97
14	Wet Soil 1**	(S_W_1)	91	25	1.07	197.75	1.00	4.96			0.16	99
15	Wet Soil 2	(S_W_2)	96	24	1.38	366.02	1.23	4.12			0.13	100
16	Wet Soil 3	(S_W_3)	93	24	1.48	381.99	1.23	3.87			0.12	100
17	Dry Activated Carbon 1	(AC_D_1)	41	25	1.42	296.01	39.30	1.43			0.04	87
18	Dry Activated Carbon 2	(AC_D_2)	43	24	1.52	297.24	45.45	1.24			0.03	85
19	Dry Activated Carbon 3	(AC_D_3)	50	24	1.49	358.65	67.55	1.13			0.03	81
20	Wet Activated Carbon 1	(AC_W_1)	95	25	1.57	383.22	126.51	0.71			0.01	67
21	Wet Activated Carbon 2	(AC_W_2)	93	26	1.25	428.67	128.97	0.96			0.02	70
22	Wet Activated Carbon 3	(AC_W_3)	91	24	0.75	356.20	1469.01	-1.89			-	
23	Peace Lily 1	(SPA_1)	95	24	1.77	311.98	41.76	1.14			0.03	87
24	Peace Lily 2	(SPA_2)	95	24	1.67	367.25	44.22	1.27			0.03	88

Test N.	Test Condition		RH*	T*	Time	N(0)	N(t)	λe	λn	λp	CADR	η
25	Peace Lily 3	(SPA_3)	94	24	1.72	348.83	46.67	1.17			0.03	87
26	Boston fern 1	(NEPH_1)	93	24	1.63	390.59	58.96	1.16			0.03	85
27	Boston fern 2	(NEPH_2)	94	24	1.58	413.93	67.55	1.14			0.03	84
28	Boston fern 3	(NEPH_3)	95	24	1.55	427.44	74.92	1.12			0.03	82
* Mean values												
** The measured formaldehyde concentration was 0<, the value used for the calculation was N(t) = 1 (μg/m^3)												
Average values used for the calculations: λn = 0.11$(h)^{-1}$; λp = 0.15$(h)^{-1}$												

Table 2
CADR of CO_2 depletion inside of the chamber.

Test N.	Test Condition		RH*	T*	Time	N(0)	N(t)	λe	λn	λp	CADR	η
			(%)	(°C)	(h)	(mg/m^3)	(mg/m^3)	$(h)^{-1}$	$(h)^{-1}$	$(h)^{-1}$	(m^3/h)	(%)
1	Zero measurement 1	(ZM_1)	53	24	2.38	756.00			0			
2	Zero measurement 2	(ZM_2)	59	24	1.52	887.40			0			
3	Zero measurement_Pot 1	(ZMP_1)	43	24	2.10	1024.21				0		
4	Zero measurement_Pot 2	(ZMP_2)	58	24	1.52	1054.81				0		
5	Dry Expanded Clay 1	(EC_D_1)	85	25	1.55	1368.01		0			-	
6	Dry Expanded Clay 2	(EC_D_2)	83	24	1.13	1297.81	1281.61	0.01			0.00	1
7	Dry Expanded Clay 3	(EC_D_3)	57	24	1.60	1243.81		0			-	
8	Wet Expanded Clay 1	(EC_W_1)	93	26	1.10	1018.81		0			-	
9	Wet Expanded Clay 2	(EC_W_2)	92	25	1.10	1051.21	1031.41	0.02			0.00	2
10	Wet Expanded Clay 3	(EC_W_3)	95	24	1.65	1351.81	1323.01	0.01			0.00	2
11	Dry Soil 1	(S_D_1)	92	24	1.27	977.40		-0.05			-	
12	Dry Soil 2	(S_D_2)	93	24	1.50	1146.61		-0.04			-	
13	Dry Soil 3	(S_D_3)	93	25	1.43	1099.81		-0.04			-	
14	Wet Soil 1	(S_W_1)	91	25	1.07	851.40		-0.13			-	
15	Wet Soil 2	(S_W_2)	96	24	1.38	932.40		-0.18			-	
16	Wet Soil 3	(S_W_3)	93	24	1.48	981.00		-0.14			-	
17	Dry Activated Carbon 1	(AC_D_1)	41	25	1.42	2190.61		-0.21			-	
18	Dry Activated Carbon 2	(AC_D_2)	43	24	1.52	1002.61		-0.06			-	
19	Dry Activated Carbon 3	(AC_D_3)	50	24	1.49	1033.21		-0.01			-	
20	Wet Activated Carbon 1	(AC_W_1)	95	25	1.57	1432.81		-0.48			-	
21	Wet Activated Carbon 2	(AC_W_2)	93	26	1.25	1222.21		-0.09			-	
22	Wet Activated Carbon 3	(AC_W_3)	91	24	0.75	1272.61		-0.17			-	
23	Peace Lily 1	(SPA_1)	95	24	1.77	1146.61	885.60	0.15			0.01	23

Test N.	Test Condition		RH*	T*	Time	N(0)	N(t)	λe	λn	λp	CADR	η
24	Peace Lily 2	(SPA_2)	95	24	1.67	1288.81	925.20	0.20			0.01	28
25	Peace Lily 3	(SPA_3)	94	24	1.72	1337.41	963.00	0.19			0.01	28
26	Boston fern 1	(NEPH_1)	93	24	1.37	1002.61	351.00	0.77			0.03	65
27	Boston fern 2	(NEPH_2)	94	24	0.97	1202.41	718.20	0.53			0.02	40
28	Boston fern 3	(NEPH_3)	95	24	0.92	1126.81	718.20	0.49			0.02	36
* Mean values measured in the chamber												

Table 3
Statistical analysis of the CADR of formaldehyde depletion caused by the selected growth media.

	Dry expanded clay	Wet expanded clay	Dry soil	Wet soil	Dry activated carbon	Wet activated carbon
Mean	0.02	0.09	0.09	0.13	0.03	0.02
SD*	0.01	0.06	0.03	0.02	0.01	0.01
SE**	0.01	0.04	0.02	0.01	0.00	0.00
* SD: Standard Deviation						
** SE: Standard Error						

Table 4
Multiple Comparisons (Tukey HSD); Dependent Variable: CADR for formaldehyde.

(I) What is the variable?	(J) What is the variable?	Mean Difference (I-J)	Std. Error	Sig.
Dry Expanded Clay	Wet Expanded Clay	-0.067	0.021	0.093
	Dry Soil	-0.063	0.021	0.122
	Wet Soil	-0.110*	0.021	0.002
	Dry Activated Carbon	-0.007	0.021	1.000
	Wet Activated Carbon	0.012	0.024	1.000
	Peace Lily	-0.003	0.021	1.000
	Boston Fern	-0.003	0.021	1.000
Wet Expanded Clay	Dry Expanded Clay	0.067	0.021	0.093
	Dry Soil	0.003	0.021	1.000
	Wet Soil	-0.043	0.021	0.488
	Dry Activated Carbon	0.060	0.021	0.159
	Wet Activated Carbon	0.078	0.024	0.070
	Peace Lily	0.063	0.021	0.122
	Boston Fern	0.063	0.021	0.122
Dry Soil	Dry Expanded Clay	0.063	0.021	0.122
	Wet Expanded Clay	-0.003	0.021	1.000
	Wet Soil	-0.047	0.021	0.403
	Dry Activated Carbon	0.057	0.021	0.205
	Wet Activated Carbon	0.075	0.024	0.090
	Peace Lily	0.060	0.021	0.159
	Boston Fern	0.060	0.021	0.159
Wet Soil	Dry Expanded Clay	0.110*	0.021	0.002
	Wet Expanded Clay	0.04	0.021	0.488
	Dry Soil	0.05	0.021	0.403
	Dry Activated Carbon	0.103*	0.021	0.004
	Wet Activated Carbon	0.122*	0.024	0.002
	Peace Lily	0.107*	0.021	0.003
	Boston Fern	0.107*	0.021	0.003
Dry Activated Carbon	Dry Expanded Clay	0.01	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.159
	Dry Soil	-0.06	0.021	0.205
	Wet Soil	-0.103*	0.021	0.004
	Wet Activated Carbon	0.02	0.024	0.992

(I) What is the variable?	(J) What is the variable?	Mean Difference (I-J)	Std. Error	Sig.
	Peace Lily	0.00	0.021	1.000
	Boston Fern	0.00	0.021	1.000
Wet Activated Carbon	Dry Expanded Clay	-0.01	0.024	1.000
	Wet Expanded Clay	-0.08	0.024	0.070
	Dry Soil	-0.08	0.024	0.090
	Wet Soil	-0.122*	0.024	0.002
	Dry Activated Carbon	-0.02	0.024	0.992
	Peace Lily	-0.02	0.024	0.998
	Boston Fern	-0.02	0.024	0.998
Peace Lily	Dry Expanded Clay	0.00	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.122
	Dry Soil	-0.06	0.021	0.159
	Wet Soil	-0.107*	0.021	0.003
	Dry Activated Carbon	0.00	0.021	1.000
	Wet Activated Carbon	0.02	0.024	0.998
	Boston Fern	0.00	0.021	1.000
Boston Fern	Dry Expanded Clay	0.00	0.021	1.000
	Wet Expanded Clay	-0.06	0.021	0.122
	Dry Soil	-0.06	0.021	0.159
	Wet Soil	-0.107*	0.021	0.003
	Dry Activated Carbon	-0.003	0.021	1.000
	Wet Activated Carbon	0.015	0.024	0.998
	Peace Lily	0.000	0.021	1.000
* The mean difference is significant at the 0.05 level.				

Table 5
Homogeneous Subsets; Dependent Variable: CADR for formaldehyde.

	What is the variable?	N	Subset for alpha = 0.05		
			1	2	3
Student-Newman-Keuls	Wet Activated Carbon	2	0.015		
	Dry Expanded Clay	3	0.027	0.027	
	Peace Lily	3	0.030	0.030	
	Boston Fern	3	0.030	0.030	
	Dry Activated Carbon	3	0.033	0.033	
	Dry Soil	3		0.090	0.090
	Wet Expanded Clay	3		0.093	0.093
	Wet Soil	3			0.137
	Sig.		0.914	0.072	0.116
Tukey HSD	Wet Activated Carbon	2	0.015		
	Dry Expanded Clay	3	0.027	0.027	
	Peace Lily	3	0.030	0.030	
	Boston Fern	3	0.030	0.030	
	Dry Activated Carbon	3	0.033	0.033	
	Dry Soil	3	0.090	0.090	0.090
	Wet Expanded Clay	3		0.093	0.093
	Wet Soil	3			0.137
	Sig.		0.056	0.110	0.437
Means for groups in homogeneous subsets are displayed.					

Table 6
Statistical analysis of the CADR of formaldehyde and CO_2 depletion caused by the selected plants.

	Formaldehyde		CO_2	
	Peace lily	Boston fern	Peace lily	Boston fern
Mean	0.03	0.03	0.01	0.02
SD*	0.00	0.00	0.00	0.00
SE**	0.00	0.00	0.00	0.00
* SD: Standard Deviation				
** SE: Standard Error				

Table 6 presents the statistical analysis of the CADR of formaldehyde and CO_2 depletion caused by the selected plants. Regarding formaldehyde depletion, both species showed the same performance. Regarding CO_2 depletion, Boston ferns showed a better performance than Peace lilies. Regarding the data set of CO_2 depletion, independent T-tests were executed to establish whether a

statistically significant difference occurred of the depletion of CO_2 between the selected plants, the results showed that Boston ferns depleted statistically significantly more CO_2 than the peace lilies (P = 0.02).

4 Discussion

This study provides data for the characterization of the removal of formaldehyde by three different substrates and two different potted plants. Four series of zero measurements were executed to evaluate the setup. Two measurements of these series were executed with a plastic pot to evaluate the effect of this element in the depletion of the formaldehyde inside of the chamber. As expected, once the plastic pot was placed in the chamber the formaldehyde level was lower than the natural decay measured during the zero-measurement evaluation. This value was used to calculate the CADR for every test condition as shown in Tables 1 and 2.

4.1 Depletion of formaldehyde

Exploration of the potential of plants to purify air from pollutants started in the early 1980s (Armijos Moya et al. 2019; Wolverton et al. 1984) and to date several plant species have been studied and identified for use in formaldehyde removal. However, previous studies have tested extremely high concentrations of formaldehyde (over ~ 2000 μg/m^3) (Dela Cruz et al. 2014), higher than the concentrations that are usually found in common indoor environments (WHO 2010). This study, presents the results of the uptake of formaldehyde with a concentration of 300 ppb (0.37 mg/m^3), which is within the boundaries of the detection threshold of formaldehyde indoors (0.03 mg/m^3-0.6 mg/m^3) (WHO 2010) and close to the guideline value based on sensory effects (0.1 mg/m^3) (WHO 2010). Furthermore, formaldehyde is soluble in water (WHO 2010), therefore, it may be depleted faster in wet environments (Aydogan and Montoya 2011). In a study published in 2011, Aydogan and Montoya reported that activated carbon alone showed the highest formaldehyde removal and the four plant species studied demonstrated similar abilities to remove formaldehyde (Aydogan and Montoya 2011). During this set of experiments, the reduction of formaldehyde concentration inside of the chamber was faster when wet substrates were present, the plant species have similar behaviour in formaldehyde removal (~ 0.03 m^3/h). However, activated carbon appeared to be a very unstable component. In none of the cases, activated carbon had an optimal performance. Figure 6 presents the results of the effect of dry activated (AC_D; n = 3), and wet activated carbon (AC_W; n = 2) on the depletion of formaldehyde in the chamber. The third sample of wet activated carbon was excluded because instead of reducing the formaldehyde concentration, the wet activated carbon released it into the chamber. The third sample of the wet activated carbon came from a different package than the other samples. The packaging material most likely was polluted, which might have caused the unstable behavior of the selected substrate.

Previous studies suggest that the depletion of formaldehyde also occurs due to photosynthesis and metabolism of the plant at daytime (Teiri et al. 2018). A growing light was used during this test to ensure the optimal conditions of the plant.

Studies with potted plants in closed chambers continue to be useful for isolating factors that may enhance removal efficiency and contribute towards the improvement of plant-based systems (e.g. plant species and growth medium). Therefore, it is recommended to use the lessons learned from this study in creating a plant-assisted botanical purifier (“Biowalls” or active green walls), which mechanically forces the air to pass through the leaves and the roots (Armijos Moya et al. 2019; Cummings and Waring 2019; Darlington et al. 2000).

4.2 Depletion of CO_2

For the evaluation of the reduction of CO_2 levels inside of the chamber, it is important to mention that in general, plants regulate the internal CO_2 concentration through a partial stomatal closure when the CO_2 concentration is too elevated to maintain adequate internal CO_2 and optimize water use efficiency (Van de Geijn and Goudriaan 1996). Stomata are pores on leaf epidermis for both water and CO_2 fluctuations that are controlled by two major factors: stomatal behaviour and density (Elliott-Kingston et al. 2016; Wang et al. 2007). The fast speed opening and closing of the stomata can save energy and increase photosynthesis and water use efficiency (Grantz and Assmann 1991). Taking this in account, Table 2 and Fig. 8 present the depletion of CO_2 inside the chamber when the potted plants were present, and they show that even though the leave area of the Boston fern is lower than the peace lily, the depletion of CO_2 inside of the chamber was faster when the Boston fern was in the chamber. In order to ensure the optimal behaviour of the plant during the experiments levels of CO_2 were controlled (Elliott-Kingston et al. 2016; Van de Geijn and Goudriaan

1996; Wang et al. 2007). Figure 8 shows that in order to provide the optimal conditions for the plant it was necessary to inject CO_2 inside of the chamber because the concentration was too low for the plants (IPCC 2014; NASA 2019). In each test condition, activated carbon permanently released CO_2 inside of the chamber, which, possibly could be compensated by the uptake of CO_2 by the plants.

4.3 Plants vs. growth media

Formaldehyde and CO_2 were used as indicators of the effect of growth media and plants in reducing gaseous pollutants in a controlled environment. Table 1 shows that, in general, growth media were more effective in the depletion of formaldehyde inside of the chamber than the plants. Regarding CO_2 reduction inside of the chamber, as expected, Table 2 shows that plants were more effective than growth media: in most of the cases with only a growth medium present, CO_2 was released instead of reduced inside of the glass chamber. Figure 9 presents the different behaviours of the potted plants regarding these two elements. Even though the leave area of the Boston fern (approx. 0.11 m^2) was smaller than the peace lily (approx. 0.14 m^2), the Boston ferns reduced the concentration of CO_2 inside of the chamber faster than the peace lilies, which indicates that the stomatal conductance of the Boston fern was higher than the peace lily, opening the hypothesis about the uptake of more gaseous pollutants by the stomata. Regarding the depletion of formaldehyde, Tables 4 and 5 show that wet soil, dry soil and expanded clay perform similarly and they are more effective than the other variables tested (Table 3).

As mentioned before formaldehyde is soluble in water (WHO 2010). However, this study shows that high levels of humidity seemed to have no effect on the formaldehyde depletion inside of the chamber as in most of the test conditions the relative humidity level was above 90%. Nonetheless, it is important to mention that in the case of the plants, high humidity levels may affect the depletion of the CO_2 and the formaldehyde inside of the chamber due to the fact that plants close their stomata at high humidity levels (Elliott-Kingston et al. 2016; Wang et al. 2007). The temperature was quite stable during the experiments (Tables 1 and 2), therefore, it seemed to have no effect on the formaldehyde and CO_2 depletion, but in general in the presence of wet growth media the depletion of formaldehyde was faster. Regarding the effect of the growth media on the depletion of formaldehyde and CO_2, it is important to mention that when the substrate (wet or dry) was tested without the plant, the whole surface of the substrate was exposed directly to formaldehyde and CO_2. However, when the plants were included, the exposed surface of the selected substrate was reduced and the results show that the depletion also was lower, which indicates that the efficacy of the growth media, in some cases, was higher. This effect is produced by the microbial activity in the root zone, where bacteria absorb the gaseous pollutants and metabolise them (Armijos Moya et al. 2019; Aydogan and Montoya 2011; Irga et al. 2018; Wolverton et al. 1989).

4.4 Potted plants and their effect in the indoor air quality

According to the ASHRAE standard 62.1–2016 the minimum ventilation rate in breathing zones in office spaces is 0.3 l/s, m^2 (1.08 m^3/h for every one square meter of floor space) (ASHRAE-62.1 2016), likewise, the standard NEN-EN 15251 – 2007 the minimum ventilation rate for new buildings and renovations is 0.35 l/s, m^2 (1.26 m^3/h for every one square meter of floor space) for very low polluting buildings (NEN-EN15251 2007). Table 1 presents that the CADR for formaldehyde depletion of the potted plants is 0.03 m^3/h, therefore, it is necessary to have 42 plants for every square meter of floor space in order to meet the standards without any additional ventilation system. Besides, Table 2 presents that the CADR for CO_2 depletion of the potted plants is 0.01 m^3/h (Peace lily*)* and 0.02 m^3/h (Boston fern). Therefore, it is necessary to have > 100 plants for every square meter of floor space in order to meet the standards without any additional ventilation system. Therefore, without any extra mechanical ventilation it is necessary an indoor forest to meet the minimum standards for ventilation rates in breathing zones just with plants, however, in real situations less plants will be required taking in account the size of the room and the ventilation system of every case.

4.5 Limitations

One of the limitations of this group of tests is the size of the chamber. Even though it has the requirements of a sealed glass container with the necessary inlets, for future research it is recommended to execute the tests in a bigger sealed glass container to prevent or reduce the stress of the plant, avoiding the closure of its stomata and reducing its metabolism.

As mentioned before, plant stress should be minimized, therefore, for future experiments the plant should be placed in the chamber one day prior the execution of the test together with the activated growing light.

5 Conclusions And Recommendations

A series of tests was performed to evaluate the effect of potted plants on reducing formaldehyde and CO_2 levels in a controlled glass chamber. The outcome of the tests showed some clear advantages and disadvantages of the different test conditions to consider for the design of an indoor plant-based system.

In terms of air 'cleaning' of formaldehyde, the measurements and analysis showed that soil, in general, was most effective in reducing formaldehyde concentrations in the chamber (~ 0.07–0.16 m^3/h). Plants (~ 0.03 m^3/h) were as effective as dry expanded clay (0.02–0.04 m^3/h). Wet and dry soil, wet expanded clay and dry activated carbon performed better than the selected plants in formaldehyde depletion. In this study, it became clear that the substrate is an important ally in reducing gaseous pollutants, such as formaldehyde.

Regarding CO_2 reduction in the chamber, potted plants (Peace lilies – 0.01 m^3/h) (Boston ferns 0.02–0.03 m^3/h) were more effective than the other tests. Specially, Boston fern which has a higher stomatal conductance than the peace lily, indicating the possibility of allowing more gaseous pollutants to be absorbed in the long term.

Studies with potted plants in closed chambers showed to be useful for isolating factors that may enhance removal efficiency and contribute towards the improvement of plant-based systems (e.g. plant species and growth medium). However, the impact of one potted plant on the cleaning of the indoor air, was insignificant. Therefore, several potted plants will be required to improve the IAQ taking in account the specific characteristics of the place such as, size and the ventilation system.

It must be noted, however, that in this study the formaldehyde was introduced in a glass chamber in which the plant and its substrate were located, hereby surrounding the plant and its substrate with formaldehyde. In a 'normal' indoor environment, usually the source of formaldehyde may not be close to the plant system. For the plant-system to take-up the formaldehyde, the polluted air needs to be transported to the vicinity of the plant. This could be realized, for example, by an active plant-substrate system, in which the contaminated air is forced to go through the plant-leaves and through the substrate-roots. Further research with active plant-based systems on the depletion of formaldehyde and other pollutants, is required.

6 Declarations

Ethical Approval: [No Applicable]

Consent to Participate: [No Applicable]

Consent to Publish: We confirm that the manuscript has been submitted solely to this journal and is not published, in press, or submitted elsewhere.

Authors Contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Tatiana Armijos Moya. The first draft of the manuscript was written by Tatiana Armijos Moya and all authors commented and contributed on previous versions of the manuscript. All authors read and approved the final manuscript. The individual contribution of the authors is described as it follows:

- Conceptualization: Tatiana Armijos Moya, Pieter de Visser, Marc Ottele, Andy van den Dobbelsteen and Philomena M. Bluyssen
- Methodology: Tatiana Armijos Moya, Pieter de Visser and Philomena M. Bluyssen
- Formal analysis and investigation: Tatiana Armijos Moya and Philomena M. Bluyssen
- Writing - original draft preparation: Tatiana Armijos Moya
- Writing - review and editing: Tatiana Armijos Moya, Pieter de Visser, Marc Ottele, Andy van den Dobbelsteen and Philomena M. Bluyssen
- Supervision: Pieter de Visser, Marc Ottele, Andy van den Dobbelsteen and Philomena M. Bluyssen

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Availability of data and materials: [No Applicable]

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Figures

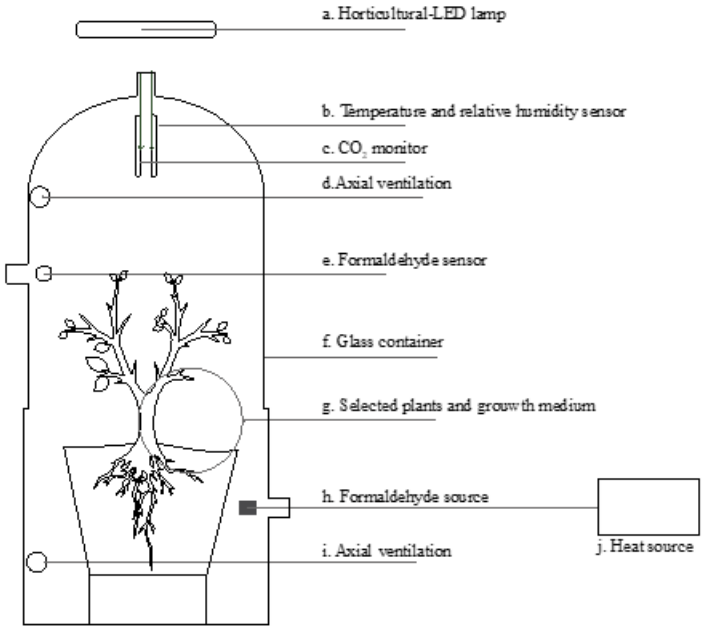

Figure 1

Schematic view of the experimental setup.

Figure 2

Selected plants: a. Spathiphyllum Wallisii Regel (Common name: Peace Lily); and b. Nephrolepis exaltata L. (Common name: Boston Fern) in the glass container.

Figure 3

Scan and calculation of the leaf area: a. Peace Lily; b. Boston Fern.

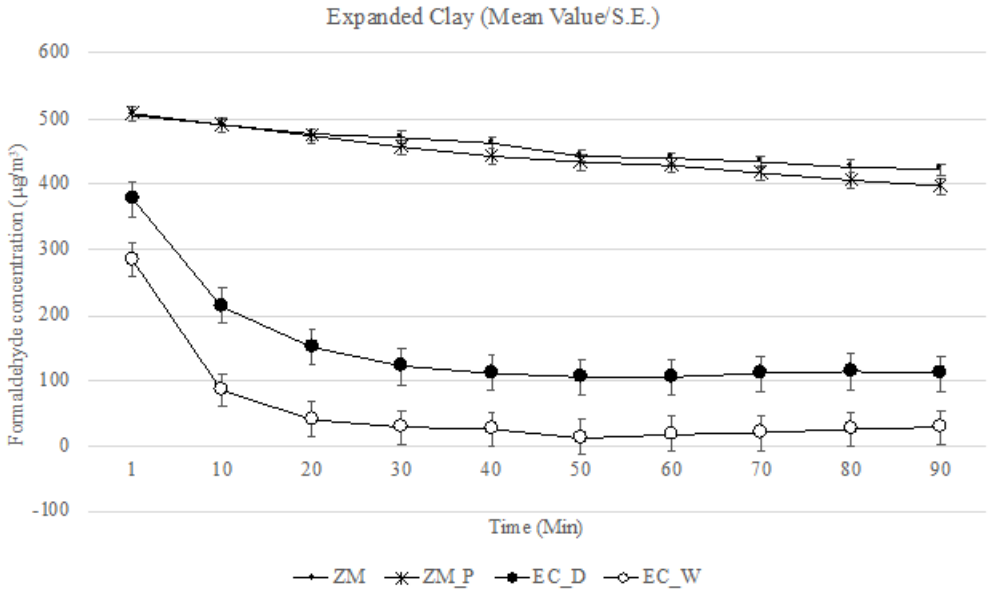

Figure 4

Measured formaldehyde concentration [(µg/m3)/h] when expanded clay samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), dry expanded Clay (EC_D), wet expanded Clay (EC_W). Data means ± SE, n=3.

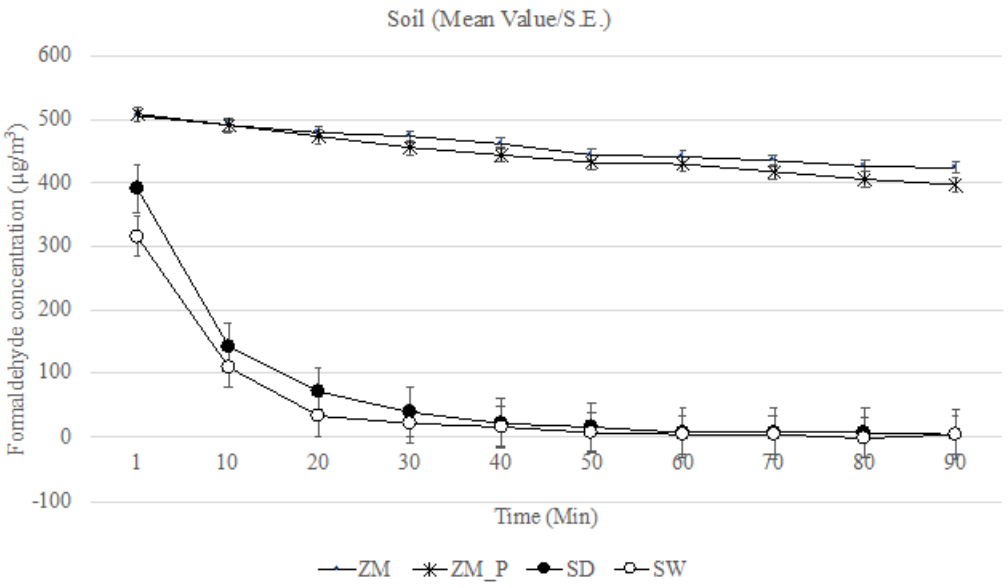

Figure 5

Measured formaldehyde concentration [(μg/m3)/h] when soil samples were tested: zero measurement (ZM1), zero measurement with the plastic pot (ZM_P), dry soil (SD), wet soil (SW). Data means ± SE, n=3.

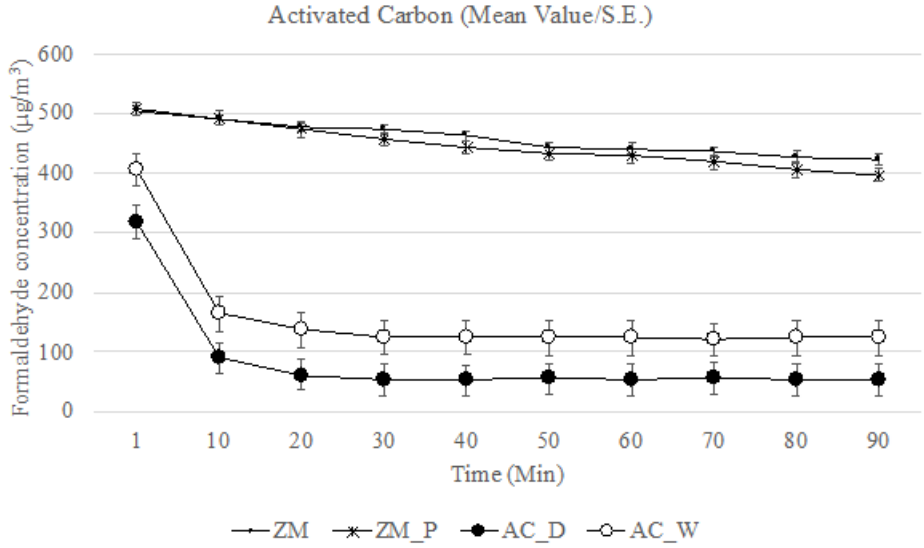

Figure 6

Measured formaldehyde concentration [(μg/m3)/h] when activated carbon samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), dry activated carbon (AC_D), wet activated carbon (AC_W). Data means ± SE, n=3 (AC_D) and, n=2 (AC_W; the third test was excluded).

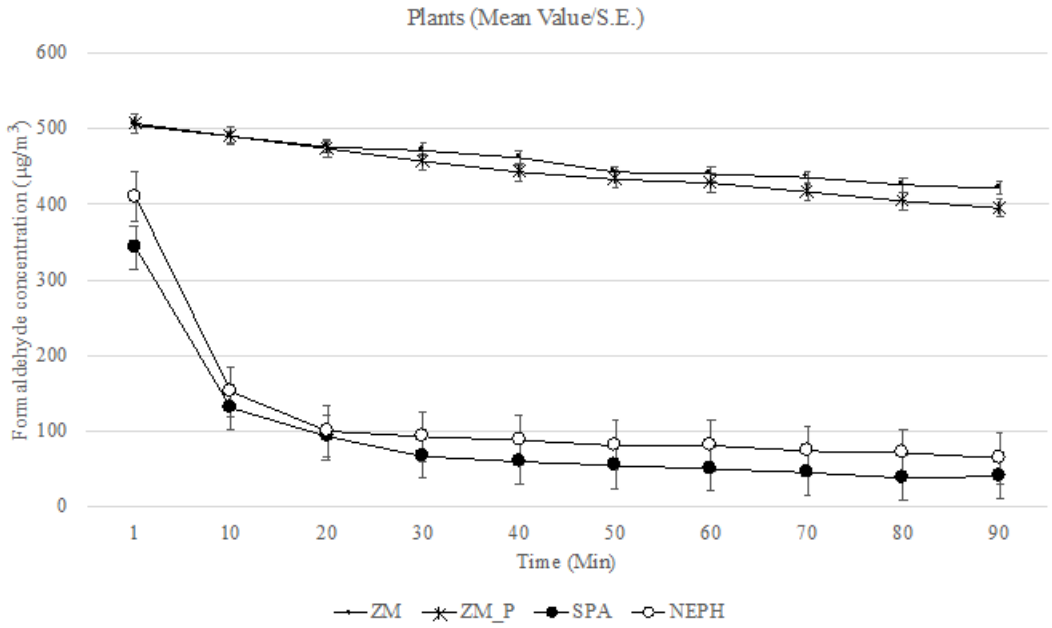

Figure 7

Measured formaldehyde concentration [(µg/m3)/h] when plant samples were tested: zero measurement (ZM), zero measurement with the plastic pot (ZM_P), Peace Lily (SPA), Boston Fern (NEPH). Data means ± SE, n=3.

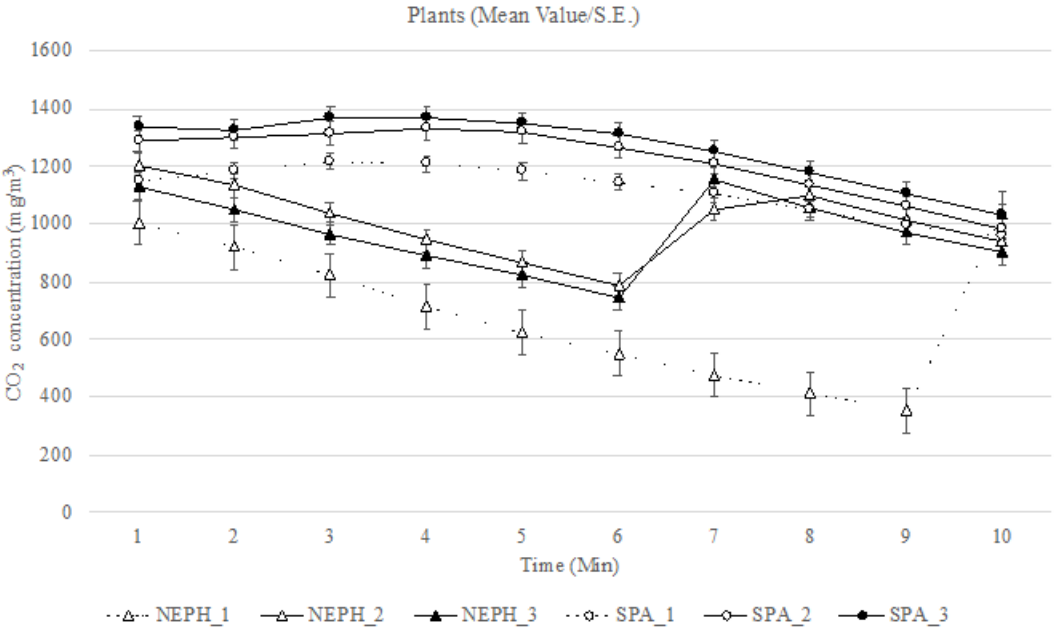

Figure 8

Depletion of CO2 (mg/m3): for the three Boston Fern (NEPH_1, NEPH_2, and NEPH_3) and for the three Peace Lilies (SPA_1, SPA_2, and SPA_3). Data means ± SE, n=3.

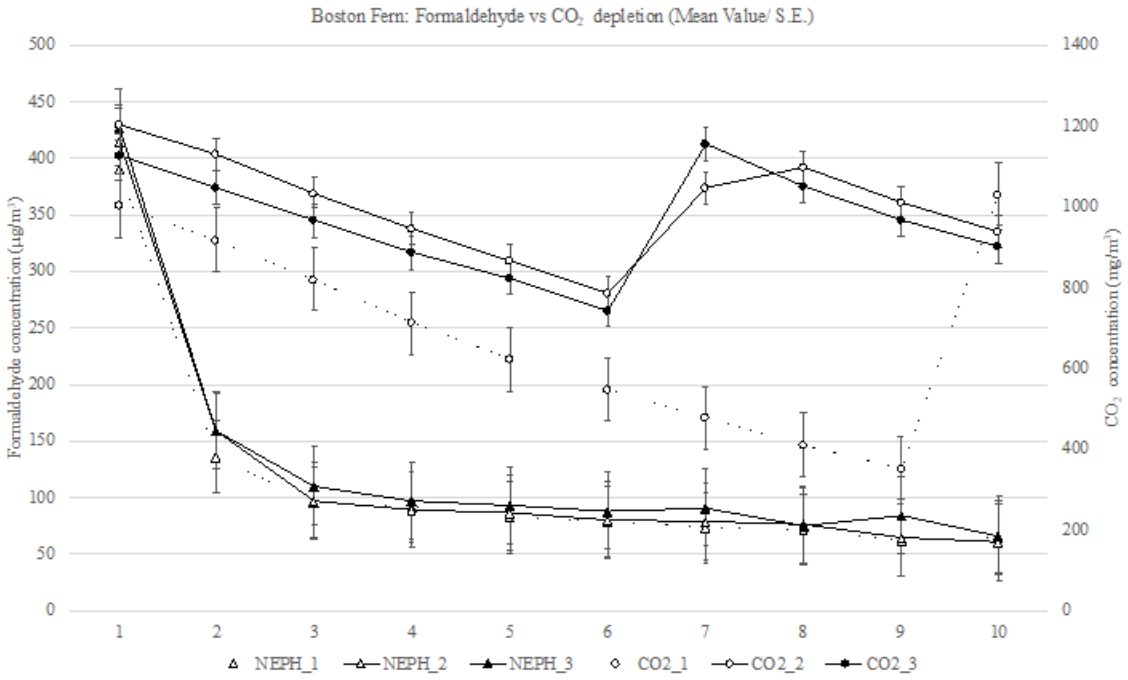

Figure 9

Depletion of formaldehyde (NEPH_1, NEPH_2, and NEPH_3) vs depletion of CO2 (CO2_1, CO2_2, and CO2_3): for the three Boston Ferns. Data means ± SE, n=3.