Article

Removal of Volatile Organic Compounds by Means of a Felt-Based Living Wall Using Different Plant Species

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Abstract: Poor indoor quality affects people's health and well-being. Phytoremediation is one way in which this problem can be tackled, with living walls being a viable option for places with limited space. The aim of this study was to evaluate the efficiency of five plant species in a living wall to remove Volatile Organic Compounds (VOCs) and to identify whether the type of pollutant has any influence. An enclosed chamber was used to add the contaminants n-hexane and formaldehyde independently. Total VOCs were measured for three days in two scenarios: (1) empty chamber, and (2) chamber with living wall. Five living walls were prepared, each with three plants of the same species: *Spathiphyllum wallisii*, *Philodendron hederaceum*, *Ficus pumila*, *Tradescantia pallida,* and *Chlorophytum comosum*. There was no correlation between leaf area/fresh weight/dry weight and the contaminant reduction. In general, all five species were more efficient in reducing TVOCs when exposed to formaldehyde than to n-hexane. *Chlorophytum comosum* was the most efficient species in reducing the concentration of TVOCs for both contaminants, *Spathiphyllum wallisii* being the least efficient by far.

Keywords: green wall; indoor air quality; TVOCs; *Spathiphyllum wallisii*; *Philodendron hederaceum*; *Ficus pumila*; *Tradescantia pallida*; *Chlorophytum comosum*

1. Introduction

People tend to spend most of their time indoors [1]. For that reason, maintaining an adequate Indoor Air Quality (IAQ) is essential, as poor levels can affect people's health (Sick Building Syndrome) [2]. Buildings are now increasingly being constructed in an airtight manner in order to maximise their energy efficiency [3], preventing adequate ventilation of indoor spaces [4]. IAQ can be affected by polluted air coming from outside the building, but there are also many indoor contaminants [5].

Volatile Organic Compounds (VOC) are mostly anthropogenic contaminants with known effects on health, going from irritation of the eyes and respiratory tract to more serious illnesses such as liver and kidney damage or cancer [6]. VOCs are widely emitted from products commonly used in construction (e.g., paints, solvents, varnishes, etc.) and many others employed on a day-to-day basis (detergents, products, air fresheners, cleaning, and personal care products, etc.) [7].

Formaldehyde is one of the most common indoor VOCs [8–10] because it originates from indoor sources in composite wood products [11]. Another common contaminant is n-hexane, which is classified as an alkane [12] and has adverse effects on the central nervous system [13] but has been less researched as an indoor contaminant.

There are many different methods proposed to improve IAQ. One of them is the use of plants, known as phytoremediation [14], which offers a solution to the energy consumption of other air purification technologies. Its efficiency depends on many different factors such as the type of system, which can be passive (potted plants) or active (filter plants, activated carbon) [15], temperature, light intensity, growing media, or VOC (identity, concentration,

potential mixture effects) [16]. However, the type of plant or species used seems to be one of the main key factors influencing VOC removal efficiency [17].

There is often limited space indoors to provide the amount of vegetation needed to improve air quality. Thus, living walls can be considered as a viable solution [18]. They also contribute to improving the aesthetical component and offer psychological benefits associated with indoor vegetation [19]. In fact, some studies [20] point to living walls being more efficient than potted plants in removing indoor contaminants.

The aim of this work was to evaluate the efficiency of five species planted in living wall modules to remove VOCs for IAQ improvement and to assess if the type of contaminant had any influence.

2. Materials and Methods

2.1. Preparations of the Tests and Environmental Conditions

A sealed glass chamber (0.8 m long; 0.4 m wide; 0.4 m high) [19] was used where contaminants were released in two scenarios: with the chamber empty and with a small living wall inside (Figure 1).
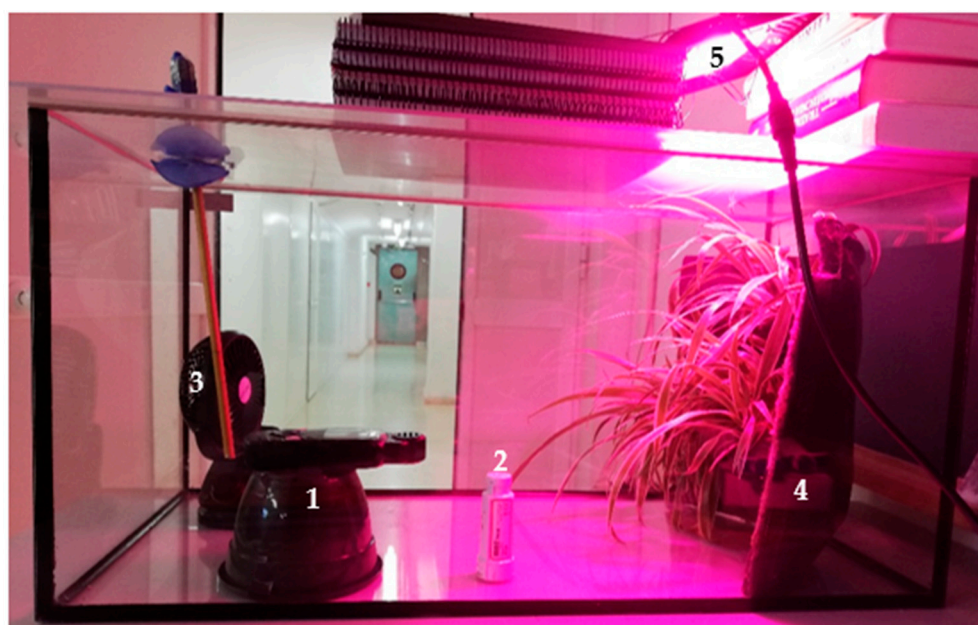

Figure 1. Sealed glass chamber where n-hexane and formaldehyde tests were performed for each plant species. (**1**) Gas detector; (**2**). HOBO sensor; (**3**) Portable fan; (**4**) Felt-based module with three plants per species; (**5**) Grow photosynthetic lamp.

The living walls used for the tests consisted of a felt-based module (Fytotextile®, Terapia Urbana, S.L., Seville, Spain) [21], 0.49 m wide by 0.36 m high. The inner geotextile layer was sawn to the exterior polyamide layer forming a grid of 2 by 3 pockets. Finally, a waterproof layer was added at the back of the living wall module in order to mimic the exact configuration of the commercial system (Figure 2). The air temperature inside the chamber was monitored by a HOBO Pro Temp-HR U23-001 sensor (Onset Computer Corp., Bourne, MA, USA). The temperature range in which the tests were carried out was 15.7 °C to 26.8 °C.

Inside the chamber, the air was mixed by means of a small portable fan to achieve a uniform distribution of the contaminant. A CF-UT01 LED Grow photosynthetic lamp (Panda Grow, Shenzhen, China) with a light cycle of 15 h was used, positioned right on the chamber at an angle of 14° to the vegetation with respect to the horizontal position and with an average illuminance of 6828 Lux [19].
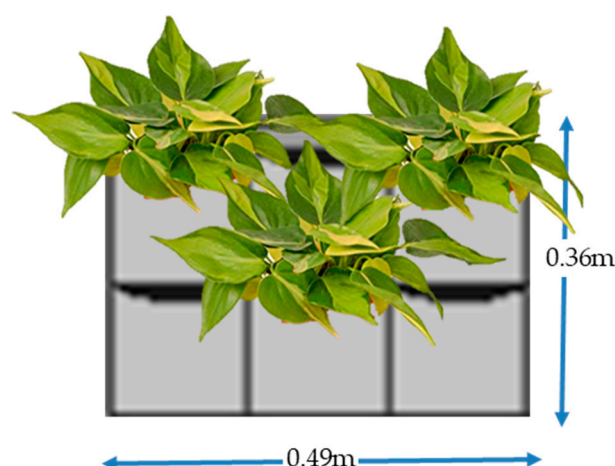
Figure 2. Felt-based module design and distribution of the three plants for each species.

2.2. Selected Plants

Five small modules were prepared specifically for the tests, each planted with a different species:

1. *Spathiphyllum wallisii* is commonly used as an ornamental houseplant due to its availability. It can withstand poor growing conditions [22] and its ability to capture atmospheric particles has been studied [23].
2. *Philodendron hederaceum* is an ornamental foliage climber plant commonly used in indoor environments. It has the potential to absorb harmful gases and clean the air inside buildings [24].
3. *Ficus pumila* tolerates shade very well [25] and is an ornamental plant that has been frequently used in green walls [26]. There are not many studies regarding its potential to improve indoor air quality.
4. *Tradescantia pallida* is a plant found in gardens and public spaces such as squares and roadsides [27] and it has shown efficiency in the removal of benzene, toluene, TCE, and α-pinene [28].
5. *Chlorophytum comosum* is one of the most studied plants for phytoremediation of indoor air contaminants [15,29] and uses formaldehyde as a source of energy for biosynthesis [30].

Three plants per species were planted in each module and maintained for two months prior to the tests to ensure full root development through the living wall felt. Two plants were placed in the lower row and one in the middle pocket of the upper row (Figure 2), by inserting inside the pocket the root ball with a Seed Pro 7030 substrate (Projar professional, Projar, Valencia, Spain) to favour the rooting of the plant.

2.3. Test Procedure and Data Collection

Two different organic compounds were used as sources of contaminants: n-hexane and formaldehyde. In order to assess the VOC removal potential of each species, the Total Volatile Organic Compounds (TVOCs) [31] levels were monitored by means of a PCE-VOC 1 gas detector (PCE Ibérica S.L., Albacete, Spain) [19].

A first test was carried out with the chamber empty (scenario one), to record the mean value of TVOCs obtained for each contaminant (pattern) when plants were not present. In scenario two, the module with the plants was placed inside the chamber (separately for the five plant species). The duration of each test was 3 days and the TVOCs values were recorded at 0.25 h, 1 h, 5 h, and 72 h from the beginning of the test (addition of the contaminant). In scenario one, the contaminants were added to the chamber with a micropipette until reaching TVOCs values slightly over 3 mg/m^3, the limit established by Spanish regulations (UNE 171330-2:2014) to be considered in the 'discomfort range'. Then,

the same volume of contaminants was added in scenario two. The chamber was sealed to avoid any loss or exchange of gases with the outside.

Three tests were carried out in each scenario for each combination of species and contaminants (3 replications × 5 species × 2 contaminants). To determine the efficiency of the species, the percentage of reduction of the contaminant concentration was calculated, considering the TVOCs value reached by each contaminant in the empty chamber as the reference. Therefore, the TVOCs reduction (%) was calculated as follows for each time (from the introduction of the contaminant):

$$\%R(n) = 100 \cdot (TVOCs(n)_0 - TVOCs(n)) / TVOCs(n)_0$$

where $\%R(n)$ is the reduction (%) of TVOCs obtained over the TVOCs average value with no vegetation inside the chamber at the same time (n); (n) is the time in hours since the contaminant is released in the chamber until the measure of the TVOCs value; $TVOCs(n)_0$ is the average TVOCs value at time (n) in the chamber without vegetation; $TVOCs(n)$ is the average TVOCs value at time (n) in the chamber with the living wall module inside.

Immediately after the tests, the total leaf area ($cm^2 \cdot plant^{-1}$) was determined for each plant species using a leaf area meter LI-3100 (Li-Cor, NE, USA), and the fresh and dry weight of the plants was measured with a precision balance D-6200 CB (I.C.T, S.L., La Rioja, Spain).

Table 1 shows the instruments used during the research with their respective descriptions.

Table 1. Instruments used during the research.

Equipment	Model	Description
HOBO	Pro Temp-HR U23-001 (Onset Computer Corp., Bourne, MA, USA)	Operation range: 0 to 100% RH, −40° to 70 °C. Accuracy: ±2.5% from 10% to 90% RH typical to a maximum of ±3.5% including hysteresis at 25 °C (77° F); below 10% and above 90% ± 5% typical
Grow lamp	A CF-UT01 LED (Panda Grow, Shenzhen, China)	Voltage: 110 V/220 V. Lamp Luminous Flux (lm): 5000 Spectrum: 560–780 nm
Portable fan	CAVN QY072-EU	5000 mAh
Gas detector	PCE-VOC 1 (PCE Ibérica S.L., Albacete, Spain)	Operation range TVOC: 0.00 to 9.99 mg/m^3 Accuracy TVOC: ±5% of full scale
Leaf area meter	LI-3100 (Li-Cor, NE, USA)	Resolution: 1 mm × 1 mm Accuracy: 10 cm^2 (+1%); 5 cm^2 (+2%); 1 cm^2 (+5%); 0.5 cm^2 (+7%). Precision was determined at the 99% level with irregular-shaped complex objects.
Precision balance	*D-6200 CB* (I.C.T, S.L., La Rioja, Spain)	Weighing capacity: 6200 g Accuracy: 0.1 g

2.4. Data Treatment and Statistical Analysis

Two General Linear Models (GLM) were carried out to compare (1) the efficiency of the five species between them for each contaminant, and (2) the efficiency of each species between n-hexane and formaldehyde. In both cases, this is done taking into account the percentage reduction of TVOCs with respect to the pattern of the n-hexane and formaldehyde in the test without plants, at different times (0.25 h, 1 h, 5 h, 72 h). The variables complied with a normal distribution and with homoscedasticity. Statistical analyses (ANOVA and LSD tests) were performed using Statgraphics Centurion 18 Version 18.1.12.

3. Results

Table 2 shows the main parameters obtained for the five plant species studied at the end of each test. *S. wallisii* was the species with more biomass, followed by *T. pallida*. Conversely, *F. pumila* and *P. hederaceum* presented a lower development of the vegetation.

Table 2. Total biomass in the living wall (fresh and dry weight), percentage of water, fresh weight media per plant, and leaf area by each plant species exposed to n-hexane and formaldehyde.

Plant Parameters	*S. wallisii*	*P. hederaceum*	*F. pumila*	*T. pallida*	*C. comosum*
Fresh weight (g)	545.30	103.50	61.60	355.10	162.10
Aerial part	351.10	74.90	36.70	336.70	97.30
Roots	194.20	28.60	24.90	18.40	64.80
Dry weight (g)	72.60	12.80	14.30	23.00	11.90
Aerial part	44.30	9.50	9.30	21.00	6.60
Roots	28.30	3.30	5.00	2.00	5.30
% Water	86.69	87.63	76.79	93.52	92.66
Aerial part	87.38	87.32	74.66	93.76	93.22
Roots	85.43	88.46	79.92	89.13	91.82
Fresh weight per plant (g)	181.77 ± 34.75	17.25 ± 10.83	10.27 ± 1.42	59.18 ± 17.26	27.02 ± 4.31
Total leaf area (cm^2)	6306.70	729.60	1418.40	2931.40	1904.30
Mean area per leaf (cm^2)	18.33	18.71	31.52	16.75	9.24
Total number of leaves	344	39	45	175	206

The tests were first performed with the chamber without the living wall, in order to obtain the baseline to compare with the tests with plants. The TVOCs maximum values for n-hexane and formaldehyde were 3.35 mg/m^3 and 3.69 mg/m^3, respectively (Table 3).

Table 3. Average $\pm$ standard deviation of the TVOCs values (mg/m^3) recorded for n-hexane and formaldehyde at different times from the introduction of the contaminant.

Contaminant	0.25 h (mg/m^3)	1 h (mg/m^3)	5 h (mg/m^3)	24 h (mg/m^3)	48 h (mg/m^3)	72 h (mg/m^3)
n-hexane	3.14 ± 0.05	3.19 ± 0.07	3.13 ± 0.01	3.35 ± 0.60	3.30 ± 0.67	3.34 ± 0.61
formaldehyde	1.96 ± 0.49	2.46 ± 0.52	2.69 ± 0.84	3.59 ± 0.33	3.69 ± 0.47	3.69 ± 0.47

In addition, the different behaviour of each pollutant is observed for the five plant species. Figure 3 shows that all five plant species are more efficient in reducing TVOCs when exposed to formaldehyde than to n-hexane. Furthermore, the reduction of TVOCs tends to be more homogeneous with the five plant species exposed to formaldehyde.

Table 4 shows the percentage of reduction (%R) of TVOCs values compared with the average in scenario 1 at the same times. There are some significant differences in the TVOCs reduction percentage between species exposed to n-hexane at 0.25 h (p-value = 0.013), at 1 h (p-value = 0.012), at 24 h (p-value = 0.043), at 48 h (p-value = 0.040), none at 5 h, and only for *S. wallisii* and the rest of species (except *P. hederaceum*) (p-value = 0.045) at 72 h. In the case of formaldehyde, significant differences were only detected for *S. wallisii* at 0.25 h (p-value = 0.050), at 1 h (p-value = 0.023), at 5 h (p-value = 0.033), at 24 h (p-value = 0.000), at 48 h (p-value = 0.000), and at 72 h (p-value = 0.015).

Comparing the efficiency within the same species in removing the two contaminants, during the first day, the five species have significant differences in the percentage reduction of TVOCs when exposed to n-hexane compared to formaldehyde, being more efficient in the absorption of the latter. At 48 h, only *S. wallisii* had differences between both contaminants. Only at 72 h were there no significant differences for any species (Table 3).
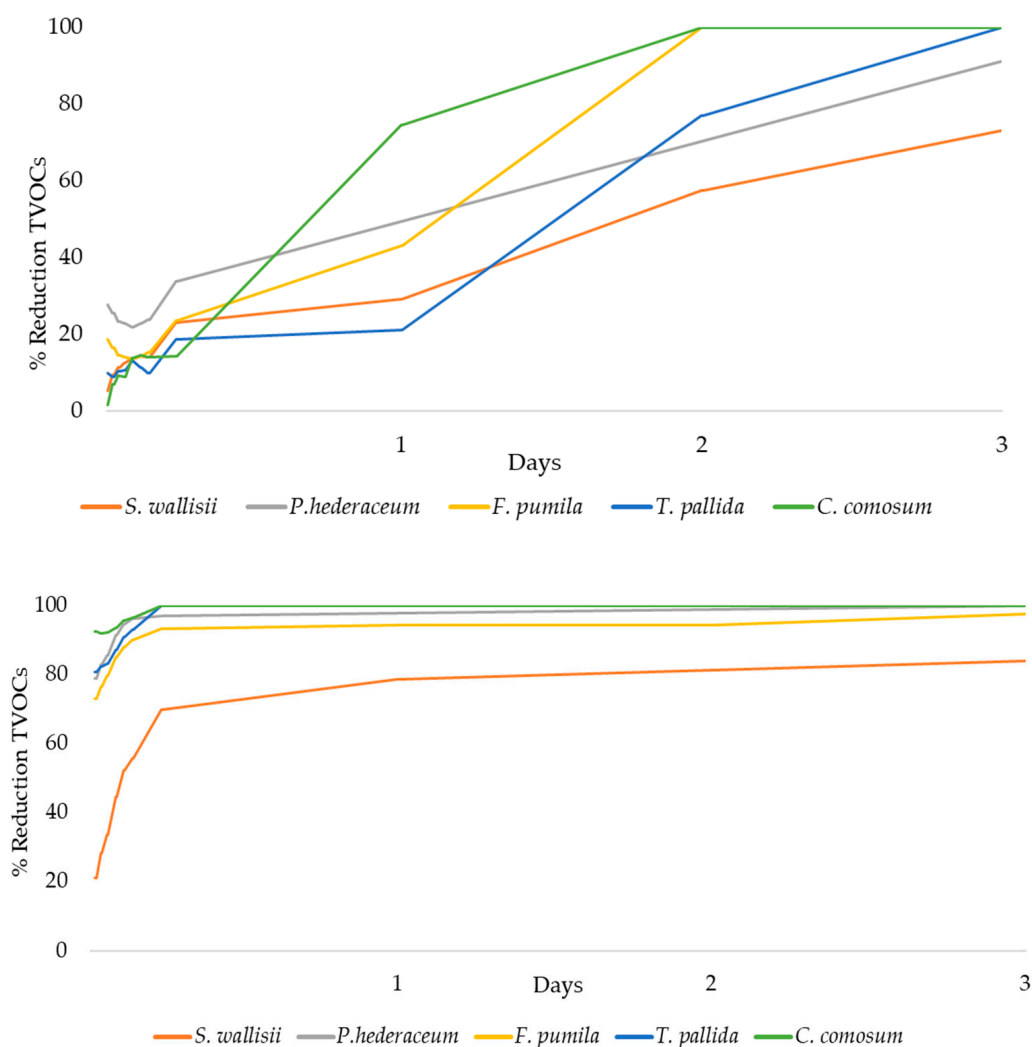
Figure 3. Evolution of the TVOCs reduction percentage for the five plant species exposed during three days to n-hexane (**up**) and Formaldehyde (**down**).

Table 4. Analysis of variance between TVOCs reduction percentage of the five species in different time ranges for each contaminant.

Contaminant	Species	%R0.25	%R1	%R5	%R24	%R48	% R72
n-hexane	*S. wallisii*	11 ± 3.6 b	14 ± 4.1 a	23 ± 3.2	29 ± 2.2 b	57 ± 18.6 b	73 ± 24.0 b
	P. hederaceum	23 ± 10.7 ab	24 ± 10.9 ab	34 ± 15.7	-	-	91 ± 11.2 ab
	F. pumila	15 ± 10.9 b	15 ± 10.8 a	24 ± 9.6	43 ± 25.1 a	100 ± 0.0 a	100 ± 0.0 a
	T. pallida	10 ± 36.8 a	10 ± 30.2 b	19 ± 39.5	21 ± 21.5 b	77 ± 32.6 ab	100 ± 0.0 a
	C. comosum	9 ± 15.4 ab	14 ± 17.4 ab	14 ± 16.7	65 ± 0.5 a	100 ± 0.0 a	100 ± 0.0 a
formaldehyde	*S. wallisii*	28 ± 7.9 b	56 ± 10.3 b	70 ± 8.4 b	79 ± 4.6 b	81 ± 4.4 b	84 ± 4.4 b
	P. hederaceum	83 ± 3.1 a	96 ± 3.6 a	97 ± 2.9 a	-	-	100 ± 0.0 a
	F. pumila	76 ± 10.0 a	90 ± 3.8 a	93 ± 3.6 a	94 ± 6.1 a	94 ± 6.1 a	98 ± 2.7 a
	T. pallida	82 ± 13.4 a	93 ± 5.8 a	100 ± 0.0 a	100 ± 0.0 a	100 ± 0.0 a	100 ± 0.0 a
	C. comosum	92 ± 0.9 a	96 ± 0.3 a	100 ± 0.0 a	100 ± 0.0 a	100 ± 0.0 a	100 ± 0.0 a

%R1/4: TVOCs reduction at 0.25 h. %R1: TVOCs reduction at 1 h. %R5: TVOCs reduction at 5 h. %R24: TVOCs reduction at 24 h. %R48: TVOCs reduction at 48 h. %T72: TVOCs reduction at 72 h. Different small letters in the same column denote significant differences, for the same contaminant, of the percentage reduction of TVOCs between the plant species according to the ANOVA and the LSD Test ($p < 0.05$).

4. Discussion

This study confirms that plants contribute to the improvement of indoor air quality by reducing the concentration of VOCs. The effect is higher the longer the air is in contact with the plants [19]. However, the efficiency in this reduction was different depending on the contaminant and on the species used.

In spite of the difference in the quantity of vegetation, there was not any correlation between the leaf area/fresh weight/dry weight and the reduction of contaminants. Therefore, the differences observed are due to the species tested. The same was also observed in a similar experiment using n-hexane and living walls planted with Nephrolepis exaltata L., comparing the effect of different quantities of vegetation [19].

In general, the five species tested (*S. wallisii*, *P. hederaceum*, *F. pumila*, *T. pallida*, and *C. comosum*) were more efficient in reducing the concentration of TVOCs when exposed to formaldehyde than to n-hexane. In fact, most species achieved a 100% reduction between 5 h and 24 h after the introduction of the formaldehyde. Conversely, only two species (*F. pumila* and *C. comosum*) attained a 100% reduction after 48 h with n-hexane.

These differences in the percent removed depending on the contaminant were also reported by other authors. For example, Wolverton et al. [32] obtained much higher reduction percentages for formaldehyde than for trichloroethylene for the same species. Formaldehyde appears to be efficiently detoxified by oxidation [30] and this mechanism is faster, while n-hexane removal has been reported to be slow, as it is more related to the microorganisms associated with the root system [33].

A different behaviour was also observed depending on the contaminant used when no vegetation was present in the chamber. Although the TVOCs' maximum values for n-hexane and formaldehyde were similar after 72 h, the TVOCs reached high values in less time when using n-hexane than with formaldehyde. This progressive increase of TVOCs with formaldehyde could be one of the factors of the better results obtained in reducing the concentration of the contaminant in the indoor environment.

C. comosum was, among those tested, the most efficient species in reducing the concentration of TVOCs for both contaminants, followed by *F. pumila* when exposed to n-hexane and *T. pallida* for formaldehyde. The three of them completely eliminated the VOCs after 72 h. *C. comosum* has also shown a higher potential for benzene [34] and ethylbenzene [35] removal than other species. *T. pallida* was considered a very effective plant for the removal of VOCs by other authors too [28,36].

For n-hexane, *P. hederaceum* reduced the concentration of TVOCs faster during the first 5 h, though after that the rate of reduction decreased and this species did not achieve the total removal of the contaminant at 72 h. For formaldehyde, *P. hederaceum* had similar behaviour to the other species (except *S. wallisii*), nearly eliminating the contaminant after one hour. Both *C. comosum* and *P. hederaceum* were catalogued among the species with a higher potential for removing formaldehyde after a review of several studies [37].

S. wallisii was the least efficient by far in reducing both contaminants. Even so, reductions of 73 and 84% were achieved at 72 h. Other studies also considered *S. wallisii* as one of the least efficient species in the removal of TVOCs [28,38]. In fact, in a study assessing formaldehyde removal by 20 different herbaceous foliage species, *S. wallisii* figured in the lower quarter [17].

Although *S. wallisii* had the largest leaf area compared to the other species, this did not influence its efficiency in reducing the concentration of TVOCs for both contaminants. Noor et al. [36] reported that leaf area plays a moderate role in VOC adsorption but is not drastically influential.

It is interesting to highlight that the reduction of VOCs starts instantly, as TVOCs values in the first minutes after releasing the contaminant never reached those obtained when the chamber had no vegetation. Furthermore, the reduction had a much higher rate in the first 15 min, decreasing rapidly over time. This was more evident for the formaldehyde. In fact, for this compound reductions between 76 and 92% were already obtained in the first 15 min (except for the case of *S. wallisii*, which only reduced around 30%).

The selection of the species is clearly important to maximise the reduction of VOCs obtained when installing a living wall indoors. Though usually, a living wall integrates several different species, their selection must respond to certain objectives that should combine the aesthetical perspective with practical issues (such as water and light requirements, maintenance, etc.) in order to maximise the benefits obtained. Thus, one way to address variability in VOC abatement efficiency between species is through the design of living walls with a combination of different species.

In a living wall system, not only the plants are responsible for VOC removal. Additionally, the substrate or soil employed will have a part, as rhizosphere microbial activity is an important mechanism for VOC reduction [33,39], as well as the direct adsorption of VOCs into the soils [40].

5. Conclusions

This study confirmed the effect that a living wall has on removing VOCs. However, the removal efficiency changed depending on the contaminant used. It was clear that the species employed were more efficient in removing formaldehyde than n-hexane. *C. comosum* exhibited the best results while *S. wallisii* was the least efficient.

The main limitation of this study is the use of a small and sealed chamber, given that it is difficult to extrapolate the results. Therefore, carrying out additional experiments in 'real life' conditions is recommended. In addition, there is still a need for further studies about this topic involving other plant species and assessing the specific mechanisms or processes involved in the VOCs removal. The influence of other variables such as environmental conditions, lighting patterns, or substrates employed are also worthy to be considered for future studies.

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