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Alternative Growing Medium for Indoor Living Walls to Foster the Removal Efficiency of Volatile Organic Compounds

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Abstract. Increasing urbanization trends led to growing concerns regarding human health risks linked to long-time exposure to poor indoor air quality. Volatile Organic Compounds (VOCs), *e.g.*, formaldehyde and benzene, are the most significant pollutants in indoor environments due to the high number of sources contributing to increase their concentration. Vertical Greening Systems (VGSs) have been proven as space-efficient nature-based solutions (NBS) using the ability of ornamental plants in removing VOCs. Growing media and rhizosphere community often play a pivotal role in removing indoor VOCs, especially in active biofilters. Although horticultural substrates are often overlooked in VGSs' applications, an increasing number of studies focus on: (i) investigating sustainable opportunities provided by organic materials to produce alternative growing media; and, (ii) exploring compositions of substrates to maximize VGSs phytoremediation efficiency. This work presents preliminary results on the influence of almond shells as an alternative growing medium for VGSs on the removal efficiency of formaldehyde. For that, a VGS module with almond shells as substrate and a single species of ornamental plant was placed in a sealed chamber – specially designed to recirculate the air contaminated by formaldehyde through the module acting as an active biofilter. The system produced a clear reduction of the formaldehyde concentration, and the plants developed correctly with the substrate. Green building-integrated systems are multifunctional NBS which address challenges such as human wellbeing and circularity at local scale. Using organic growing media to improve the biofiltration capability of these systems is a promising alternative towards successful implementation in the built environment.

Keywords: Nature-Based Solutions · Green Infrastructure · Vertical Greening Systems · Indoor Air Quality · Formaldehyde

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1 Introduction

In the framework of cities' densification, Vertical Greening Systems (VGSs) – well known as green walls or living walls (synonyms) – are adopted as technological nature-based solutions (NBS) to improve citizens' well-being through the naturalization of the built environment [1–3]. This term refers to a wide umbrella concept that describes varied technological NBS adopted for growing plants vertically, attached or not to a building facade or to an interior wall [2–6]. Many scientific studies assert that the adoption of VGS technology and solutions provide multiple benefits in outdoor applications, such as the improvement of air quality; the mitigation of the urban heat island (UHI) effect; the improvement of buildings' performance – by acting as thermal insulation and reducing the UHI effect; the support of biodiversity enhancement in cities; and, the management of stormwater [6–8]. However, the increasing urbanization trend led people to spend almost 80–90% of their daily time in indoor environments such as schools, homes, workplaces, and other interior public spaces [9]. Besides ambient pollution, urban areas present critical issues linked to the indoor air quality (IAQ); and there is a growing public awareness regarding risks linked to the long-time exposure to poor IAQ at home and workplaces in terms of health diseases [10]. Volatile Organic Compounds (VOCs), such as formaldehyde (CH_2O) and benzene (C_6H_6), are the most significant pollutants in indoor environments due to the relative high number of sources – *e.g.*, paints, furniture, and textiles – that contribute to increase their concentration in interiors if compared to outdoor air pollution.

Some scientific studies have investigated the ability of ornamental potted-plants species in removing VOCs from air [11, 12]. Even if potted-plants demonstrate significant removal efficiency of indoor air pollutants, on-site application highlights space-related limitations in order to obtain consistent effects in air cleaning process. Vertical Greening Systems have been tested as a space-efficient strategy to expose a greater plant biomass to indoor air pollutants. As an example, previous studies have tested the performance of felt-based living wall set-ups with different ornamental plant species, obtaining promising results concerning the reduction of total VOCs [13, 14]. In this framework, Godish and Guindon [15], and Wolverton *et al.* [16] demonstrated independently in the year 1989 that plant's cultivation substrate plays a pivotal role in removing VOCs from indoor air than plant's foliage responsible of gas exchanges. Later, outcomes obtained by Hörmann *et al.* in 2018 [17] revealed the important role of the rhizosphere during air biofiltration. These findings lead to focus on cultivation substrate composition, such as the activated carbon substrate [18], and treatment conditions that stimulate the growth of active microbiota able to degrade pollutants. This is particularly important for the application of active air biofilters that use pressure to increase the volume of air in contact with the vegetation and substrate cultivation to increase the phytoremediation efficiency of VOCs – if compared to passive living walls, as reported by Pettit *et al.* [12] and Irga *et al.* [19]. As there is an increasing interest on the ability of VGSs to reduce airborne contaminants, further studies are needed to better understand how environmental conditions and living wall characteristics may influence the potential of indoor vegetation for the IAQ improvement.

Growing media play a crucial role to obtain successful VGSs in terms of aesthetical values and efficiency of phytoremediation processes. Varied inorganic and organic growing media can be used depending by the kind of VGS to be implemented. Nowadays, increasing attention must be focused on investigating alternative substrates obtained by reusing waste and by-products derived from local industries and activities such as the agri-food sector related, in order to enhance these bio-resources under a circular economy (CE) perspective and increasing the sustainability of VGSs [20]. In this framework, the present study investigates the phytoremediation efficiency of a VGS module that adopts almond shells as a growing media for common indoor ornamental plants. Almond shells have been selected due to the large availability of this ligneous by-product in Andalusia (southern Spain) with potential features to be exploited towards circular bioeconomy strategies [21, 22]. This research study aims to enhance almond shells as a potential growing medium for VGS applications thanks to their properties [22] and to fill the knowledge gap on how the use of varied alternative growing media for indoor living walls may influence the formaldehyde removal ability of common ornamental plants. The research focuses on the knowledge improvement regarding phytoremediation processes of formaldehyde, as the most widespread VOC in interiors that cause severe health diseases if people are exposed for long periods. Moreover, the research conducted on alternative growing media is inspired by the principles of CE; moving towards an eco-design approach and by reducing the environmental impact of substrates used in VGSs [1–3, 6, 23, 24].

2 Materials and Methods

This study has been designed to compare the evolution trend of formaldehyde concentration in a glass sealed chamber with and without a VGS module. A Fytotextile system® of 1 m^2 – *i.e.*, 1 m length; 1 m height – and composed of 49 pockets has been adopted to set up the VGS module. *Chlorophytum comosum* (Thunb.) Jaques, commonly known as spider plant, has been selected due to its diffusion as ornamental and evergreen perennial indoor plant species. Moreover, *C. comosum* is often used in indoor VGS applications thanks to its ability to remove airborne contaminants from indoor air [16]. Eighteen plants of *C. comosum* were arranged in pockets of the Fytotextile module filled with almond shells as growing medium (Fig. 1). Almond shells were previously collected from a local company operating in the cultivation and processing of almonds (DAFISA S.A., La Carlota, Córdoba, southern Spain). Almond shells were cleaned with regular water to remove small particles and dust than can affect the performance of the VGS module inside the sealed chamber. The VGS module was placed in interiors for 4-weeks acclimatization and growth stabilization supplied with artificial lighting and irrigation.

Almond shells-growing medium was characterized determining its physical properties: (i) the particle size distribution; (ii) the dry bulk density ($g \cdot cm^{-3}$); (iii) the total porosity (%); and, (iv) the water holding capacity (%). The particle size distribution was performed by using a set of mesh sieves with opening dimensions between 0.5 mm and 16 mm. While the dry bulk density and the water holding capacity were determined through the procedure proposed by Maiti [25], and the total porosity following the method indicated by Landis [26].

Fig. 1. On the left, almond shells collected and cleaned before being used as growing media; and, on the right, a plant of *Chlorophytum comosum* set up in almond shells-growing medium contained in a pocket of Fytotextile VGS module.

Formaldehyde was released in a sealed glass chamber of 2 m^3 volume – *i.e.*, 2 m length; 1 m depth; 1 m height – equipped with artificial lighting, at an orientation angle of 14º to the horizontal, and a recirculating ventilation system used to circulate air thorough the VGS module with an air flow of 0.5 $m{\cdot}s^{-1}$. Formaldehyde concentration ($mg{\cdot}m^{-3}$) inside the sealed chamber was monitored using the YESAIR 8-Channel IAQ Monitor (Critical Environment Technologies Inc.); a portable air quality detector that was placed inside the sealed chamber during tests. The air quality detector is also equipped with a sensor to monitor temperature (ºC) and relative humidity (%). Initial volume of 1 ml formaldehyde was used to reach the maximum concentration inside the sealed chamber – close to the safe threshold limit of 0.37 $mg{\cdot}m^{-3}$, indicated by the Instituto Nacional de Seguridad y Salud en el Trabajo (INSST), Spain [27]. The formaldehyde was released through a pipette into the sealed chamber once at the beginning of each test, and the formaldehyde concentration trend was monitored in continuous for 60 min; being 1 min sampling.

The study has been performed to compared two scenarios of formaldehyde concentration trend: (1) in the empty sealed chamber (control test); and, (2) the sealed chamber equipped with the VGS module working as biofilter. In the second scenario, the VGS module was placed inside the sealed chamber and connected to the recirculating ventilation system in order to force the contaminated air to pass and recirculate through the vegetation. Tests have been performed in triplicates for both scenarios, and at a temperature range of 24.2–30.0 ºC.

3 Results and Discussion

3.1 Characterization of Almond Shells as Growing Medium for Vertical Greening Systems

Two of the main functions of growing media are to provide support for roots growth; and, retain and make water available. Physical properties of a substrate provide important indication to establish the suitability of alternative materials to be used as growing media for soilless cultivations. Table 1 shows initial physical properties of almond shells used as growing medium for ornamental plants. Almond shells have been used as collected by the local company without any pre-treatment process. They present a coarse particle size distribution consisting of 89.62% particles with a diameter equal or greater than 8 mm.

Table 1. Physical properties of almond shells used as growing medium in this study.

Distribution of particle size	
Diameter (mm):	Particle size distribution (% particles):
16	4.91
8	84.71
4	9.26
2.5	1.04
1	0.04
0.5	0.04
<0.5	0.01
Dry bulk density: 0.31 g·cm^3	
Total porosity: 68%	
Water holding capacity: 20%	

This result indicates that almond shells produce a porous and aerated substrate that presents an adequate initial dry bulk density of 0.31 g·cm^{-3}; according to Fernandes and Corá [28]. On the other hand, the total porosity and the water holding capacity presented values quite low, compared with those ranges recommended for an optimal substrate [29, 30]. Indeed, authors as Schafer and Lerner [29] and Evans [30] indicated that the total porosity of an ideal substrate should be between 75% and 90% [29, 30], while the water holding capacity is recommended to be between 50% and 65% [30]. Anyway, Tripepi [31] indicated that total porosity in the range of 50–85% is considered satisfactory; and, that the general range of water holding capacity is between 20% and 60% for many substrates used as potting mix. Considering the low water holding capacity of almond shells, the irrigation system of VGS module used in this study has been set to supply water during 15 min·h^{-1} for 24 h.

3.2 Comparison of Formaldehyde Concentration Trends

The comparison of formaldehyde concentration trend in the sealed chamber with and without the VGS module is shown in Fig. 2. In all cases, the initial formaldehyde concentration inside the sealed chamber was 0 mg·m^{-3}. Figure 2 shows both trends when formaldehyde concentration reached the maximum level. In tests with the empty sealed chamber, a single injection of formaldehyde in liquid state – *i.e.*, 1 ml volume – produced a maximum mean value of 0.53 mg·m^{-3} (see Fig. 2) that was consistently higher than in experiment that use vegetation as biofilter (0.35 mg·m^{-3}); being a difference of 0.18 mg·m^{-3}.

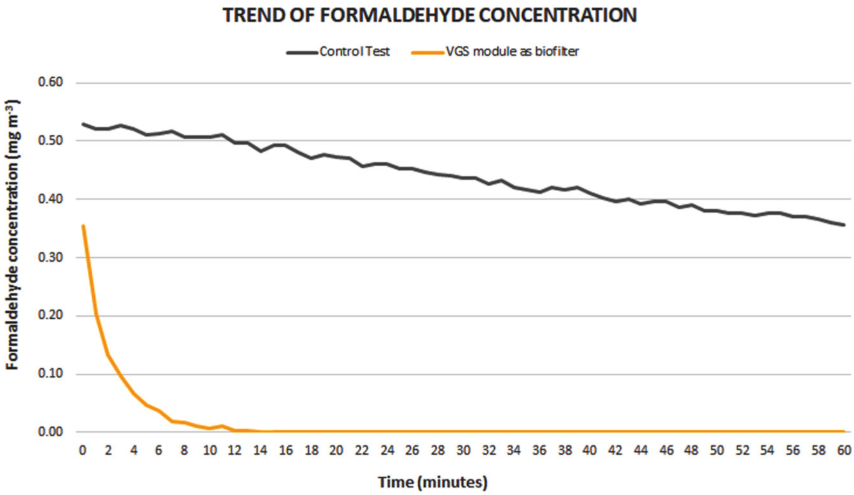

Fig. 2. Comparison of the concentration trend of formaldehyde (CH_2O) measured in the glass sealed chamber during the control test (dark grey line trend); and, the test performed using the vertical greening system (VGS) module acting as biofilter (orange line trend).

The formaldehyde concentration presented decreasing trends in both scenarios during 1 h of monitoring. In the test performed in the empty chamber the concentration of formaldehyde decreased by 0.17 mg·m^{-3} from the maximum value, reaching 0.36 mg·m^{-3} after 1 h of monitoring. While in tests with VGS module as botanical filter, the formaldehyde concentration decreases to 0 mg·m^{-3} from the maximum value, after 12 min of monitoring.

These results show the effectiveness of VGSs as botanical filter, and their contribution to the improvement of IAQ. The presence of vegetation inside the sealed chamber contributed to mitigate the concentration of formaldehyde. Indeed, formaldehyde reached a concentration value of 0.53 mg·m^{-3} – that is above the limit indicated by the INSST (0.37 mg·m^{-3}) [27]. On the other hand, the contaminated air inside the sealed chamber, that was in contact with plants and substrate of the VGS module, presented a maximum value of formaldehyde concentration, which was below the safe threshold limit of the INSST.

The control test presented a decreasing trend of 0.00–0.01 mg·m^{-3}·min^{-1} maintaining consistent the concentration of formaldehyde produced by a single inject during the whole experiment. On the other hand, the presence of the VGS module was fundamental to limit and reduce the formaldehyde concentration – *i.e.*: the maximum level registered was 0.35; and, after 1 min the concentration value was reduces to 0.20 mg·m^{-3} (−0.15 mg·m^{-3} from the maximum value) and after 5 min it is at 0.05 mg m^{-3} (−0.30 mg m^{-3} from the maximum value). This result demonstrates the efficiency of the removal ability of the VGS module at the beginning of the monitoring; after that, the formaldehyde concentration reached the maximum value.

4 Conclusions

The present research outcome highlights the importance of Vertical Greening Systems (VGSs) that use active airflow to improve the indoor air quality by efficiently removing formaldehyde, as one of the most significant volatile organic compounds. The results of this study are in line with those obtained in previous studies [13, 14]; and they suggest promising outcomes concerning the use of alternative materials for VGS substrates. This research contributes to the knowledge improvement about the role of VGSs as botanical biofilters [12, 19]; and, in particular, it demonstrates their effectiveness when exposed to low concentration of air contaminants. The physical characterization of almond shells as growing medium showed potential results for current and future studies in the research field. Further investigations are recommended to better understand the evolution trend of almond shells as alternative growing medium for VGSs, in terms of biological stability and chemical properties. This contribution demonstrates potentialities offered by VGSs as tool to ameliorate the quality of air inside buildings, especially in those equipped with mechanical ventilation systems. The present results obtained using almond shells also suggest exploring the opportunities of other by-products and waste materials to be used as alternative growing media, moving towards a circular economy perspective in vertical greening applications.

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