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IMPACT OF VERTICAL GREENERY SYSTEM ON INDOOR AIR QUALITY: CASE STUDY IN A LUXEMBOURG ADMINISTRATIVE BUILDING

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Abstract

Vertical greenery systems (VGS) have become increasingly popular in indoor environments due to their aesthetic value and potential to improve air quality. However, their real impact on indoor air and occupant health remains under-documented, especially in operational public buildings. This case study assesses the effects of VGS on indoor air quality (IAQ) in a recently renovated administrative building in Luxembourg, where five VGS comprising both depolluting and ornamental plant species were installed across three floors. Over 46 weeks, concentrations of formaldehyde, volatile organic compounds (VOCs), and airborne mold spores were systematically monitored near the VGS and in reference locations without VGS, alongside environmental parameters and qualitative feedback from staff. Formaldehyde concentrations were consistently lower in areas equipped with VGS compared to reference sites, with reductions of up to 40% in separate zones. While the overall VOC burden remained similar with and without VGS, a significant decrease was observed in the concentration of aromatic compounds and ketones near VGS installed in confined or well-ventilated zones. However, the presence of VGS led to increased mold spore concentrations, particularly where high humidity or suboptimal maintenance favored fungal growth. No toxic or pathogenic molds were detected. The study demonstrates that VGS can contribute to lowering certain indoor air pollutants, primarily formaldehyde, yet underscores the importance of proper design and maintenance to control mold risks. Recommendations address irrigation, substrate hygiene, and system location for optimal IAQ and user acceptability.

Keywords : Vertical greenery system (VGS), Indoor air quality, Volatile organic compounds, Mold, Formaldehyde

1. Introduction

Homes, vehicles, and enclosed workplaces have become the everyday environment in which people spend most of their time [1]. However, without special attention, the air we breathe can be polluted and thus harmful to the occupants' health [2,3]. Indoor air quality is one of the criteria defining sick building syndrome (SBS) [4], a syndrome encompassing a set of unexplained symptoms related to buildings. The symptoms experienced by occupants depend on their sensitivity and can range from a simple runny nose to more serious cases such as chronic respiratory infections and headaches [5]. The sources of indoor pollution are numerous and varied, as are the pollutants themselves. Whereas building finishing materials and furniture can emit pollutants over the long term [6], pollutants emitted on an ad hoc basis are mainly related to the behavior of the occupant (e.g., use of household products [7], cooking, smoking, burning incense [8] and so on [9]). As a result, indoor air can become laden with volatile organic compounds (VOCs - from paints, glues, etc.), particles (from wear and tear, etc.) [10], microbial volatile organic compounds, spores from molds, and in some cases radon [3,11,12], depending on the geology of the soil. Each of these pollutants can have harmful effects on human health [12,13]. Wargocki [14] estimated the annual SBS-related health costs within the United State of America, to range between \$15 billion and \$40 billion for 2011, making SBS therefore both a health and economic problem. As a result, indoor air quality has become a major issue in recent decades. It is therefore recommended to ensure a good air exchange rate by opening windows or installing HVAC systems (heating, ventilation, and air conditioning). At the same time, labels guaranteeing low pollutant emissions have been developed for building materials as well as for finishing and furnishing products [15].

In this context, any strategy aimed at improving indoor air quality should be viewed as an integrated system.

Over the past years, vertical greenery systems (VGS) have become increasingly common in indoor spaces, initially for aesthetic reasons and more recently as potential levers for improving thermal comfort, cognitive performance, and air quality through the pollutant-removal properties of specific plant species [16]. These phytoremediation effects rely on several complementary mechanisms, including stomatal uptake and metabolic transformation in leaves, sorption and microbial degradation in the root zone and growing medium, and interactions with biofilms associated with the system. Several reviews have shown that, under controlled conditions, these processes can contribute to the removal of various VOCs and aldehydes [17–19].

However, the VGS can both reduce certain chemical pollutants but can also generate unintended effects, such as increased relative humidity or microbiological loads [20–23]. The challenge is therefore not only to lower indoor pollutant concentrations (e.g., VOCs, aldehydes, particles), but to achieve a balance between chemical air quality and biological safety (e.g., molds, bioaerosols) under realistic building operating conditions. Elevated indoor fungal spore concentrations have been associated with respiratory symptoms and asthma exacerbation, and various agencies have proposed guideline values for total culturable fungi in indoor air, even though no universal threshold exists [24,25]. This dual perspective highlights the need to simultaneously consider chemical pollutants and biological agents when assessing indoor air quality.

Numerous chamber and small-room studies have reported significant reductions of formaldehyde and aromatic VOCs when using potted plants or green-wall systems, particularly with species such as *Chlorophytum comosum, Spathiphyllum wallisii, Hedera helix*, or *Nephrolepis exaltata* combined with active air circulation through the substrate [26–30]. However, other studies conducted under more realistic indoor conditions have reported limited or inconsistent VOC reductions, emphasizing that room volume, air exchange rates and source strength often dominate pollutant dynamics and can mask any plant-related effects. In such in-use environments, changes in VOC levels are frequently intertwined with variations in occupancy patterns and ventilation operation, which makes it difficult to attribute observed concentration changes solely to the presence of plants or green walls [24,31,32].

At the same time, most research on greening systems has focused on energy performance and outdoor microclimate, whereas far fewer long-term in situ studies have documented their impact on indoor air quality in occupied public buildings. In corridors, for instance, the presence of VGS has been associated with changes in air temperature, relative humidity, and certain pollutants, with potential effects on space use and occupants' perception of the indoor environment. In addition, VGS can locally increase humidity through the combined effects of irrigation and plant evapotranspiration and provide organic substrates that favor fungal growth; several studies have reported mold development on green walls, with direct implications for air quality and airborne spore concentrations [20–23]. As a result, VGS may simultaneously provide chemical benefits-in terms of reduced concentrations of specific pollutants-and increase biological risks by promoting mold growth, particularly when maintenance and ventilation are suboptimal.

Overall, VGS therefore emerge as promising solutions for mitigating some indoor pollutants, while at the same time potentially shifting risks toward the biological dimension, which justifies jointly assessing their chemical benefits and their impacts on molds and bioaerosols under real operating conditions. In this work, we explicitly distinguish between expected benefits (reduction of formaldehyde and selected VOC families) and potential risks (increased humidity and airborne fungal spores), and we analyze how this trade-off depends on building configuration and VGS design.

Despite growing interest in indoor VGS, there is still a lack of long- term, in-use studies that jointly evaluate their chemical and biological impacts on indoor air in public buildings recently renovated with low- emission materials. Evidence is also limited regarding how design parameters (VGS surface area versus room volume, ventilation strategy, and space configuration) modulate these effects. This study addresses the following research questions:

i. To what extent are formaldehyde and selected VOC families reduced in the vicinity of indoor VGS compared with reference locations without VGS under real operating conditions?
ii. Under the same conditions, does the presence of VGS contribute to increased airborne mold spore concentrations, and how are these changes related to humidity, ventilation, and maintenance practices?
iii. How do building characteristics (room volume, ventilation strategy, VGS surface area) influence the magnitude and direction of these chemical benefits and biological risks?

We hypothesize that (H1) indoor VGS are associated with lower formaldehyde concentrations compared with reference zones, while (H2) they may be associated with higher concentrations of airborne fungal spores in poorly ventilated or poorly maintained configurations.

To address these questions, this article presents a case study measuring the impact of a VGS in an indoor environment. The study was conducted in a fully renovated administrative building in the Grand Duchy of Luxembourg, with the materials used for the walls, floors, and furniture being selected based on their low chemical emissions and environmental friendliness. This study, conducted over a period of 46 weeks, began shortly after the completion of the work and the official reopening of the administration to employees and visitors (VGS already present). Concentrations of aldehydes, VOCs, and mold spores were measured according to a predefined sampling schedule. This study was supported by the Luxembourg Ministry of Energy and Spatial Planning through the Climate and Energy fund, and carried out by a consortium including the engineering office Neobuild (https://neobuild.lu), the Luxembourg Ministry of Energy and Spatial Planning (Climate and Energy), the "Sensing of Atmospheres and Monitoring" team at the University of Liège, Sound Ecology (https://www.sound-ecology.com/) and Cita-Verdi (https://www.citaverdi.com/).

2. Material and methods

2.1. BUILDING DESCRIPTION

The building is composed of one basement and four floors (from −1 to +4, ground level = +1), with each floor having different finishing materials. There are two stairwells with the first one connecting floors +1 and +2, located at the main entrance, and the second one being reserved for staff members only, serving each floor.

2.1.1. FINISHING MATERIALS

The building has been restored with an emphasis on well-being and respect for the environment. Materials and furniture have been selected based on their low emission of chemical compounds and their respect for the environment. However, some materials were left unchanged, such as the plaster ceiling. Table 1 describes the materials used on each floor.

The clay walls consist of a mixture of clay, silt, sand, or gravel to which hemp, flax or cellulose may be added. Lime walls are used as an alternative to plaster or cement walls. This traditional material is made from calcium carbonate, to which sand and water are added to make a mortar.

Mineral paints contain mineral binders (silicate or lime). According to AFNOR standard NFT 30,808 specific to facade coatings with mineral components, mineral paints are those with an organic content of less than 5 % [33].

The used carpet is a special carpet from Desso Air master® [34], which according to Desso Air Master® uses a technology to capture a maximum amount of dust and volatile compounds to prevent the captured particles from becoming re-suspended in the air in the room. The design is such that the dust can be easily released during cleaning, avoiding accumulation or transferring to the ambient air.

The used oak parquet consists of a semi-massive parquet from the Tarkett® brand. Solid parquet, unlike laminate parquet, is made up of layers of wood, a wear layer of noble wood and a load-bearing layer (there is sometimes a third layer). Tarkett® parquet is varnished and dried by UV. According to the EN 14,342 standard for wooden floors and parquet, it is classified as E1 meaning that it emits less than 0.124 mg/ m³ of formaldehyde, i.e. 8 mg/100 g of material [35].

The plasterboard used in the ceilings is made out of a Gyplat™ board from Gyproc® [36].

2.1.2. VENTILATION AND HEATING

Only the first and second floors have no mechanical ventilation, whereas the other floors have double flow ventilation with a flow rate of 380 m³/h. The stairwell for employees has a higher flow rate of 450 m³/ h. This system is controlled by a ComfoAir Q600 air-handling unit, in which the air is drawn in, filtered and conditioned (heating, cooling or humidification), and then supplied to the stairwell.

Heating is provided by traditional radiators with thermostatic valves on the second and fourth floors and via the walls on the third. The used wall heating system follows the same principle as underfloor heating. Additionally, each office has its own thermostat.

2.2. VERTICAL GREENERY SYSTEM - VGS

The VGS is a passive system using natural air convection. It consists of a substrate, in which the plants are rooted. An irrigation system to meet the plants' water requirements is integrated within the system, alongside a specific substrate, consisting of sphagnum moss (*Sphagnum*), contained in galvanized steel baskets (modular system), fixed to the wall and covered with a tarpaulin (Fig. 1).

Additionally, a mixture of so-called depolluting and ornamental plants make up the VGS (10 species in total: 80 % depolluting -*Nephrolepis exaltata, Chlorophytum comosum, Dracaena fragrans, Hedera helix, Aglaeonema commutatum, Chamaedora elegans, Epipremnum wallisii, Spatiphyllum wallisii*- and 20 % ornamental -*Begonia rex, Tradescantia zebrina*-). In total, 5 VGS have been placed in the building, spread over the three upper floors. On the second and third floors, the VGS are in a corridor (VGS +2: 8m² with 220 plants -twenty-two units of each species-; VGS +3: 6.3m² with one hundred plants -eight units of each depolluting species and ten for the ornamental species-). The fourth floor is an open-plan space containing 3 VGS (5m² with one hundred plants -like VGS +3-; 2 VGS of 2.8m² with sixty plants -six units of each species-). The drip irrigation is automatized and scheduled as follows:

- Monday at 5pm for 3 h continuously for the VGS on the fourth floor only.
- Tuesday at 5pm for 3 h continuously for the VGS on the 2nd and 3rd floors.
- Fridays at 5pm for one hour continuously for the VGS on the 3rd and 4th floors.

2.3. SAMPLING LOCALIZATION

VGS 1 is located in a large corridor (+2), opposite to the wooden stairs leading to the ground floor (+1). Samples representative of VGS 1, called M1, were taken next to VGS 1. Sample representing similar conditions without VGS, corresponding to reference air, were taken at the bottom of the staircase and will be referred to as *B1* within this study (Fig. 2.a and b).

VGS 2 is located in a small corridor (+3), en-closed by two doors. This corridor is the only way to reach the offices on this floor and the floor above, besides being a waiting room for the public. Samples representative of VGS 2, called M2, were taken at VGS 2. Samples representing similar conditions without VGS, corresponding to reference air, were taken in an unoccupied storeroom containing file archives and are called B2 (Fig. 2.c and d). The corridor and the storeroom are separated by approximately 3 m.

VGS 3, 4 and 5 are located in the open space (+4), which is isolated from the +3 floor by glass walls and a glass door. VGS 3 and 4 are on the right-hand side of the open space, near the meeting room, which is isolated from the open-space area. VGS 5 is located opposite the other VGS. Samples representative of VGS 3 to 5, called M3, were taken in the middle of the open space. In contrast, samples representing similar conditions without VGS, corresponding to reference air, were taken in the meeting room and are called B3 (Fig. 2.e and f).

In each case, the B locations were selected as the most practical reference sites without VGS on the same floor, given the functional and access constraints of an occupied public building. However, they do not constitute a perfect control/reference: as shown in Table 1, finishing materials and room layouts differ between some M-B pairs, and ventilation conditions range from shared stairwell volumes (M1/B1) to closed corridors and separate rooms (M2/B2, M3/B3). These differences are potential confounding factors and are taken into account in the interpretation of the results.

Samples were also taken outside the building, at the level of the second-floor balcony to avoid traffic pollution and are catalogued as Out.

Table 2 lists the various sampling locations and provides information on room dimensions, ventilation rates, and occupancy rates.

2.4. SAMPLING AND ANALYSIS

During sampling, as well as 12 h prior to sampling, windows are closed, and mechanical ventilation is 380 m^3/h for the floors with ventilation.

VOCs were sampled on adsorbent cartridges composed of Tenax® (200 mg Tenax TA 60/80). The sampling was made with a Sensidyne® Gilair plus pump at a flow rate of 200mL/min for 30 min. Restitution of the compounds is conducted in laboratory by thermal desorption (TD100-xr, Markes®) and the compounds are analyzed using gas chromatography coupled to mass spectrometry (Thermo Electron Trace GC ultra with a Trace DSQ II mass spectrometer (Thermo Fisher Scientific®), equipped with a Rxi-624Sil MS (Restek®) column). The cartridges are analyzed according to the parameters presented in Table 3. As the instrument was used for several projects, a change in the sensitivity of the photomultiplier was required for another project between calibration and sample analysis. Consequently, quantitative analysis could not be carried out. Therefore, only a qualitative identification and a comparison of the absolute peak areas of VOC families were made. The absolute peak areas are reported as relative abundance indicators rather than as absolute concentrations.

The chromatograms obtained are analyzed through the following methodology: *i*. for each chromatogram, only peaks with a relative area greater than 1 % are retained (Tables S1 summarize the percentage of peak area not taken into account in the analyses); *ii*. identification of compounds using the NIST database (applied to the mass spectrum); *iii*. grouping of compounds by chemical family for each location across all weeks (dataset comprising of family, absolute area, and localization); *iv*. division of the dataset (B1/M1, B2/M2, B3/M3 and Out); *v*. removal of families with fewer than ten compounds per pair (6 for Out).

Sampling on DNPH cartridges, specifically for aldehyde analysis, was executed by our team, whilst the analyses were conducted by an external laboratory (AnBUS Analytik GmbH - Fürth - Germany 90,762) in accordance with the ISO16000–3 standard of 2022. The aldehydes were specifically sampled on 2,4-dinitrophenylhydrazine (DNPH) using a BIVOC 2 pump (from Umweltanalytik Holbach GmbH), with a flow rate of 1.22L/min for 41 min. Fifteen aldehydes were analyzed: formaldehyde, acetaldehyde, propanal, butanal, pentanal, hexanal, octanal, nonanal, decanal, 3-methylbutanal, 2-ethylhexanal, benzaldehyde, acetone, and butanone.

The molds were sampled from the air using a Petri dish impactor (Holbach® MBASS 100) at a rate of 100L/min for 1 min. The samples were taken on two different culture media in Petri dishes, malted agar (detection of a large spectrum of molds [37]) and DG18 (Dichloramphenicol - xerophilic mold detection [37]). The sample media were then incubated at 25 °C and 43 % of relative humidity for 7 days, before the total number of colonies was counted. The results are based on the agar with the highest growth of the species or genus in question (number of colonies) [37]. The sampling of molds, as well as the counting and identification of species was carried out jointly by Laboratoires Réunis Luxembourg S.A. and R. Baden, an expert in indoor air quality and health working for the Luxembourg Ministry of Energy and Spatial Planning.

Temperature (°C) and relative humidity (%) were measured continuously.

2.5. SAMPLING SCHEDULE

The campaign was conducted over 46 weeks between [Marsh/2022 - January/2023] (covering spring, summer, autumn and midwinter and the sampling was conducted on a regular basis (during the week, not at the weekend). However, climatic conditions (for outdoor sampling) and instrument problems affected the previously established schedule. Table 4 summarizes the realized schedule for VOCs, aldehydes, and molds sampling (determination and/or counting). Active sampling was carried out on one morning during the weeks indicated in Table 4. Samples close to walls and their equivalents without green walls were taken simultaneously (e.g., B1 at the same time as M1). Mold sampling was also carried out in the morning during the weeks indicated in Table 4, but on successive days.)

3. Results

3.1. ALDEHYDES WITH DNPH CARTRIDGES

On the fifteen aldehydes analyzed by the laboratory, only formaldehyde showed differences between the localization VGS (M2 and M3) and reference (B2 and B3) (Table 5). The expanded uncertainty is 25 % for values below 7 µg/m³ and 10 % for values above 14 µg/m³. These uncertainties are provided by the accredited external laboratory, based on their internal validation protocol and ISO 160,00-3 requirements.

The results of the Wilcoxon test show a significant difference between M2 and M3 compared with B2 and B3 respectively ($p < 0.05$). M2 has values between 9±0.93 and 13±0.79 µg/m³ compared to B2 which has values between 13±0.79 and 19±0.95 µg/m³. M3 had values between 8 ± 0.92 and 13±0.79 µg/m³ compared with B3, which had values between 11±0.91 and 20±1 µg/m³. The differences between the M-B medians are 4 ± 0.5 µg/m³ for M2 and 6 ± 0.92 µg/m³ for *M3*.

Based on the HPLC results for total aldehydes, decreases ranging from 5 to 30 % were observed for M1, and only during weeks 28, 37, 45, and 47. For M2 and M3, reductions in concentrations ranged from 9 to 58 % and 10 to 48 %, respectively, and these decreases were observed for all measurement weeks. In most cases, the sum of ketone concentrations shows a similar behavior to the sum of aldehyde concentrations (Table S2).

3.2. MOLDS IN THE AIR

Before sampling, the doors and windows were closed, and the ventilation was working. Occupants are only allowed to reopen the windows after all the day's measurements have been completed.

Table 6 presents the spores' concentrations in the air, and several observations can be made:

- The number of spores was higher outside (Out) in summer (W35- August-) than during any other time.
- The mold concentration in B1 was higher than that measured outside only for the W12 (March) and W17 (April) measurements (B1/out ratios of 13.10 and 1.47 respectively). The ratios for M1 follow the same trend as those for B1 in relation to outdoor measurements, except for W22 (June), which had a ratio of 2.4 (M1/out ratios of 11.50, 2.08 and 2.40 for W12, W17 and W22 respectively). During W17, W22 and W35, the mold concentration in M1 was higher than B1, with M1/B1 ratios of 1.42, 2.56 and 1.47 respectively.
- The values measured in B2 were always lower than the measurements in M2 and do not appear to be influenced by outdoor concentrations. The M2 values were the highest measurements observed during the campaign. The ratio M2/out was inferior at 1 only for W35.
- With regard to location three, the ratio of B3 and M3 to the outside was similar to that of B2 and M2 to the outside, except for M3 in W22 (0.55 and 2.67 for M3/Out and M2/Out respectively). M3 showed higher values than B3, with M/B ratios ranging from 1.85 to 4.78, while this ratio varied between 8.06 to 13 for M2 and B2.

The genus and species of airborne mold spores were determined during weeks 12, 22 and 5 (2023). Table 7 shows the species and the associated number of colonies.

The dominant mold in the various measurements during W12 was *Penicillium monoverticillate*. The highest spore load of this mold was found at M2 (2290 CFU/m³). It was also present at the administration's other sampling points, but at much lower levels than those observed in M2. However, the values obtained in B1 (900 CFU/m³), M1 (950 CFU/ m³) and M3 (830 CFU/m³) were not negligible. The outside air was free of *Penicillium monoverticillate* and *Aspergillus*.

W22 showed an important level of *Penicillium* (all) in the indoor environment (140 to 1620 CFU/m³) compared with the outdoor environment (150 CFU/m³). Conversely, *Cladosporium* was much more present in the outdoor environment (670 CFU/m³) than in the indoor environment (20 to 260 CFU/m³). Compared with these two species, the other species found were negligible.

Like W12 and W22, the indoor environment was dominated by *Penicillium* in W5 (2023), particularly for M2 (1420 CFU/m³). *Aspergillus* was the dominant mold in the outdoor environment (330 CFU/m³).

3.3. VOCS WITH TENAX®CARTRIDGES

Over the campaign, 110 compounds were identified in all zones after removing peaks below 1 % and known interferents (e.g., siloxane-type compounds from the chromatographic column). Table S1 shows the percentage of peak areas not analyzed (< 1 %). Twenty-five different families or combinations of families were determined. After filtering using the method described in Section 2.4, a Mann-Whitney statistical analysis was applied to each remaining family for each location (applied between the absolute areas of the chromatograms). The distribution of areas by family retained after cleaning the dataset containing all samples is shown in Fig. 3. Table S3 shows the compounds identified with 80 % or more certainty.

The range of the concentration outdoor VOC is lower than the indoor concentration (Fig. 3). Within each pair (B and M), only the statistical tests performed for the aromatic and ketone families at location No. 2 (B2 and M2) have a p-value lower than 0.05 in favor of VGS (Fig. 3.b).

Based on Fig. 3, we can see that the alcohol family is more significant at location No. 1 (M1 and B1). We also see that the aromatic-furan, ether, and terpene categories have the highest values in terms of absolute area distribution. Outside of the aromatic-furan category, these observations also apply to location 2. Location 3 has smaller absolute areas for the ether family in 3 than for locations 1 and 2. However, location 3 has organic acid values well above those of locations 1 and 2. In terms of the families present in the outdoor air, it can be seen that compounds belonging to the ether and organic acid families have not been identified.

4. Discussion

These findings must be interpreted in the context of the building's actual configuration. M1 and B1 both sample the large stairwell and therefore capture essentially the same air volume, whereas M2 and M3 are located in more confined or more voluminous rooms with different ventilation strategies. In practice, the contrasts between M and B thus result from a combination of VGS presence, room size, spatial connectivity and ventilation, which is an inherent limitation when working in occupied buildings. In addition, the reference spaces do not strictly mirror the VGS zones in terms of materials and use (e.g. storeroom vs. corridor, meeting room vs. open-plan office), so the observed M-B differences should be regarded as indicative trends for these specific configurations rather than as strict causal estimates of the isolated effect of VGS. Similarly, on the mechanically ventilated floors, the supply-air filters primarily limit the ingress of outdoor particles, but our measurements do not allow us to disentangle their specific contribution from that of overall ventilation rates and indoor source strengths, so the influence of the HVAC system on the observed pollutant patterns can only be discussed qualitatively.

4.1. CHEMICAL OUTCOMES: FORMALDEHYDE AND VOCS

The formaldehyde concentrations measured in all samples were below the limit recommended by the World Health Organization, which is 100 µg/m³ for an average exposure of 30 min [3] but the majority of the values are above 10 µg/m³, the value recommend by ANSES [38]. A difference was observed between zones M and B, more specifically on floors +3 and +4. As expected, no marked difference was observed between M1 and B1, because these two locations share the same large stairwell air volume and are directly connected, so they essentially sample a single well-mixed space. In contrast, M2/B2 and M3/B3 correspond to more segregated rooms, where the VGS zones are partly decoupled from their references, which facilitates the emergence of measurable differences in formaldehyde. As a result, in this study, the presence of vertical greening systems (VGS) helped reduce formaldehyde concentrations in the air, as well as the summed concentrations of aldehydes and ketones. These results are similar to most of those found in the literature, which state that the presence of plants reduces formaldehyde concentrations in the air [18,26–28,39]. According to the literature [40], this reduction could be explained by the enzymatic activity within the plant that breaks down formaldehyde after absorption. This phenomenon occurs in both the root system and the aerial parts of the plant. However, not all studies point in this direction. Depending on the experimental conditions, the results may vary, as was notably the case for the ADEME study conducted under real-life conditions [24]. The latter showed that formaldehyde concentrations did not decrease over time in the presence of plants. The experiment involved studying twelve potted plants of the same variety (Scindapsus aureus) in a room in which a source of formaldehyde was introduced. However, these real-life conditions are quite different from our case study. The study conducted within the administration aimed to measure the impact of VGS on indoor air. In addition, these VGSs are composed of 80 % of plants known to be pollution-reducing (between 60 and 220 plants per VGS), and their design means that the substrate is in contact with the ambient air due to the convection mechanism of air currents.

As a result, the reduction in formaldehyde concentrations observed within the administration can be explained by the activity of the plant and/or the activity of microorganisms present in the sphagnum moss but could also be due to the high solubility of formaldehyde in water. This latter hypothesis is based on the affinity of formaldehyde for water. Due to its small size and polarity, formaldehyde can be easily dissolved in the aqueous phase present in sphagnum moss after watering. In addition, the temporal evolution shown in Table 4 is influenced by indoor temperature and relative humidity, which modulates emission rates. In our campaign, higher concentrations were generally observed during warmer periods, when elevated temperatures and humidity favor emissions and reduce sorption, whereas lower levels were measured during cooler months.

Several chemical families have been identified (Table S3), and the VOCs listed therein are known from the literature to originate from finishing materials, furniture, cleaning products, as well as from occupants through exhalation, skin, and other biological emissions [9]. Some VOCs along originate from fungal activity (microbial VOC) [6,41].

The presence of high levels of alcohol compounds like isopropyl alcohol, and especially in the entrance, could be explained by the fact that in 2022, people were required to disinfect their hands using hydroalcoholic gels provided at various locations throughout the administration building. The main ingredients of hydroalcoholic gels are alcohol compounds (ethanol, propane-1-ol, propane-2-ol) [42]), water, an emollient (often glycerin) and a thickening agent. Alcoholic compounds are also present in cleaning products.

Some of the VOCs identified within the administration are harmful to health. These include ethylbenzene, xylene and/or furfural (overlapping peaks during chromatogram analysis preventing correct identification).

In each sample B1–3 and M1–3, ethylbenzene and xylene were present. They are used in the manufacture of paints, varnishes, inks, adhesives, fuels and cleaning products [43]. Ethylbenzene is considered by the International Agency for Research on Cancer (IARC) [44] to be potentially carcinogenic to humans (group 2B) [45] and xylene belong to group 3 (not classified as carcinogenic to humans [43,46]). Furfural was also identified. It is used in the manufacture of resins, solvents and plastics [46]. These compounds are known as potentially harmful to health, but this study does not allow us to pronounce their dangerousness.

The distributions observed for aldehydes sampled on Tenax cartridges are consistent with the HPLC results for total aldehydes, showing a decrease in zones M2 and M3, with the exception of M1, which shares its air volume with B1.

The results showed that only aromatic compounds and ketones exhibited significant differences in concentration in favor of space M2 (lower concentration). Among the plant species incorporated into the walls, some of them have already been studied for their ability to reduce certain VOCs aromatics. These include *Aglaeonema commutatum* [30], *Chlorophytum comosum* [30,47–49], *Hedera helix* [48,50,51], *Spatiphyllum wallisii* [13,50,52] and *Nephrolepis exaltata* [29].

In the case of M2, the difference can be explained by the fact that the ratio between the surface area of the VGS and the volume of air in the room (closed corridor), as well as the healthy growth of the plants, increase the effectiveness of the plants' air purification effect in terms of aromatic compounds. Regarding ketone concentrations, the effect of the plants cannot be proven. This is because the corridor is a passageway (no human emissions), with minimal furniture (two chairs) and a significantly reduced surface area of finishing materials due to the large wall surface area (6.3 m^2 with one hundred plants). As a result, the sources of ketone emissions are relatively low compared to the sampling locations.

During the campaign, VOC were also collected passively sampling using Radiello® (exposure for 15 days, four times during the period). Differences were observed between the number of compounds per family, and, in some cases, the trends were reversed compared to those observed during spot sampling with Tenax® (e.g., reversed aromatic ratio B2/M2). However, we decided not to present the Radiello® results because there were unknowns in the interpretation of the results: occupant activities (cleaning-cleaning technique, placement of products or buckets-personal perfumes, coffee) can influence the concentrations adsorbed by Radiello®.

It is important to remember that the TD-GC–MS configuration used here was designed for qualitative and semi-quantitative family-level analysis, and no full multi-compound calibration curve was available. As a result, the VOC data presented in Fig. 3 should be interpreted as relative abundance indicators rather than absolute concentrations, and they are not suiTable for direct comparison with guideline values or health-based thresholds.

4.2. BIOLOGICAL OUTCOMES: MOLDS AND HUMIDITY

An increase in outdoor values is observed from week 12 to week 35. The high concentration outdoors during W35 can be explained by climatic conditions (elevated temperature and humidity, optimal dispersion conditions) and the high availability of organic matter.

The median ratio of M1/B1 spore concentrations is 1.42, with a maximal ratio for W22 (2.56) and a minimal ratio for W12 (0.88). This low ratio can be explained by the fact that B1 and M1 share the same air volume due to a large open stairwell. In cases where the ratio is greater than 1, this could be explained by the opening of the main entrance, resulting in a slight air exchange.

In October 2022, 100 new plants were replanted following the death of a large number of them over time. This degradation of the VGS over time (before planting) could also explain the development of mold following greater availability of organic matter and the high values of CFU/m³ in W22 and W35.

The measurements taken in W5 (2023), after replanting, are significantly lower than previous measurements and the values are close to the outdoor one.

Plant growth was more significant for VGS 2 than for the other VGS. The temperature (median close to 20 °C), relative humidity (median of 57 %) and availability of organic matter were conducive to the growth of mold on the VGS substrate (sphagnum moss has a high-water retention rate after watering). High concentrations were observed near VGS 2 (median ratio M2/B2 is 9.94, with minimal value of 8.06 and a maximum value of 11.25), these values can be explained by the VGS 2 location. It is in a corridor closed off by two doors with no ventilation (ventilation was supposed to be provided by the office adjacent to the corridor (reception), but due to COVID, plexiglass panels were installed to reduce air flow - Fig. 2.c).

The top floor, where 3 VGS units are located, sampled M3, has a greater air volume than the floor where the VGS unit sampled M2 is located. The median ratio of M3/B3 spore concentrations is 3.57, with minimal value of 1.85 and a maximum value of 4.78. These values are lower than M2 value, higher than the M1 values. Functional ventilation without obstruction could explain the differences observed between M2 and M3. However, ventilation was not sufficient to reduce concentrations below the threshold of 500 CFU/m³ (WHO recommendation [53]).

There is no universal threshold for CFU/m³ concentration in the air, with each country defining its own limits [24,25]. However, in their literature review, Rocchi and al. conclude that the thresholds considered risky or accepTable vary between 500 CFU/m³ and 10,000 CFU/m³ (total fungal flora) according to the countries, the organizations, and the groups of experts, without there being any differentiation between the species [25]. It is widely accepted that the presence of certain molds has an impact on health. As example, the 4 genera *Aspergillus, Alternaria, Penicillium* and *Cladosporium* exacerbate asthma [25], while other species are considered toxic (e.g. *Stachybotrys chartarum*) [53]. Which is why a threshold value is sometimes set for just one species.

Among all the species recorded, none of them were toxic or pathogenic. However, a rare species was present at M3 (W5 (2023)) with the species *Acromonium*, the concentrations measured (20 CFU/m³) were lower than the regulatory limit specified in Portaria n.° 353-A/2013, de 4 de dezembro (50 CFU/m³) [54]. The presence of *Penicillium* is due to the presence of VGS. Some of the concentrations encountered are well above 1000 CFU/m³ [37], which could lead to health problems for vulnerable occupants or irritation of the eyes or respiratory tract following chronic exposure.

Our monitoring covered a period during which the VGS were functional but still evolving, with episodes of plant mortality and subsequent replanting. Although this reflects realistic operating conditions in a recently installed system, it also means that the vegetation, substrate microflora and maintenance practices were not yet stabilized over time, which may have influenced both emission dynamics and occupant exposure. For this reason, the present results should not be overinterpreted as representative of a fully mature and stably maintained VGS, and longer-term follow-up studies would be needed to confirm whether IAQ and bioaerosol levels converge towards more sTable patterns in the longer run.

Overall, these results show that indoor VGS can only be considered safe with respect to fungal growth when adequate ventilation and moisture control are ensured. In our case-study building, the highest spore loads were systematically observed near VGS installed in confined corridors with obstructed air renewal and high water-retention in the substrate (M2), whereas more voluminous and properly ventilated spaces (M3) exhibited lower, although still elevated, concentrations. This underlines that safe implementation of VGS in real buildings requires particular attention to the choice of location, ventilation strategy and irrigation/maintenance practices in order to limit mold-related risks.

5. Conclusions

This study highlighted several methodological challenges related to measuring indoor air quality in an environment characterized by constant human activity and specific sampling constraints (employee movement, difficulty establishing a reference location due to the diversity of spaces and building materials, etc.). For these reasons, the results should be interpreted with caution. Moreover, they are only applicable to vertical greening systems (VGS) using a sphagnum substrate.

The presence of VGS appears to effectively reduce formaldehyde concentrations, as lower levels were consistently observed in the equipped zones. While the specific mechanism driving this reduction remains unclear, what ultimately matters under real-life conditions is to consider the VGS as an integrated system rather than isolating its individual components.

The analysis of volatile organic compounds (VOCs) focused on identifying the main chemical families. Decreases in the levels of aromatic compounds and ketones were observed at the +3 floor VGS. These findings should be interpreted cautiously, as spot samples collected using Tenax® cartridges do not allow for evaluation of VOC exposure.

It appears that implementing VGS in indoor environments is not without risks: depending on the maintenance practices, these systems may promote mold growth due to improper watering and the increased presence of organic matter. Rigorous control over maintenance conditions, particularly irrigation, is therefore essential to ensure healthy plant growth while minimizing the risk of fungal development on the substrate.

To strengthen the robustness of future studies investigating the influence of VGS on indoor air quality, several methodological aspects should be carefully considered. First, control sampling sites should be predefined and homogenized as much as possible. Because materials and room configurations often vary widely, mapping ventilation patterns, surface materials, and occupant activities can help identify the most relevant comparison points and suiTable sampling locations.

It is also essential to account for the diversity of occupancy and environmental conditions. Performing measurements during both occupied and unoccupied periods, and across different seasons, provides deeper insight into fluctuations related to building use and operation.

A combined monitoring approach is recommended, integrating both spot and continuous measurement techniques. The use of passive samplers (e.g., Radiello®) alongside active ones (e.g., Tenax®/DNPH) and continuous sensors enhances data completeness and supports a more accurate assessment of actual exposure to VOCs and other pollutants.

Equally important is the integration of ventilation flow analysis. Characterizing air exchange rates, window openings, HVAC operation, and physical barriers (such as doors or partitions) allows for the interpretation of pollutant variations within specific airflow contexts.

Maintaining detailed records of VGS maintenance activities-such as watering, plant replacement, and substrate renewal-is crucial to link potential pollutant peaks or biological growth episodes with identifiable causes.

Documenting exceptional events (including cleaning, furniture relocation, or changes in occupancy) and conducting health or well- being surveys among staff can provide valuable complementary information, helping to connect measured air quality variations with perceived effects within the studied environment.

In practical terms, the findings of this case study suggest that indoor VGS are most appropriate in spaces with clearly defined air volumes and adequate ventilation, where they can contribute to lowering formaldehyde while keeping mold levels under control. Conversely, installing VGS in poorly ventilated or confined corridors with high moisture retention in the substrate should be avoided, as such configurations strongly favor fungal proliferation. Designers and decision-makers should therefore consider VGS as part of an integrated strategy that simultaneously addresses room size, connectivity between spaces, ventilation strategy and maintenance practices when aiming to improve indoor air quality.

Finally, it would be particularly valuable to supplement these observations with laboratory experiments under controlled conditions. Such studies would enable detailed evaluation of the impact of VGS on pollutant concentrations and mold growth by independently varying several critical parameters: maintenance protocols (watering, cleaning), VGS composition (choice and diversity of plant species), system size (vegetated surface area/room volume), and substrate type (organic vs. inorganic). The objective of these controlled investigations would be to identify optimal scenarios that maximize benefits for indoor air quality while minimizing associated risks and to provide actionable recommendations for the design, maintenance, and integration of VGS in built environments.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in the writing process (grammar correction and improvement of the text for readability). After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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CRediT authorship contribution statement

C. Falzone: Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **J. Martin:** Writing – review & editing. **AC. Romain:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Falzone Claudia reports financial support was provided by Ministry of Energy and Spatial Planning with the Climate and Energy of Grand Duchy of Luxembourg. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2026.114318.

Data availability

Data will be made available on request.

Tables

Table 1
Localization of finishing materials.

	Materials	Floors
Walls	Colored clay	+2, +3
	Plasterboard and paint	+4
	Lime and mineral paint	Corridors
Ground	Carpet	Offices +2 & +3, corridors +3, +4
	Oak flooring	Corridor +2, meeting rooms +1
Ceiling	Historic plaster ceiling + painting	+2
	Suspended acoustic plasterboard ceilings + painting	+3, +4

Table 2
Summaries of the sampling localization.

	VGS (m^2)	Area (m^2)	Ceiling height (m)	Volume (m^3)	Ventilation Rate (m^3/h)	Average Occupancy
B1 *	-	59.21	± 4.34	≅ 257	Natural	Unknown, Waiting room
M1 *	8	19.07	3.95	≅ 75.3	Natural	0p, Corridor
B2	-	18.17	2.55	46.3	20	0p, Archives
M2	6.3	11.31	2.55	28.8	Natural	0p, Corridor
B3	-	31.47	Sloped ceiling	-	38	Max 14p, Meeting room
M3	5, 2 × 2.8	84.84	Sloped ceiling	-	38	5p, Office

* With Staircase.

Table 3
TD-GC–MS programming for Tenax® cartridges.

Thermal desorption		Oven		
General		*Ramps*		
Split on	10		Initial	Ramps 1
Flow path temp. (°C)	150 °C	Rate		5 °C/min
GC cycle time	50 min	Temp	50 °C	250 °C
		Hold Time	5 min	5 min
Minimum carrier press.	5 psi	*Acquisition Time*		
Pre-desorption		Oven Run-Time	40 min	
Pre-purge	1 min	*Oven*		
Split on (split flow)	20 ml/min	Max Temperature	300 °C	
Tube desorption		Prep Run Time Out	999 min	
Desorb time 1	15 min	Equilibration Time	0.5 min	
Desorb temp. 1	280 °C			
Trap in line (trap flow)	2 ml/min	Mass spectrometer		
Split on (split flow)	10 ml/min	Scan mode	Full scan	
Trap settings		Mass range	33–300	
Trap purge time	1 min			
Trap purge flow	20 ml/min			
Trap low temp.	−10 °C			
Trap heating rate	MAX °C/s			
Trap high temp.	300 °C			
Trap desorp. Time	2 min			

Table 4
Sampling schedule.

Weeks (month)	M/B 1	M/B 2	M/B 3	Out	Weeks (month)	M/B 1	M/B 2	M/B 3	Out
12 (03.2022)	Mdc	T,D,Mdc	Mdc	Mdc	28 (07)	T,D	T,D	T,D	T
14 (04)	T,D	-	T,D	T	33 (08)	T	T	T	T
16 (04)	T,D	T,D	T,D	T	35 (08)	D,Mdc	D,Mdc	D,Mdc	Mdc
17 (04)	Mc	Mc	Mc	Mc	37 (09)	D	D	D	-
20 (05)	T,D	T,D	T,D	T	41 (10)	T,D	T,D	T,D	T
22 (06)	Mdc	Mdc	Mdc	Mdc	45 (11)	T,D	T,D	T,D	T
24 (06)	T,D	T,D	T,D	T	49 (12)	T,D	T,D	T,D	T
26 (06)	T	T	T	T	5 (02.2023)	Mdc	Mdc	Mdc	Mdc

T: Tenax ®; D: DNPH; M: Mold D-determination- and c-counting-.

Table 5
Campaign formaldehyde concentration (μg/m³).

Weeks	B1	M1	B2	M2	B3	M3
12	-	-	12	10	-	-
14	14	14	-	-	13	10
16	11	12	14	9	18	9
20	13	15	19	10	18	10
24	14	11	15	9	15	8
28	12	12	18	13	20	13
35	8	9	17	12	16	9
37	11	11	14	10	15	11
41	11	9	14	10	16	9
45	11	11	14	10	14	9
49	7	8	13	10	11	10
Mean	*11.2*	*11.2*	*15*	*10.3*	*15.6*	*9.8*
Sd	*2.3*	*2.2*	*2.3*	*1.3*	*2.6*	*1.4*
Median	*11*	*11*	*14*	*10*	*15.5*	*9.5*

Table 6
Spores' concentrations in the air (CFU/m³) and the medians of the temperature and the relative humidity during the campaign (week 28 to week 49). *W*=week; *R*= ratio in/out.

	W12	*R*	W17	*R*	W22	*R*	W35	*R*	W5[1]	*R*	Temp. (°C)[2]	RH (%)[2]
Out	100		360		670		2070		460		14.9	70.8
B1	1310	13.1	530	1.47	630	0.94	1000	0.48	350	0.76	22	49.4
M1	1150	11.5	750	2.08	1610	2.40	1470	0.71	360	0.78	22.2	49
B2	240	2.4	100	0.28	180	0.27	120	0.06	180	0.39	22.3	45.7
M2	2340	23.4	1300	3.61	1790	2.67	1350	0.65	1450	3.15	21.5	57.2
B3	180	1.8	140	0.39	200	0.30	320	0.15	150	0.33	23.4	40.4
M3	860	8.6	500	1.39	370	0.55	990	0.48	710	1.54	23.9	46.6

[1] Year 2023

[2] T/RH measurements are shifted in time due to a delay in the delivery and installation of the monitoring devices

Table 7
Identification of the genus and associated species and counting of the varied species (CFU/m^3).

	Genus and species	Out	B1	M1	B2	M2	B3	M3
W12	*Penicillium monoverticillate*	-	900	950	100	2290	150	830
	Aspergillus spp.	-	-	100	50	10	-	10
	Aspergillus sydowii	-	410	100	-	20	20	10
	Cladosporium spp.	60	-	-	-	20	10	-
	Hyphomycetes spp.	20	-	-	50	-	-	-
	Penicillium terverticillate	10	-	-	30	-	-	-
	Penicillium biverticillate	-	-	-	10	-	-	10
	Geotrichum spp.	10	-	-	-	-	-	-
W22	*Penicillium monoverticillate*	-	130	1250	50	1240	20	170
	Penicillium terverticillate	150	90	-	30	380	100	-
	Wallemia sebi	-	-	120	-	-	-	-
	Cladosporium spp.	670	260	200	20	130	60	130
	Penicillium bi-terverticillate	-	110	-	50	-	-	-
	Mucor spp.	10	-	-	-	-	-	-
	Eurotium spp.	10	-	-	-	-	-	-
	Hyphomycetes spp.	10	-	-	-	30	-	-
	Aspergillus sydowii	-	20	-	-	-	-	-
	Candida spp.	-	10	-	10	-	10	-
	Botrytis spp.	-	10	30		-	-	-
	Penicillium biverticillate	-	-	10	10	10	-	-
	Fusarium spp.	-	-	-	10	-	10	-
W5 (2023)	*Penicillium monoverticillate*	-	280	290	120	1340	100	690
	Penicillium bi-terverticillate	-	-	20	-	50	-	-
	Cladosporium spp.	-	10	-	-	10	-	-
	Mucor spp.	-	-	-	10	-	-	-
	Eurotium spp.	-	-	-	-	-	-	-
	Paecilomyces spp.	-	30	40	-	20	-	-
	Acremonium	-	-	-	-	-	-	20
	Aureobasidium spp.	-	-	-	-	-	20	-
	Hyphomycetes spp.	60	-	-	40	-	10	-
	Candida spp.	10	-	-	-	-	-	-
	Botrytis spp.	20	-	10	-	-	-	-
	Wallemia sebi	20	-	-	-	-	-	-
	Penicillium biverticillate	20	-	-	10	30	10	-
	Geotrichum spp.	-	20	-	-	-	-	-
	Aspergillus spp.	320	10	-	-	-	10	-
	Aspergillus glaucus	10	-	-	-	-	-	-

Figures

***Fig. 1**. a. Schematic view of the VGC used in the administration; b. one of VGS present on +3 floor without plants (picture made during the renovation).*

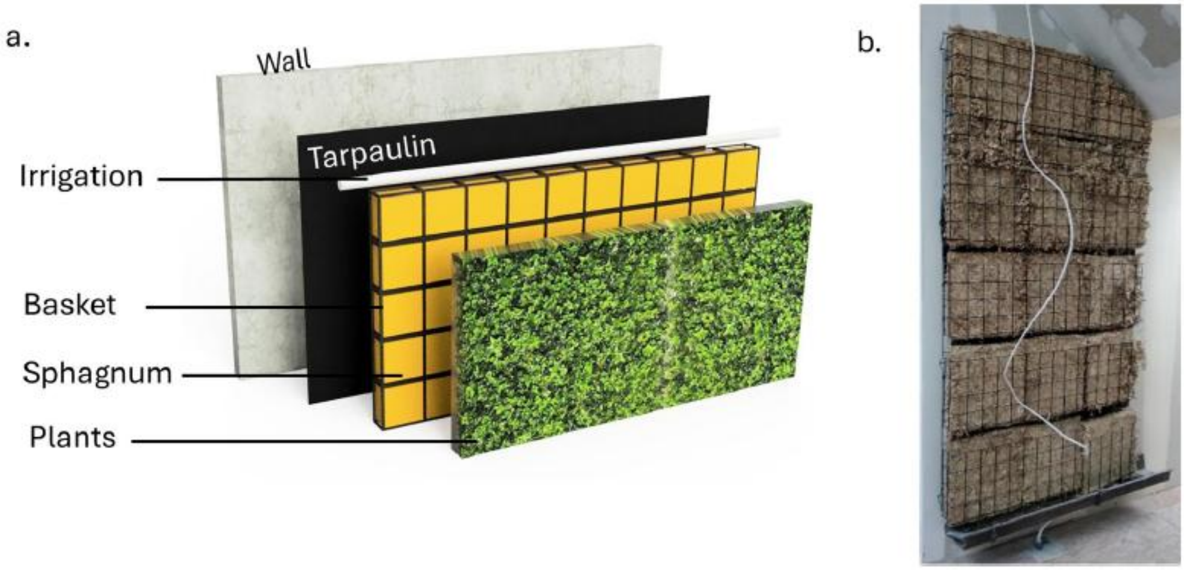
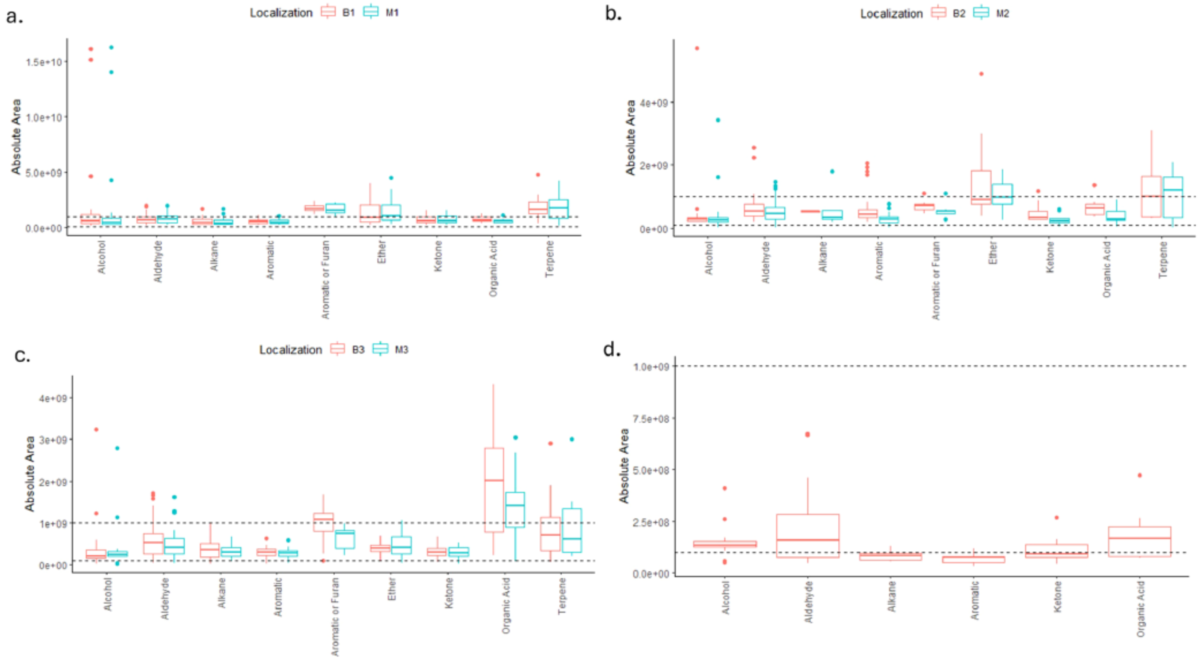


***Fig. 2.** a. Sampling next to VGS 1 called M1; b. Sampling at the bottom of the stairs called B1; c. Sampling next to VGS 2 (doors closed) called M2; d. Sampling in the storeroom called B2; e. Sampling between VGS 3 and VGS 5 called M3; f. Sampling in the meeting room called B3. Red stars: location of spot samples taken using Tenax®, DNPH, and MBASS cartridges.*

Fig. 3. *Distribution of areas by family retained after cleaning the dataset containing all samples. Dotted lines represent a comparison range area from* 10^8 *to* 10^9 *of absolute area (Tenax®).*



References

[1] *N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (2001) 231–252, https://doi.org/10.1038/sj.jea.7500165.*

[2] *J.A. Bernstein, N. Alexis, H. Bacchus, I.L. Bernstein, P. Fritz, E. Horner, N. Li, S. Mason, A. Nel, J. Oullette, K. Reijula, T. Reponen, J. Seltzer, A. Smith, S. M. Tarlo, The health effects of nonindustrial indoor air pollution, J. Allergy Clinic. Immunol. 121 (2008) 585–591, https://doi.org/10.1016/j.jaci.2007.10.045.*

[3] *G. Adamkiewicz, World Health Organization, WHO guidelines for indoor air quality: selected pollutants, World Health Organization, Regional Office for Europe, Copenhagen, Denmark, 2010.*

[4] *A. Mendes, J.P. Teixeira, Sick building syndrome, in: encyclopedia of toxicology, Elsevier, 2014, pp. 256–260, https://doi.org/10.1016/B978-0-12-386454-3.00432-2.*

[5] *J. Douwes, W. Eduard, P.S. Thorne, Bioaerosols. International encyclopedia of public health, Elsevier, 2017, pp. 210–218, https://doi.org/10.1016/B978-0-12-803678-5.00032-1.*

[6] *J. Ruiz-Jimenez, I. Heiskanen, V. Tanskanen, K. Hartonen, M.-L. Riekkola, Analysis of indoor air emissions: from building materials to biogenic and anthropogenic activities, J. Chromatograph. Open 2 (2022) 100041, https://doi.org/10.1016/j.jcoa.2022.100041.*

[7] *G. Karr, M. Nicolas, F. Maupetit, M. Ramel, Cleaning product emissions and indoor built environments: exposure and health risk assessments from experiments under realistic indoor conditions, Build. Environ. 206 (2021) 108384, https://doi.org/ 10.1016/j.buildenv.2021.108384.*

[8] *P.-G. Kim, A. Lee, J. Shin, E. Song, Y. Koo, S. Sochichiu, D.F.M.S. Mohamed, S. Choi, Y. Hong, J.-H. Kwon, Increase of the indoor concentration of volatile organic compounds after the use of incense and scented candle in studio apartments determined using passive sampling, Chemosphere 359 (2024) 142344, https://doi.org/10.1016/j.chemosphere.2024.142344.*

[9] *M.-H. Yuan, S. Kang, K.-S. Cho, A review of phyto- and microbial-remediation of indoor volatile organic compounds, Chemosphere 359 (2024) 142120, https://doi. org/10.1016/j.chemosphere.2024.142120.*

[10] *K.L. Abdullahi, J.M. Delgado-Saborit, R.M. Harrison, Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: a review, Atmos. Environ. 71 (2013) 260–294, https://doi.org/10.1016/j.atmosenv.2013.01.061.*

[11] *T.K. Abed, M.A. Fayad, A.A. Al-Amiery, H.A. Abdul Wahhab, J.K. Mohammed, H. Sh. Majdi, Radon gas emission from home appliances: understanding sources, implications, and mitigation strategies, Result. Eng. 22 (2024) 102133, https://doi.org/10.1016/j.rineng.2024.102133.*

[12] *N. Autsavapromporn, A. Duangya, P. Klunklin, I. Chitapanarux, C. Kranrod, C. Jaikang, T. Monum, A. Paemanee, S. Tokonami, Serum biomarkers associated with health impacts of high residential radon exposure: a metabolomic pilot study, Sci. Rep. 15 (2025) 5099, https://doi.org/10.1038/s41598-025-89753-z.*

[13] *X. Shen, Q. Sun, G. Mosey, J. Ma, L. Wang, M. Ge, Benchmark of plant-based VOCs control effect for indoor air quality: green wall case in smith campus at Harvard University, Sci. Total Environ. 906 (2024) 166269, https://doi.org/10.1016/j.scitotenv.2023.166269.*

[14] *P. Wargocki, Productivity and health effects of high indoor air quality. Encyclopedia of environmental health, Elsevier, 2011, pp. 688–693, https://doi.org/10.1016/B978-0-444-52272-6.00270-1.*

[15] *Labelling of building and decoration products with respect to VOC emissions, Anses - Agence Nationale de Sécurité Sanitaire de l'alimentation, De L'environnement et Du Travail. (2013). https://www.anses.fr/en/content/labelling-building-and-decoration-products-respect-voc-emissions. accessed July 3, 2025.*

[16] *R.A. González-Lezcano, Editorial: design of efficient and healthy buildings, Front. Built Environ. 9 (2023), https://doi.org/10.3389/fbuil.2023.1210956.*

[17] *X. Ma, M. Du, P. Deng, T. Zhou, B. Hong, Effects of green walls on thermal perception and cognitive performance: an indoor study, Build. Environ. 250 (2024) 111180, https://doi.org/10.1016/j.buildenv.2024.111180.*

[18] *F. Brilli, S. Fares, A. Ghirardo, P. De Visser, V. Calatayud, A. Muñoz, I. Annesi-Maesano, F. Sebastiani, A. Alivernini, V. Varriale, F. Menghini, Plants for sustainable improvement of indoor air quality, Trends Plant Sci. 23 (2018) 507–512, https://doi.org/10.1016/j.tplants.2018.03.004.*

[19] *T. Pettit, P.J. Irga, F.R. Torpy, Towards practical indoor air phytoremediation: a review, Chemosphere 208 (2018) 960–974, https://doi.org/10.1016/j.chemosphere.2018.06.048.*

[20] *A.J. Ghazalli, C. Brack, X. Bai, I. Said, Alterations in use of space, air quality, temperature and humidity by the presence of vertical greenery system in a building corridor, Urban Forestry Urban Greening 32 (2018) 177–184, https://doi.org/10.1016/j.ufug.2018.04.015.*

[21] *B. Raji, M.J. Tenpierik, A. van den Dobbelsteen, The impact of greening systems on building energy performance: a literature review, Renew. Sustain. Energy Rev. 45 (2015) 610–623, https://doi.org/10.1016/j.rser.2015.02.011.*

[22] *C. Du, B. Li, W. Yu, Indoor mould exposure: characteristics, influences and corresponding associations with built environment-A review, J. Build. Eng. 35 (2021) 101983, https://doi.org/10.1016/j.jobe.2020.101983.*

[23] *D. Tudiwer, A. Korjenic, The effect of an indoor living wall system on humidity, mould spores and CO 2 -concentration, Energy Build. 146 (2017) 73–86, https:// doi.org/10.1016/j.enbuild.2017.04.048.*

[24] *C. Damien, H. Benjamin, B. Gaëlle, G. Julien, N. Mélanie, C.-R.M. Amélie, Faculté des sciences pharmaceutiques et biologiques Lille, Universite Lille Ii, Pc2a, Cstb, Epuration Et Biosurveillance Par Les Plantes Des Polluants De L'air Intérieur (PHYTAIR 1, 2, 3) (2012). https://librairie.ademe.fr/air/1198-epuration-et-biosur veillance-par-les-plantes-des-polluants-de-L-air-interieur-phytair-1-2-3.html. accessed June 3, 2025.*

[25] *S. Rocchi, G. Reboux, Indoor fungi threshold levels. Viruses, bacteria and fungi in the built environment, Elsevier, 2022, pp. 231–250, https://doi.org/10.1016/ B978-0-323-85206-7.00003-4.*

[26] *Z. Xu, L. Wang, H. Hou, Formaldehyde removal by potted plant-soil systems, J. Hazard. Mater. (2011) S0304389411006583, https://doi.org/10.1016/j.jhazmat.2011.05.020.*

[27] *A Aydogan, L.D. Montoya, Formaldehyde removal by common indoor plant species and various growing media, Atmos. Environ. 45 (2011) 2675–2682, https://doi.org/10.1016/j.atmosenv.2011.02.062.*

[28] *H. Teiri, H. Pourzamani, Y. Hajizadeh, Phytoremediation of VOCs from indoor air by ornamental potted plants: a pilot study using a palm species under the controlled environment, Chemosphere 197 (2018) 375–381, https://doi.org/ 10.1016/j.chemosphere.2018.01.078.*

[29] *Y.-J. Liu, Y.-J. Mu, Y.-G. Zhu, H. Ding, N. Crystal Arens, Which ornamental plant species effectively remove benzene from indoor air? Atmos. Environ. 41 (2007) 650–654, https://doi.org/10.1016/j.atmosenv.2006.08.001.*

[30] *W. Sriprapat, P. Suksabye, S. Areephak, P. Klantup, A. Waraha, A. Sawattan, P. Thiravetyan, Uptake of toluene and ethylbenzene by plants: removal of volatile indoor air contaminants, Ecotoxicol. Environ. Saf. 102 (2014) 147–151, https://doi.org/10.1016/j.ecoenv.2014.01.032.*

[31] *F. Caron, R. Guichard, L. Robert, M. Verriele, F. Thevenet, Behaviour of individual VOCs in indoor environments: how ventilation affects emission from materials, Atmos. Environ. 243 (2020) 117713, https://doi.org/10.1016/j.atmosenv.2020.117713.*

[32] *S. Matheson, R. Fleck, P.J. Irga, F.R. Torpy, Phytoremediation for the indoor environment: a state-of-the-art review, Rev. Environ. Sci. Biotechnol. 22 (2023) 249–280, https://doi.org/10.1007/s11157-023-09644-5.*

[33] *Peintures et vernis pour le bâtiment - Guide relatif aux produits de peinture et systèmes de revêtement pour façades - revêtements minéraux, revêtements organiques. https://www.boutique.afnor.org/fr-fr/norme/fd-t30808/peintures-et-vernis-pour-le-batiment-guide-relatif-aux-produits-de-peinture/fa187004/57727, 2016 accessed May 22, 2025.*

[34] *DESSO AirMaster Classic: aide à améliorer la qualité de l'air intérieur, n.d. https://professionnels.tarkett.be/fr_BE/collection-C001031-airmaster-classic, 2025. accessed May 22*

[35] *Planchers et parquet en bois - caractéristiques, Évaluation De Conformité et Marquage (2013). https://www.boutique.afnor.org/fr-fr/norme/nf-en-14342/planchers-et-parquet-en-bois-caracteristiques-evaluation-de-conformite-et-m/fa157 302/42028. accessed May 22, 2025.*

[36] *Gyplat®, Gyproc, in: https://pro.gyproc.be/fr/les-produits/gyplat, 2019 accessed May 22, 2025.*

[37] *Comité d'experts: évaluation des risques lié aux milieux aériens, AVIS et RAPPORT de l'Anses relatif aux moisissures dans le bâti. https://www.anses.fr/fr/conten t/avis-et-rapport-de-lanses-relatif-aux-moisissures-dans-le-b/C3/A2ti, 2016 accessed June 4, 2025.*

[38] *Formaldéhyde et effets sur la santé • cancer environnement, Cancer Environnement, 2025 n.d. https://www.cancer-environnement.fr/fiches/expositions-environnementales/formaldehyde/. accessed October 8*

[39] *T. Pettit, P.J. Irga, F.R. Torpy, Towards practical indoor air phytoremediation: a review, Chemosphere 208 (2018) 960–974, https://doi.org/10.1016/j.chemosphere.2018.06.048.*

[40] *M. Giese, U. Bauer-Doranth, C. Langebartels, H. Sandermann Jr, Detoxification of formaldehyde by the spider plant (Chlorophytum comosum L.) and by soybean (Glycine max L.) cell-suspension cultures, Plant Physiol 104 (1994) 1301–1309, https://doi.org/10.1104/pp.104.4.1301.*

[41] *E. Kemmler, M.C. Lemfack, A. Goede, K. Gallo, S.M.T. Toguem, W. Ahmed, I. Millberg, S. Preissner, B. Piechulla, R. Preissner, mVOC 4.0: a database of microbial volatiles, Nucleic Acid. Res. 53 (2025) D1692–D1696, https://doi.org/10.1093/nar/gkae961.*

[42] *Gel hydroalcoolique: composition, fonctionnement, efficacité, ldmédical. https://www.ld-medical.fr/blog/post/51-gel-hydroalcoolique-composition-fonctionnement-efficacite, 2022 accessed July 2, 2025.*

[43] *IARC working group on the evaluation of carcinogenic risks to humans, re- evaluation of some organic chemicals, hydrazine and hydrogen peroxide, World Health Organization, International Agency for Research on Cancer, Lyon, France, 1999. https://publications.iarc.who.int/89.*

[44] *Homepage - IARC, n.d. https://www.iarc.who.int, 2025. accessed July 4*

[45] *International Agency for Research on Cancer, Some industrial chemicals: this publication represents the views and expert opinions of an IARC working group on the evaluation of carcinogenic risks to humans, which met in Lyon, 15 - 22 February 2000, IARC, Lyon, 2001.*

[46] *IARC working group on the evaluation of carcinogenic risks to humans, dry cleaning, some chlorinated solvents, and other industrial chemicals, World Health Organization, International Agency for Research on Cancer, Geneva, 1995. https://publications.iarc.who.int/81.*

[47] *J.J. Cornejo, F.G. Muñoz, C.Y. Ma, A.J. Stewart, Studies on the decontamination of air by plants, Ecotoxicology 8 (1999) 311–320, https://doi.org/10.1023/A:1008937417598.*

[48] *W. Sriprapat, P. Thiravetyan, Efficacy of ornamental plants for benzene removal from contaminated air and water: effect of plant associated bacteria, Int. Biodeterior. Biodegradation 113 (2016) 262–268, https://doi.org/10.1016/j.ibiod.2016.03.001.*

[49] *W. Sriprapat, P. Boraphech, P. Thiravetyan, Factors affecting xylene-contaminated air removal by the ornamental plant Zamioculcas zamiifolia, Environ. Sci. Pollut. Res. 21 (2014) 2603–2610, https://doi.org/10.1007/s11356-013-2175-y.*

[50] *M.Hwa Yoo, Y.J. Kwon, K.-C. Son, S.J. Kays, Efficacy of indoor plants for the removal of single and mixed volatile organic pollutants and physiological effects of the volatiles on the plants, Jashs 131 (2006) 452–458, https://doi.org/10.21273/JASHS.131.4.452.*

[51] *D.S. Yang, S.V. Pennisi, K.-C. Son, S.J. Kays, Screening indoor plants for volatile organic pollutant removal efficiency, Horts 44 (2009) 1377–1381, https://doi.org/ 10.21273/HORTSCI.44.5.1377.*

[52] *I.Parseh, H. Teiri, Y. Hajizadeh, K. Ebrahimpour, Phytoremediation of benzene vapors from indoor air by Schefflera arboricola and Spathiphyllum wallisii plants, Atmos. Pollut. Res. 9 (2018) 1083–1087, https://doi.org/10.1016/j.apr.2018.04.005.*

[53] *E. Heseltine, J. Rosen, World Health Organization. WHO guidelines for indoor air quality: dampness and mould, WHO, Copenhagen, 2009.*

[54] *Ministério da Saúde, Portaria n.° 353-A/2013, de 4 de dezembro. https://diariodarepublica.pt/dr/detalhe/portaria/353-a-2013-331868, 2013 accessed November 7, 2025.*