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Research article

Implementation of a botanical bioscrubber for the treatment of indoor ambient air

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ABSTRACT

This study explores the effectiveness of a botanical bioscrubber system using Golden Pothos (*Epipremnum aureum*) in hydroponic setups to mitigate common indoor atmospheric pollutants. Over a 100-day operation, levels of SO_2, NO_2, O_3, TVOC, CO, CO_2, PM_{10}, and $PM_{2.5}$ were monitored, with a significant reduction in carbon-based compounds and particulate matter-. Notably, CO_2 and $PM_{2.5}$ removal efficiencies were significantly correlated with the foliar area, suggesting that the interaction between pollutants and plant leaves plays a crucial role in the phytoremediation process. In contrast, CO, PM_{10}, and TVOC exhibited varied removal efficiencies, hinting the involvement of mechanisms beyond leaf interaction, such as adsorption in irrigation water or root system capture. The absence of significant correlations for PM_{10} emphasized the need for further investigation into alternative removal processes, potentially mediated by the root system. Overall, our findings suggest that botanical bioscrubbers, particularly those utilizing Golden Pothos, hold promise for indoor air purification through plant-based systems.

1. Introduction

In urban environments, where pervasive air pollution is a concern, individuals typically spend a significant portion of their daily routines indoors, whether in residential, institutional, or occupational settings. Regrettably, these indoor environments often fail to meet the air quality guidelines stipulated by the World Health Organization. The term indoor air quality (IAQ) refers to the sense of well-being and comfort for the inhabitants of closed spaces, such as rooms, houses, buildings, and other structures. Indoor air pollution represents a detrimental effect for their occupants through a chronic exposition of compounds, such as VOCs, CO_2, CO, PM_{10}, and $PM_{2.5}$ which can lead to chronic health conditions, and the potential economic cost associated with health care costs and loss of productivity (EPA, 2024a; EPA, 2024b; Liu et al., 2019; Lunderberg et al., 2021). Thus, there is an urgent need to prioritize measures aimed at ensuring optimal indoor air quality to protect the health and comfort of occupants. (Abedi et al., 2022; González-Martín et al., 2024; Kwon et al., 2021; Li et al., 2021; Liu et al., 2019; Lunderberg et al., 2021; Tang, 2023; Kumar et al., 2023; Zhang et al., 2020).

Improving indoor air quality can be achieved through various strategies, including eliminating, limiting, or replacing pollution sources, increasing outdoor ventilation rates to dilute indoor pollutants, or employing physicochemical or biological purification technologies. The selection of a purification technology depends on factors such as the characteristics of the space, desired efficiency, and operational budget (Abedi et al., 2022; González-Martín et al., 2024; Guieysse et al., 2008; Hernández-Díaz et al., 2021; Masi et al., 2022; Pettit et al., 2019). Despite the effectiveness of many purification systems, their significant costs and maintenance requirements often limit their widespread application. However, one cost-effective and environmentally friendly solution for indoor air pollution is air phytoremediation (Barn et al., 2018; Han et al., 2022; Luengas et al., 2015; Permana et al., 2022). This approach combines biotechnology, environmental engineering, and horticulture to create nature-based solutions like botanical biofiltration. Botanical biofiltration offers several advantages over traditional air purification methods. It is a sustainable and cost-effective solution that integrates plants into indoor environments to naturally remove pollutants. Unlike mechanical and chemical air filters, botanical biofilters use

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the natural processes of plants to adsorb, absorb, and degrade pollutants. This not only improves air quality but also enhances the aesthetic appeal of indoor spaces and contributes to environmental sustainability by reducing the need for energy-intensive air purification systems (Abdo et al., 2019; Han et al., 2022; Matheson et al., 2023). This purification technology can achieve acceptable removal capacities of a broad spectrum of pollutants on large infrastructures, with special emphasis on carbon-based compounds (VOCs, CO_2, CO), particulate matter (PM_{10} and $PM_{2.5}$), even volatile inorganic compounds (NO_2, O_3, SO_2) (Abdo et al., 2019; Barn et al., 2018; Gubb et al., 2022; Ibrahim et al., 2021; Irga et al., 2019; Mukhopadhyay et al., 2024; Saxena and Sonwani, 2020; Sharma et al., 2022).

This system uses plants that have the ability to remove common air pollutants due a combination of various complex mechanisms of adsorption and absorption. These removal processes involve different parts of the plant like the leaves, the roots/growing media, and the rhizosphere (Abedi et al., 2022; Paull et al., 2021; Saxena and Kulshrestha, 2016; Soreanu et al., 2013; Torpy et al., 2017). The removal mechanisms involve the adsorption of compounds by various leaf structures, including trichomes, carbon allocation pathways, grooves, and the attachment to the leaves' cuticular wax, or can absorb the gaseous pollutants and small particulates via gas exchange in the stomata, then store them in vacuoles or degraded and convert them to non-toxic compounds (Chen et al., 2017; Lee et al., 2021; Liang et al., 2016; Paull et al., 2019; Permana et al., 2022; Popek et al., 2018; Saxena and Kulshrestha, 2016). On the other hand, the removal mechanism of the roots involves first the absorption of the pollutants on growing media through mechanically-assisted ventilation, or on the water phase for its posterior adsorption, accumulation or degradation via root system (Kumar et al., 2022; Mannan and Al-Ghamdi, 2021; Rybarczyk et al., 2019; Soreanu et al., 2013). For last, the microbial community present in the foliage (phyllosphere), inside the plant, or in the root system (rhizosphere), can catabolize harmful contaminants, specially the carbon-based compounds, and use them as carbon source for growth and energy (Lee et al., 2020; Montaluisa-Mantilla et al., 2023; Soreanu et al., 2013; Zhao et al., 2019).

Previous studies on the use of botanical biofilters have primarily emphasized the evaluation of various designs and adjustments in operational parameters to enhance contaminant removal efficiency. These reports often emphasize aspects such as the design of the filters and the selection of plant species for the systems, rather than specific details such as contaminant types, pollutant concentrations, airflow rates, etc. (Kazemi et al., 2020; Luengas et al., 2015; Montaluisa-Mantilla et al., 2023; Mukhopadhyay et al., 2024). Even so, most reports have evaluated either commercial products, proof-of-concept, green walls in rooms, or experimental chambers for testing synthetic emissions (Abedi et al., 2022; Ibrahim et al., 2021; Irga et al., 2017; Kazemi et al., 2020; Mannan and Al-Ghamdi, 2021; Montaluisa-Mantilla et al., 2023; Permana et al., 2022; Pettit et al., 2018, 2019; Plitsiri and Taemthong, 2022; Srbinovska et al., 2021; Zhu et al., 2024). Based on the plants interaction with the pollutants present in the indoor air, the botanical biofilters are usually categorized into passive and active biofilters. Passive biofilters are based on potted plants or green roofs and do not have direct aeration to the plants. On the other hand, active biofilters facilitate the passage of treated air through both the root system and foliage, aided by mechanical ventilation. Moreover, implementing systems that enable the absorption of pollutants in the irrigation water could enhance the rate of purified air, potentially enabling operation as a botanical bioscrubber filter (Abedi et al., 2022; Irga et al., 2019; Pettit et al., 2018). Therefore, an active botanical bioscrubber can remove pollutants better than potted plants by the increase on the volumetric rate of pollutant transfer to the plant tissue or irrigation water phase, as well as the directing the treated air to the biological and non-biological parts of the system, improving the use of all the parts of the used plants rather than only the aerial parts (Rybarczyk et al., 2019; Soreanu et al., 2013).

Various ornamental plant species have demonstrated efficiency in removing indoor air pollutants, with selection playing a crucial role in pollutant removal rates (de la Cruz et al., 2014; Kumar et al., 2023; Xu et al., 2011). Several authors report the use of a vast amount of plat species used to improve the indoor air quality, such as *Chlorphytum comosum, Dracaena deremensis, Zamioculcas zamiifolia, Aloe vera, Cordyline fruticosa, Philodendron martianum, Dieffenbachia maculate, Spathiphyllum wallisii, Sansevieria hyacinthoides, Aglaonema rotundum, Tradescantia spathacea, Guzmania lingulata, Cyperus alternifolius, Hemigraphis alternata, Hedera helix, Hoya carnosa, Asparagus densiflorus, Tradescantia pallida* or *Epipremnum aureum*. (Bhargava et al., 2021; Hormann et al., 2018; Kumar et al., 2023; Moya et al., 2019; Yoo et al., 2006). The selection of the plants needs to be based on characteristic like the tolerance against indoor air pollutants, fast growth rate, large leaf area and large root structure (Abedi et al., 2022; Irga et al., 2019; Luengas et al., 2015; Paull et al., 2019, 2021). The stress tolerance capacity of the plants can be evaluated by measuring the APTI (Atmospheric Pollutant Tolerance Index). This index is an empirical relationship that assesses the general stress tolerances of any plant species though biochemical parameters such as relative water content, specific physiological characteristics of the plant, such as total chlorophyll, ascorbic acid and the leaf pH, and discarding other stress generators beyond the presence of atmospheric pollutants (light source, nutrient deficiency, water deficiency or predation (Achakzai et al., 2017; Chauhan et al., 2022; Shahrukh et al., 2023). The APTI values could be employed as an indicator of plant health, as well as a parameter for selecting plants to be used in remediation systems (Molnár et al., 2020).

For the present work *Epipremnum aureum (E. aureum)* was selected as model plant to be grown in the hydroponic system. *E. aureum*, commonly referred to as devil's ivy, silver vine and golden pothos, is an evergreen epiphyte belonging to the Araceae family. *E. aureum* is a widely planted invasive species in subtropical and tropical climates around the world (Moodley et al., 2017). This species, a creeper and climber, is widely cultivated for ornamental use as garden and indoor plants because of its popular variegated foliage, low maintenance and its capacity to remove some air pollutants like VOCs, CO_2 or particulate matter (Abedi et al., 2022; Cao et al., 2019; De la Cruz et al., 2014; Han et al., 2022; Ibrahim et al., 2021; Moodley et al., 2017; Plitsiri and Taemthong, 2022; Xu et al., 2011; Zhu et al., 2024).

In this study, our goal is to analyze the capacity of *E. aureum* to eliminate common indoor atmospheric pollutants via a botanical bioscrubber system. Furthermore, we seek to evaluate the foliar removal mechanism and the overall physiological health of the plant to ascertain its efficacy in indoor air purification.

2. Methodology

2.1. Reactor configuration and operation

Six hydroponic pots of golden pothos (*E. aureum*) were prepared, containing a mixture of perlite and vermiculite (1:1) along with polyurethane sponge to support the root system. These pots were placed inside a PVC hydroponic column (88.0 cm in height, 11.0 cm in external diameter) connected to a water reservoir for irrigation (with a volume of 2.5 L). Fig. 1 illustrates the configuration of the botanical bioscrubber (BBs), both on the exterior and interior of the hydroponic column.

The hydroponic column was positioned within an acrylic chamber (55.4 cm long, 89.1 cm high and 55.4 cm base) with a volume of 0.28 m^3, in order to isolate the hydroponic column from the general room environment. Various LED lights were placed inside this chamber to serve as the source of illumination for the plants. Ambient air from outside side the acrylic cabin (ambient laboratory air) was circulated through the foliage using fan. Also, another pump directs air inside the chamber towards the water reservoir within the column in order to oxygenate the irrigation water, passing air through the root system, and

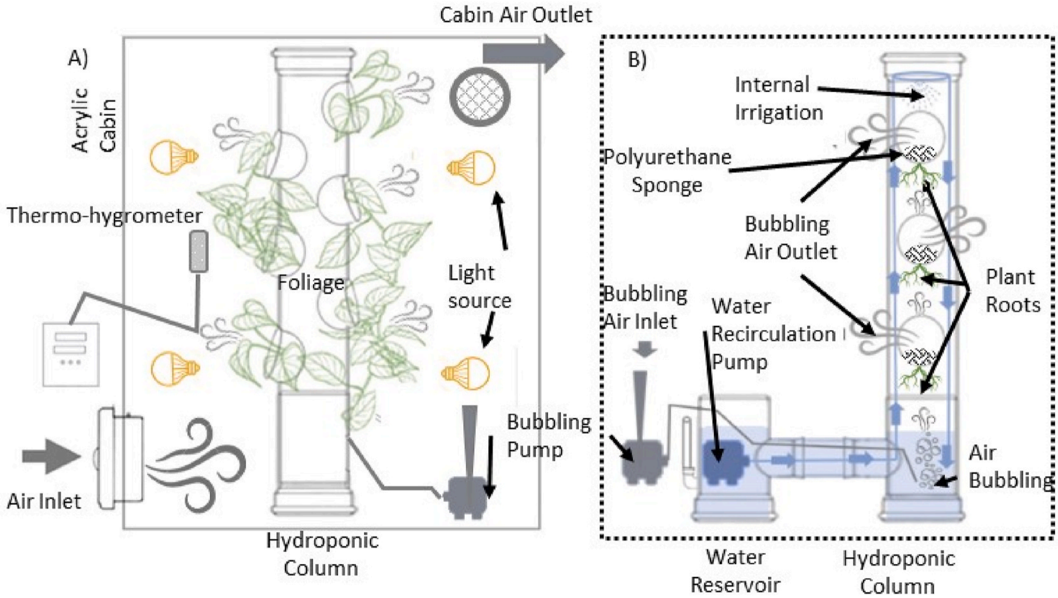

Fig. 1. Botanical Bioscrubber scheme. A) Components outside the hydroponic column. B) Components inside the hydroponic column.

capture the hydrophilic pollutants. The bubbling air exits from inside the column through the plant and pot support to the cabin environment. On the other hand, the interior of the hydroponic column contains both, the root system, and the internal irrigation system (coupled to the bubbling air stream).

The BBs operation was divided into four operational stages based on variations in external and bubbling air flow rates (Table 1). During these 100 days, data were collected on air operational parameters, as well as water phase, potted plant care and operational parameters, which are described below.

The external air flow rates were set at 11.7 m^3 day^{-1} and 32.17 m^3 day^{-1} using a speed fan. The bubbling air flow rates were adjusted between to 0.58 m^3 day^{-1} and 0.17 m^3 day^{-1}. The photoperiodicity was kept at 8/16 h along the operation with an average light intensity of 2562 ± 31.90 lux. On the other hand, the irrigation water flow was kept during the light period at 200 mL min^{-1}, the irrigation water reservoir was maintained and refiled at a volume of 2.5 L. The pH was controlled at values of 7.0 using HCl 1.0 N and phosphate buffer (1:1), the pH was measured and adjusted each week. The irrigation water volume was completely replaced at the beginning of each operational stages. In the same way, plant nutrients were added into the irrigation water at the beginning of each stage, this nutrient solution consist on a 2.0 g L^{-1}_{water} of commercial fertilizer Vigoro 17-17-17 (17% Nitrogen (N–NH_4), 17% Phosphorus pentoxide (P_2O_5), 17% potassium oxide (K_2O)).

2.2. Air pollutants measurement

The levels of common indoor pollutants were monitored at the BBs inlet and outlet, these compounds include particulate matter (PM_{10} and $PM_{2.5}$), CO_2, carbon monoxide, total volatile organic compounds, ozone, nitrogen dioxide, sulfur dioxide, and H_2S. This measurement was performed daily through the use of specialized GrayWolf sensors (DirectSense®II and Handheld 3016).

Table 1
Operational stages differences.

Stage	External flow (m^3 day^{-1})	Bubbling flow (m^3 day^{-1})	ACH[a] (h^{-1})
1	11.70	0.58	1.70
2	11.70	0.17	1.70
3	32.17	0.17	4.8
4	32.17	0.58	4.8

[a] ACH = Air change per hour as air exchange rate.

The daily Inlet loads and Outlet loads of each pollutant were determined according to equation (1), in which the concentration of each pollutant, the external air flow and BBs volume were related. Similarly, the Elimination Capacity refers to the difference between the inlet and outlet loads (Equation (2)). Also, the foliar elimination capacity was calculated according to equation (3).

$$L_{I/O} = X_{I/O} * \frac{Q}{V * 0.0416} \quad \text{(Eq. 1)}$$

$$EC = IL - OL \quad \text{(Eq. 2)}$$

$$FEC = (X_I - X_O) * \frac{Q}{FA * 0.0416} \quad \text{(Eq. 3)}$$

where $L_{I/O}$ are the daily Inlet or Outlet load for each measured pollutant ($mg_{pollutant}$ m^{-3}_{BBs} day^{-1}), Q is the external air flow during each operational stage (m^3_{air} h^{-1}), V is the BBs acrylic box volume (0.28 m^3), $X_{I/O}$ is the specific inlet or outlet pollutant concentration (mg m^{-3}_{air}), EC is the elimination capacity of the BBs ($mg_{pollutant}$ m^{-2}_{leaf} day^{-1}), IL and OL are the specific pollutant inlet and outlet load ($mg_{pollutant}$ m^{-3}_{BBs} day^{-1}), FEC is the daily foliar elimination capacity for each measured pollutant ($mg_{pollutant}$ m^{-2}_{Leaf} day^{-1}), FA is the foliar area of the golden pothos leafs (m^2_{Leaf}), *0.0416* is the conversion from days to hours (day $hours^{-1}$). These equations were adapted from Abedi et al. (2022) and Zhu et al. (2024).

2.3. Aqueous phase analysis

Throughout the operation of the BBs, irrigation water samples were collected weekly prior its refilling or replacement. These samples were analyzed for pH, total suspended solids, volatile suspended solids, total dissolved organic carbon, and total dissolved inorganic carbon. For this purpose, the methods under Mexican norm (NMX-AA-034-SCFI-2015) were used for the measurement of suspended solids, as well as the equipment of Shimatzu-L Carbon-Analizer for the quantification of carbon content.

2.4. Foliage analysis

Foliar area was determined using the methodology proposed by Da

Silva Ribeiro et al. (2018, 2020). For this purpose, the leaves were classified into three categories according to its perimeter (Table 2) and the area was estimated using ImageJ software, several measurements were performed on different plants to establish an average size for each leaf type of classification.

$$FA = \sum_{L,M,S} \left(n^{\circ}_{Leaves} * ALA\right) \quad \text{(Eq. 4)}$$

where L, *M, S* are Large, Medium and Small leaves size, respectively, n°_{Leaves} is the number of leaves according to its size, and *ALA* is the Average Leaf Area (cm^2).

The atmospheric pollutant tolerance index (APTI) was determined periodically throughout the operation of the BBs. For this purpose, the methodology reported by Shahrukh et al. (2023) and Sapkota & Shrestha (2024) was adapted, in which three "medium" leaves were collected from the hydroponic column to perform the measurement of ascorbic acid content, total chlorophyll, pH of leaf extracts, and the relative water content of the leaves according to equation (5):

$$APTI = \frac{A(T+P)+R}{10} \quad \text{(Eq. 5)}$$

where *A* is the ascorbic acid content (mg_{AA}/g_{leaf}), *T* is the total chlorophyll content ($mg_{chlorophyll}/g_{leaf}$), *R* is the relative water content of leaves (%) and *P* is the pH of the leaf extract.

2.5. Data treatment

The generated database was processed using R studio and OriginPro software. Univariate analysis was performed for assessing significant differential abundances of EC, FEC and accumulated concentration between the four operational stages, as well as the significant differential of the APTI values per stage ($p \leq 0.05$). Normality and homogeneity of variances were evaluated by means of Shapiro-Wilk and Bartlett's tests ($\alpha = 0.05$). On one hand, the one-way repeated measures ANOVA and Tukey's contrasts were carried out for the comparison of the BBs performance, APTI, FA and aqueous phase data among stages. To establish the potential relationship between FA and FEC, correlation analyses were conducted using both linear and non-linear methods. Significant correlations ($\alpha = 0.05$) were evaluated by applying Pearson correlation for linear relationships and distance correlation (dCor) for non-linear relationships, respectively.

3. Results

3.1. BBs pollutant removal performance

For comparative purposes, the analysis of BBs pollutant removal performance was conducted by categorizing them based on the nature of the compounds. Three groups were established: carbon-based compounds (CO_2, CO, and TVOC), particulate matter (PM_{10} and $PM_{2.5}$), and volatile inorganic compounds (O_3, H_2S, NO_2, and SO2). Figs. 2 and 3 illustrate the BBs' performance for carbon-based compounds and particulate matter, respectively, over the 100 days of operation. Also, Table 3 resume the means of Elimination Capacity and Foliar Elimination Capacity.

The IL values of the various carbon-based compounds varied

Table 2
Classification of leaf types according to perimeter and average area.

Classification	Perimeter cm	Average Leaf Area cm^2
Small	<8.0	20.83 ± 2.6
Medium	≥8.0 < 12	52.87 ± 11.36
Large	>12	80.27 ± 8.65

The number of leaves for each classification was weekly counted throughout the BBS operation, and the total foliar area was calculated according to equation (4).

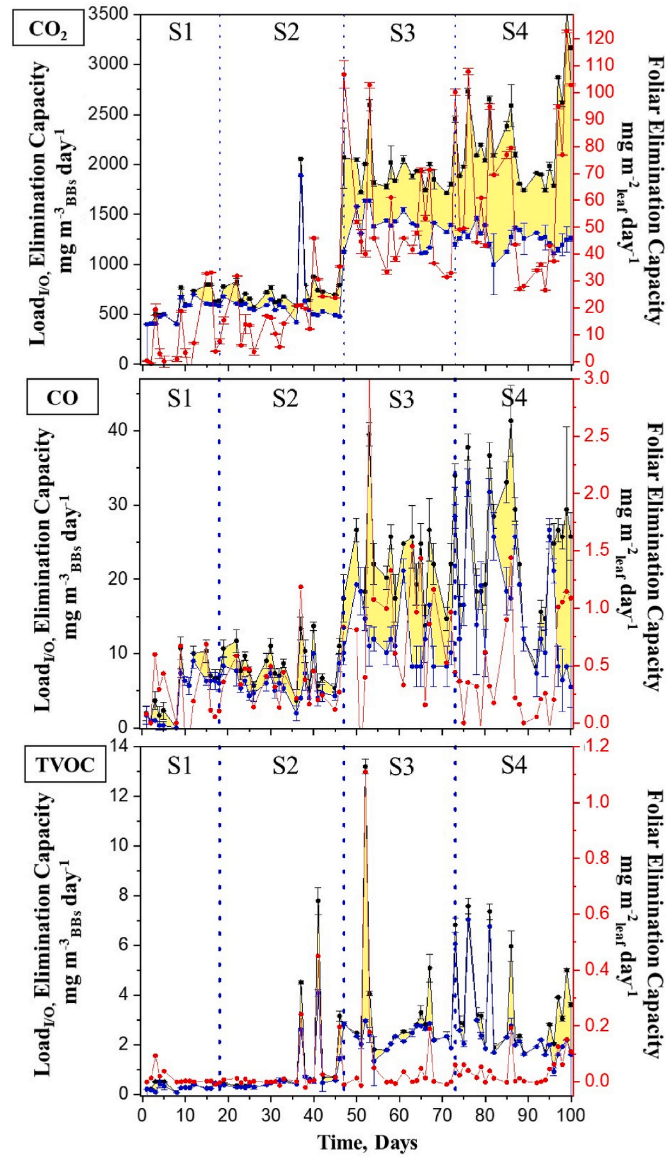

Fig. 2. BBs performance for CO_2, CO and TVOC. ● Inlet Load, ● Outlet Load, ● Foliar Elimination Capacity, ■ Elimination Capacity.

significantly during the different operational stages. The IL for TVOC ranged from 0.08 ± 0.002 mg m^{-3} day^{-1} to 13.2 ± 3.02 mg m^{-3} day^{-1}. Notably, the BBs demonstrated relatively low removal performance during stages 3 and 4, with TVOC showing the lowest removal among all the monitored species. The highest EC reached for this compound was on day 52 at values of 10.23 ± 6.24 mg m^{-3} day^{-1} (stage 3), along with a maximum FEC of 1.11 ± 0.68 mg m^{-2} day^{-1}, both values well above the average removal values observed in other stages. Meanwhile, the IL values for CO were higher than those reported for TVOC, ranging from 1.0 mg m^{-3} day^{-1} to 43.4 mg m^{-3} day^{-1}, with maximum IL values observed during stages 3 at values of 41.36 mg m^{-3} day^{-1}. In contrast to TVOC, the system exhibited significant removal capacities for CO from stage 1 onwards, particularly notable during stages 3 and 4, where the maximum reached values of EC and FEC were 43.4 ± 4.8 mg m^{-3} day^{-1} and 3.06 mg m^{-2} day^{-1}, respectively. Furthermore, CO_2 values had the highest IL, EC and FEC values. A clear distinction in removal performance was observed between two periods, with an average EC of 70.94 $\pm$ 49.0 mg m^{-3} day^{-1} and 149.18 ± 89.91 mg m^{-3} day^{-1} for stages 1 and 2, respectively, and 555.01 ± 201.68 mg m^{-3} day^{-1} and 1017.70 $\pm$ 507.35 mg m^{-3} day^{-1} for stages 3 and 4, respectively. Stage 4 recorded

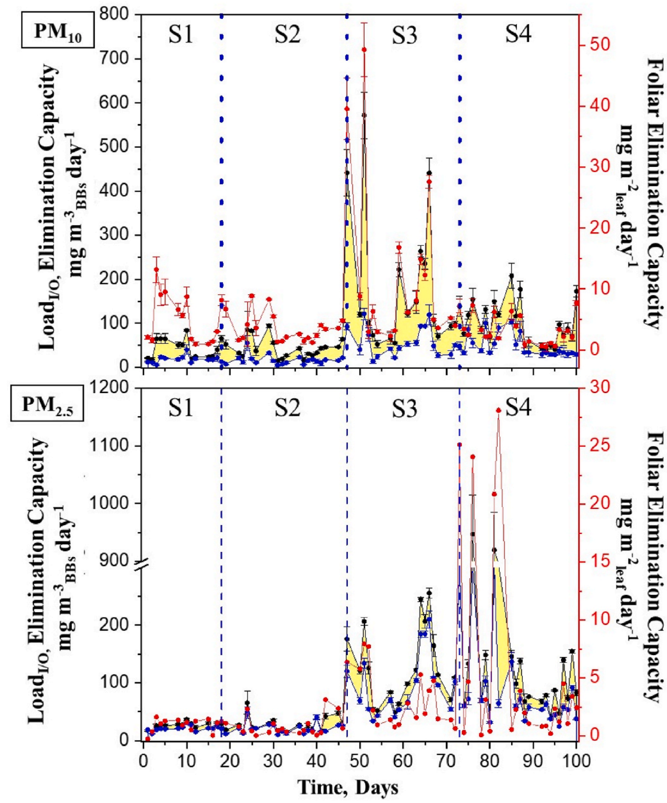

Fig. 3. BBs performance for $PM_{2.5}$ and PM_{10}. ● Inlet Load, ● Outlet Load, ● Foliar Elimination Capacity, ■ Elimination Capacity.

Table 3
Means of elimination capacity, foliar elimination capacity and ANOVA.

	Mean values	Operational Stage			
		S1	S2	S3	S4
CO_2	EC mg m^{-3} day^{-1}	70.94^{A} ± 49.00	149.18^{A} ± 89.91	555.01^{B} ± 201.68	1017.70^{C} ± 507.35
	FEC mg m^{-2} day^{-1}	12.37^{A} ± 8.82	19.09^{A} ± 10.65	53.18^{B} ± 22.13	63.02^{B} ± 29.57
CO	EC mg m^{-3} day^{-1}	1.07^{A} ± 0.38	3.12^{A} ± 0.54	9.58^{B} ± 2.11	5.74^{AB} ± 1.75
	FEC mg m^{-2} day^{-1}	0.21^{A} ± 0.07	0.43^{A} ± 0.07	0.94^{B} ± 0.21	0.37^{A} ± 0.10
TVOC	EC[a] mg m^{-3} day^{-1}	0.05 ± 0.03	0.14 ± 0.13	0.95 ± 0.72	0.54 ± 0.22
	FEC[a] mg m^{-2} day^{-1}	0.01 ± 0.01	0.01 ± 0.01	0.10 ± 0.08	0.04 ± 0.01
PM_{10}	EC mg m^{-3} day^{-1}	26.20^{A} ± 5.18	26.96^{A} ± 4.99	144.46^{B} ± 36.50	57.79^{A} ± 8.61
	FEC mg m^{-2} day^{-1}	5.22^{A} ± 1.07	3.72^{A} ± 0.70	14.39^{B} ± 3.90	3.45^{A} ± 0.57
$PM_{2.5}$	EC mg m^{-3} day^{-1}	4.97^{A} ± 0.80	5.10^{A} ± 1.08	35.11^{A} ± 6.35	120.10^{B} ± 41.40
	FEC mg m^{-2} day^{-1}	0.96^{A} ± 0.14	0.61^{A} ± 0.15	3.63^{AB} ± 0.65	7.82^{B} ± 2.73

[A, B, C] indicate statistically significant similitudes and differences between stages ($p \leq 0.05$).
[a] Differences of means values considered non-significant ($\alpha > 0.05$).

the maximum EC and FEC values, with 2266.92 ± 52.5 mg m^{-3} day^{-1} and 122.88 ± 2.84 mg m^{-2} day^{-1}, respectively.

Similar to the carbon-based compounds, the concentrations and removal capacities of particulate matter (PM_{10} and $PM_{2.5}$) also varied, not only between the two species but across different operational stages of the BBs. A noticeable shift in the BBs' performance was observed, dividing the operational timeline into two distinct periods that correspond to stages 1–2 and 3–4. In the first period, IL values for $PM_{2.5}$ were recorded in the range of 13.30 ± 1.25 mg m^{-3} day^{-1} to 65.62 ± 19.2 mg m^{-3} day^{-1}. The average EC during this period was 6.06 ± 5.85 mg m^{-3} day^{-1}, peaking at 26.06 ± 4.02 mg m^{-3} day^{-1}. This translated to an average FEC of 0.92 ± 0.71 mg m^{-2} day^{-1} to 67.53 mg m^{-2} day^{-1}, with a maximum of 3.13 ± 0.48 mg m^{-2} day^{-1}. The contrast between the two periods becomes evident with the second period's data, where IL values surged to between 37.76 ± 2.45 mg m^{-3} day^{-1} and an unprecedented 946.94 ± 67.53 mg m^{-3} day^{-1}, marking the highest IL for $PM_{2.5}$ at day 76 of operation. This upward trend in particulate matter concentrations reflected in the BBs' removal capacity. The average EC for the second period significantly increased to 99.4 ± 62.9 mg m^{-3} day^{-1}, with the peak EC reaching 441.19 ± 18.68 mg m^{-3} day^{-1} on day 82. Consequently, the average FEC values also rose to 6.96 ± 4.67 mg m^{-2} day^{-1}, with the highest recorded value being 28.09 ± 1.19 mg m^{-2} day^{-1} on the same day.

During the stage 1, the BBs recorded an average IL for PM_{10} at 44.13 ± 22.33 mg m^{-3} day^{-1}, with a peak of 94.50 ± 3.66 mg m^{-3} day^{-1} observed on day 29. However, this stage also exhibited relatively low removal efficiency, with an average EC of 26.72 ± 17.48 mg m^{-3} day^{-1}, peaking at 63.92 ± 1.11 mg m^{-3} day^{-1} on day 25. This translated into FEC values averaging at 4.23 ± 3.22 mg m^{-2} day^{-1}, with the highest efficiency recorded at 13.18 ± 2.1 mg m^{-2} day^{-1} on day 3. As observed with other pollutants, both the IL and the removal efficiency for PM_{10} showed a significant increase during the second phase of operation, reaching their highest values over the entire 100-day period. The average IL for this later stage surged to 137.04 ± 109.65 mg m^{-3} day^{-1}, with a remarkable peak of 571.71 ± 52.78 mg m^{-3} day^{-1} recorded on day 51. This marked increase in pollutant load translated into substantially higher FEC values, averaging 9.99 ± 7.21 mg m^{-2} day^{-1}, and reaching a maximum efficiency of 49.29 ± 4.40 mg m^{-2} day^{-1}, respectively. The BBs demonstrated varying efficiencies in removing volatile inorganic compounds, which were influenced by either the levels detected or the system's ability to remove the compounds. For example, NO_2, H_2S, and SO_2 exhibited negligible variances between inlet and outlet loads throughout the operation, showing average EC values of 0.01 ± 0.02 mg m^{-3} day^{-1}, 0.062 ± 0.12 mg m^{-3} day^{-1}, and 0.03 ± 0.05 mg m^{-3} day^{-1}, respectively. Meanwhile, O_3 levels were mostly detected at concentrations below the instrumental quantification limit, with an average inlet load (IL) of 0.007 ± 0.002 mg m^{-3} day^{-1}. Detailed performance metrics and comparisons are provided in the Supplementary Material (Fig. S1). Therefore, the system's inability to remove these pollutants can be attributed to the low concentrations in the case of O_3, or to the limited capacity of the plants or associated microorganisms to metabolize NO_2, H_2S, and SO_2. The case of NO_2 is particularly noteworthy, as its biological assimilation in the gas phase through leaves has been proven (Chaparro-Suarez et al., 2011). However, there are specific reports about plant species with the metabolic capacity for this assimilation. Consequently, abiotic factors and system design parameters (humidity, temperature, substrate type, presence of other pollutants, or solar radiation) are shown to significantly influence the removal and assimilation process through their interaction with the aqueous phase or with other atmospheric pollutants (Abhijith et al., 2017; Chaparro-Suarez et al., 2011; Pettit et al., 2019; Weyens et al., 2015; Jayasooriya et al., 2017; Saumitra and Ghosh, 2014). Nonetheless, based on the data presented herein, there is not enough information available to discuss this further.

As mentioned in the introduction, the air pollutant removal capacity of *E. aureum* has been proven for a wide range of pollutants, including carbon-based compounds and particulate matter. For instance, Cao et al. (2019) used a sealed chamber with *E. aureum* pots to demonstrate the passive removal capacity of the plant for $PM_{2.5}$ from cigarette smoke, reporting removal efficiencies between 59% and 71% for initial $PM_{2.5}$ concentrations of 200–300 μg m^{-3}. Similarly, Plitsiri and Taemthong (2022) tested various ornamental plants, including *E. aureum*, for their passive leaf absorption capacities for CO_2 removal inside a chamber, finding that this plant had an average CO_2 absorption capacity of 2.26 ppm min^{-1} under natural light and 0.97 ppm min^{-1} under artificial light (1000–2000 lux). Zhu et al. (2024) tested potted *E. aureum* plants for CO removal along with three other ornamental plants, finding that *E. aureum* had the best CO removal performance compared to *Chlorophytum comosum*, *Sansevieria trifasciata*, and *Spathiphyllum kochii*, achieving 100% removal efficiency for CO concentrations below 50 ppm, though higher concentrations caused leaf damage. Regarding to active removal processes, Ibrahim et al. (2021) used *E. aureum* in an experimental biofilter design to treat TVOC, PM_{10}, and $PM_{2.5}$, achieving removal efficiencies of 46%, 65.42%, and 54.5%, respectively, which were attributed to adsorption and absorption processes in all plant parts (leaves and roots). Abedi et al. (2022) used a botanical biofilter with six plant species, including *E. aureum*, in vertical modules to treat formaldehyde emissions, reporting a 99.9% removal rate for formaldehyde at flow rates of 0.8 L s^{-1} and 0.25 m^2 of leaf area. However, they did not specify the capacities or mechanisms for each plant species.

Comparing our system with those in other studies is challenging due to differences in plant disposition, system designs, passive versus active processes, the use of multiple plant species, and specific VOC monitoring in active systems. Most biofilters referenced in these studies facilitate the flow of polluted air through both the roots and foliage of the plants, emphasizing the need to separate monitoring strategies for active and passive systems, elucidate specific pollutant removal mechanisms, and expand information on the capacities of individual plants for pollutant removal, either alone or in combination with other species. Unifying removal parameters as proposed by Foliar Elimination Capacity can help standardize comparisons when leaf interaction is identified as the main removal mechanism.

To the best of the authors' knowledge, there are no reports specifically addressing the use of *E. aureum* for the removal of NO_2, O_3, or SO_2. However, the effectiveness of other plant species for these pollutants has been documented. For example, Pettit et al. (2019) used *S. wallisii* and *S. podophyllum* for simultaneous NO_2 and O_3 treatment in an active botanical biofiltration system, achieving average NO_2 clean air delivery rates of 661.32 and 550.8 m^3 h^{-1} m^{-3} of biofilter substrate, respectively. Saumitra and Ghosh (2014) used a green facade with *Vernonia elaeagnifolia* for SO_2 treatment, indicating stomatal interaction related to leaf area as the main removal mechanism, with a removal rate of 1.11×10^{-6} s^{-1} at an air velocity of 1.53 mm s^{-1}. These tests were conducted on green walls in outdoor spaces, highlighting the need for comprehensive testing of different plants, individually and in combination, to achieve thorough contaminant removal to safe levels for occupants in environments where these biofilters are implemented.

Regarding the ANOVA (Table 3), several key observations emerge regarding the removal efficiency of the monitored pollutants by BBs. For TVOC the analysis revealed no statistically significant differences between EC and FEC values across all operational stages. Similarly, for the other pollutants, stages 1 and 2 exhibited no significant differences, while stage 3 presented a marked variance from the others, particularly for carbon dioxide (CO_2) and carbon monoxide (CO), where the disparity between EC and FEC was notably pronounced in stage 4. A distinct pattern was observed for $PM_{2.5}$, which displayed differential removal behaviors across stages. Specifically, stage 3 mirrored the removal patterns of other stages, yet stages 1 and 2 significantly diverged from stage 4. This highlighted a variation in behavior between EC and FEC, especially evident for CO_2, CO, and $PM_{2.5}$. Notably, there were no significant differences in average FEC values between stages 3 and 4 for these pollutants. This suggests that when removal data is normalized to leaf area, the removal efficiencies recorded in stage 3 (where peak removal was noted) closely align with those of stage 4. It was also observed that FEC values were considerably lower than EC values across pollutants, stages, and days. This analysis reaffirms the influence of FA on the removal capacities of BBs for CO_2 and $PM_{2.5}$, particularly during stages 3 and 4, indicating leaf interaction as a primary removal mechanism. This is supported by literature indicating foliage's significant role in pollutant uptake (Montaluisa-Mantilla et al., 2023; Paull et al., 2019). However, this relationship appears less clear for CO, TVOC, and PM_{10}, potentially implicating other mechanisms, such as interactions with irrigation water and the root system (Mannan and Al-Ghamdi, 2021; Kumar et al., 2023). Although the removal of CO_2 through foliar uptake and the removal of TVOC and PM via substrate interactions are well-established processes, numerous studies highlight the critical role of plant physiology and substrate composition in this removal capacity (Ibrahim et al., 2021; Cao et al., 2019). While our study suggests that multiple mechanisms are involved in the phytoremediation process, a thorough investigation of these mechanisms extends beyond the scope of this research. To gain a comprehensive understanding of how plants and their associated microbiomes mitigate indoor air pollution, further studies are necessary. Future research should focus on elucidating the physiological, biochemical, and genetic foundations of phytoremediation processes through detailed experimental studies. Additionally, conducting systematic reviews and meta-analyses could provide valuable insights by synthesizing data from various studies, thereby identifying overarching patterns and evaluating the effectiveness of different phytoremediation strategies.

3.2. Foliage data analysis

Fig. 4 summarizes the information by stage of the APTI and FA values obtained along the BBs operation. On one hand, APTI remained at average values of 9.475 ± 0.11 throughout the 4 operational stages, with no significant differences between stages. Since APTI is an estimate of the plant's susceptibility to stress caused by exposure to atmospheric pollutants, the fact that it did not vary significantly over 100 days of operation indicates that the plant was not affected by the different levels of pollutants to which it was exposed. In addition, the APTI for the Golden Pothos values recorded are similar to those reported by other authors for various indoor spaces, with APTI values of around 9.3 (Chauhan et al., 2022; Kumar et al., 2022; Agarwal, 2017). Such uniformity in the plant's performance, despite exposure to different pollutant concentrations, highlights its robustness and adaptability, making it a viable candidate for large biofiltration applications. The main challenge with active botanical filtration lies in ensuring the health of the planted species and their associated microbial communities. Contaminant uptake can adversely affect plant health and, therefore, its performance in its application as a treatment system. (Irga et al., 2019; Pettit et al., 2019). Ensuring optimal conditions for both plants and their microbial partners is critical for maintaining effective filtration performance. The specific values for the APTI parameters are resumed on

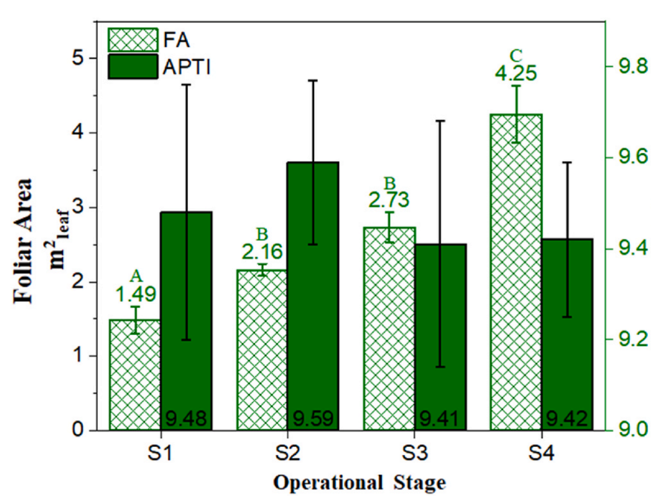

Fig. 4. Foliage data of *Epipremnum aureum* during BBs operation. [A, B, C] indicate statistically significant similitudes and differences between stages ($p \leq 0.05$).

supplementary material (Figure S2).
al (Fig. S2).

Leaf area plays a crucial role in determining the FEC values, representing the removal efficiency associated with the interaction of contaminants with leaves, including their capture via adsorption on cuticular waxes or absorption through stomata (Montaluisa-Mantilla et al., 2023; Paull et al., 2019). Thus, an increase in leaf area becomes pivotal for enhancing the performance of the system. Examining the fluctuation in Foliar Area (FA) over the operational period (Fig. 4), a gradual escalation is evident, starting from an initial value of 1.211 m^2 and culminating at 5.201 m^2 by day 100. Notably, the average FA values per stage exhibit significant variance, with the exception of stages 2 and 3. This observation, coupled with the fact that stage 3 recorded the highest degradation levels for all monitored compounds (Figs. 2 and 3), and considering that the bubbling flow remained constant throughout (Table 1), highlight a key operational discrepancy between stages 2 and 3 where the external flow velocity was notably higher in stage 3.

As previously noted, an examination of the trend of FEC values in relation to FA (Fig. 5) reveals a distinct pattern, particularly for carbon-based compounds and suspended particles. Notably, there is an observable increase in FEC values for CO_2, $PM_{2.5}$, and CO, contrasting with the relatively constant FEC values observed for PM_{10} and TVOC despite the increase in FA throughout the stages. To validate these observed trends and establish the correlation between these two parameters, linear and non-linear regression analysis were conducted for all five compounds (Table 4). The linear analysis affirmed the trend of increased removal for CO_2 and $PM_{2.5}$ as FA increased in the hydroponic column. In essence, the greater the foliar area occupied by healthy plants, the greater the daily removal of these pollutants within the system. Conversely, while CO exhibited a linear trend, it was not statistically significant (p-value >0.05). Similarly, the notion that PM_{10} and TVOC are removed through alternative mechanisms can be supported

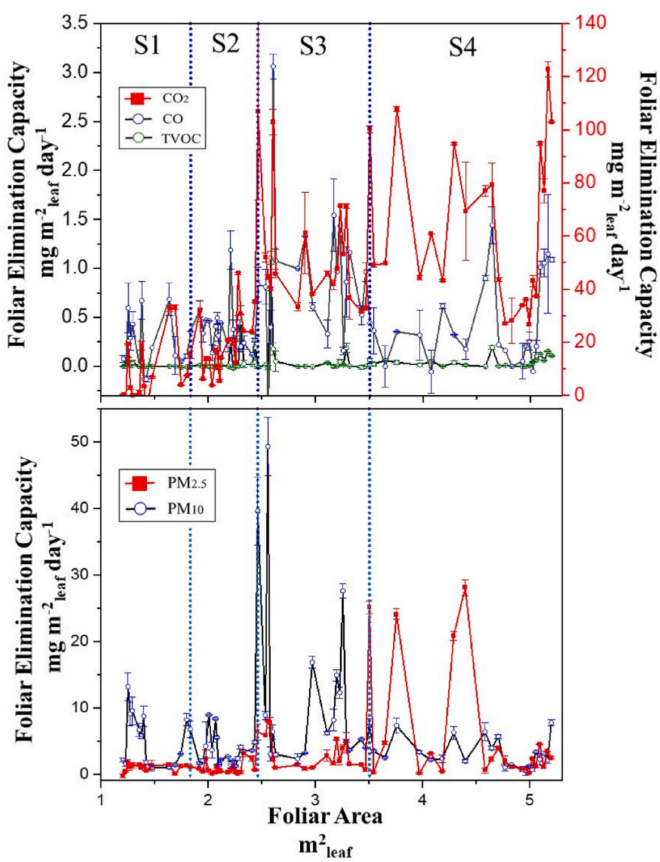

Fig. 5. FEC *vs.* FA. A) Carbon-based compounds, B) Particulate matter.

Table 4
Lineal correlations of foliar area *vs.* foliar elimination capacity.

Pollutant	Foliar Area *vs.* Foliar Elimination Capacity			
	Lineal correlation r / p_{value}		Non-lineal correlation dCor / p_{value}	
TVOC	0.1279	0.7364	**0.0481**	**0.006**
CO_2	**0.8776**	**$<2.2*10^{-16}$**	**0.4230**	**$< 2.2*10^{-16}$**
CO	0.1769	0.0692	**0.0503**	**0.004**
PM_{10}	0.1183	0.8750	0.0306	0.060
$PM_{2.5}$	**0.222**	**0.0306**	**0.0930**	**$< 6.531*10^{-07}$**

Values considered significant ($\alpha = 0.05$) are highlighted on grey and bold.

given the absence of a discernible trend in FEC values across the operational stages of the BBs. These lineal and non-lineal correlations are visually depicted in the supplementary material (Fig. S3).

In a similar way, a non-linear correlation analysis was conducted for all the monitored compounds (Table 4). It is expected that compounds with strong linear relationships (r, Pearson) would also exhibit high distance correlation values (dCor). Additionally, compounds demonstrating significant non-linear correlation would indicate a more complex removal phenomenon, possibly involving processes beyond foliage interaction. Interestingly, a considerably greater number of significant relationships were identified in the non-linear correlation analysis, except for PM_{10}. This suggests that the removal of PM_{10} may be attributed solely to a phenomenon unrelated to foliage interaction, contrasting with the other pollutants.

The authors acknowledge the limitations of the present study in delving into more advanced analyses to determine specific removal processes not associated with foliage interaction. However, several other studies have highlighted the primary role of plant-root and foliage interaction in pollutant remediation. Plant-associated microorganisms play a crucial role in this process by utilizing VOCs as energy and carbon sources. Nevertheless, the efficiency of degradation varies based on pollutant characteristics such as type, composition, hydrophobicity, toxicity, and solubility, as well as factors like light intensity, and pollutant load (Han and Ruan, 2020; Han et al., 2022; Montaluisa-Mantilla et al., 2023). Different plant areas, including root and aerial regions, exhibit varying efficiencies in pollutant remediation (Soreanu et al., 2013; Su et al., 2019). Notably, photosynthesis, a well-established process by which plants absorb CO_2 and produce O_2, also enables the absorption of other gaseous pollutants, bioaerosols, and particulate matter via stomata, leading to their accumulation within the plant's internal structure (Khalifa et al., 2023).

3.3. Aqueous phase data analysis

Figs. 6 and 7 depict the registered values of the suspended solids in the aqueous phase and the carbon content and pH of the irrigation water along the BBs operation, respectively.

The overall average concentration of TSS was 3.04 ± 1.23 g L^{-1}, with a peak level of 6.37 ± 0.08 g L^{-1} during S2, while the average VSS concentration was 2.03 ± 0.9 g L^{-1}, with a maximum of 4.07 ± 0.08 g L^{-1} also during S2. Notably, the average concentration values differed among the stages for both TSS and VSS. This observation is significant, considering that the irrigation water was completely replaced at each stage change, indicating that the values recorded per stage are independent phenomena. Interestingly, it appears that the average values of TSS and VSS follow a trend resembling the change in bubble flow (Table 1). Specifically, as the bubble flow decreases, higher values of suspended solids are recorded. However, the ANOVA data indicates that there are no significant differences for TSS and VSS values between S1

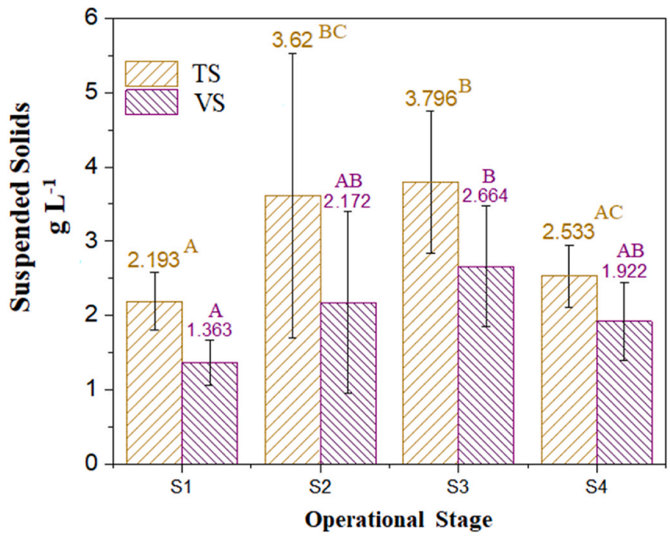

Fig. 6. Total suspended solids (TS) and volatile suspended solids (VS) of aqueous phase along BBs operation. [A, B, C] indicate statistically significant similitudes and differences between stages ($p \leq 0.05$).

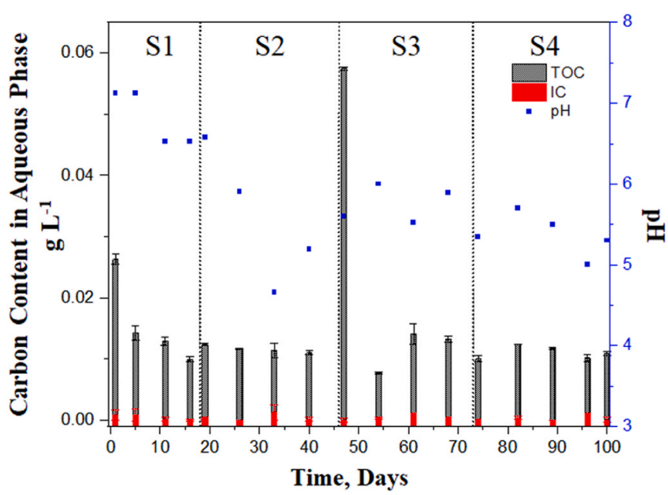

Fig. 7. Carbon content and pH of the irrigation water along BBs operation. ***TOC*** = Total Organic Carbon, ***IC*** = Inorganic Carbon.

and S4. Similarly, there are no significant differences between S2 and S3. Moreover, the lack of significant differences among S3, S3, and S4 suggests that this trend is not consistently sustained throughout the operation.

Fig. 7 illustrates that the irrigation water tends to acidify during the operation of the BBs, with stage 2 showing particular relevance in this acidification trend. The minimum pH value was 4.66, maintaining an average pH of 5.85 ± 0.71 across the four stages. Despite the variability in pH and the independent nature of the phenomena by stage, no variations were observed in the content of organic carbon (TOC) and inorganic carbon (IC). The average TOC value remained at 0.0151 ± 0.011 g L^{-1}, with only days 1 and 47 considered outliers (Fig. S4). Similarly, the IC values remained consistently below 0.001 g L^{-1} throughout the entire operation, indicating negligible IC content regardless of the stage. Regarding PM_{10} removal, the capture in the liquid phase and removal via the root system emerge as significant mechanisms, particularly when considering the limited influence of foliage on the removal capacity of the hydroponic column (Cardinali et al., 2023). Nonetheless, the results of carbon content and suspended solids do not appear to correspond to the values found in the gas phase, given the low values encountered throughout the BBs operation. Nevertheless, it is important to note that this analysis is limited in scope due to several factors, including the lack of characterization of the type of particles entering the system, insufficient information regarding the solubility of PM_{10} and $PM_{2.5}$, and limitations in determining specific removal mechanisms via roots due to the necessity of sacrificing the plants to elucidate metal content in different parts of the plants. Therefore, elucidating these removal mechanisms remains a perspective for future research endeavors.

4. Conclusions

The present work addresses the use of a botanical bioscrubber to remove common atmospheric pollutants within an indoor space using golden pothos in hydroponic pots. The input and output levels of the chemical species SO_2, NO_2, O_3, TVOC, CO, CO_2, PM_{10}, and $PM_{2.5}$ were monitored over a period of 100 days.

Performance analysis across four different stages revealed that carbon-based pollutants, including TVOC, CO, and CO2, were removed with varying efficiencies. TVOC exhibited low removal rates, while CO removal was notably more effective, especially in later stages. CO_2 showed the highest removal efficiency among all monitored compounds, with its performance improving along the increase of foliar area. Particulate matter removal also varied, with $PM_{2.5}$ being significantly more efficiently removed than PM_{10}. The relationship between foliar area and foliar elimination capacity suggests a direct correlation between plant health, foliage and pollutant filtration efficiency. Linear regression analyses indicated a strong positive correlation between FA and the removal efficiencies for CO_2 and $PM_{2.5}$, highlighting the critical role of the leaf surface in the phenomena. In contrast, CO, PM_{10}, and TVOC did not show this correlation, implying that their removal may involve additional factors beyond leaf interaction. Non-linear correlation results suggested that TVOC and CO removal might be influenced by multiple simultaneous processes, including irrigation water capture, rhizosphere microorganism degradation, and root system capture. The lack of significant correlation for PM_{10} removal points to alternative mechanisms that may not involve foliar interactions such as irrigation water capture, along with the TOC and IC results warranting further exploration into root-mediated removal processes.

The data related to FA, and its correlation with the FEC, elucidated the removal mechanism and the role of plant health in pollutant removal. Linear regression analysis revealed a positive correlation between FA and removal efficiencies for CO_2 and $PM_{2.5}$, indicating that their interaction with the leaves is the main removal mechanism. However, this trend was not observed for CO, PM_{10} and TVOC, suggesting the involvement of other factors in their removal process. Non-linear correlation analysis results elucidated that the elimination of TVOC and CO involves various simultaneous removal processes along with leaf interaction, such as capture in irrigation water, rhizosphere interaction, or capture in the root systems. The absence of significant correlation for PM10 suggests the main involvement of alternative removal mechanisms beyond foliage interaction, highlighting the need for further investigation into root system-mediated removal processes.

The findings emphasize the importance of considering pollutant-specific removal mechanisms, operational parameters, and plant species and health. Future research may focus on variety, quantity and types of plants, and elucidate the specific mechanisms driving pollutant removal and the limits of the used species, either the maximum removal capacity, or the maximum concentrations prior to health impairment. In conclusion, while the results presented herein highlight the *E. aureum*'s potential for air purification, they also emphasize the need for more detailed investigations into specific issues in order to improve plant-based air purification systems.

CRediT authorship contribution statement

José Octavio Saucedo-Lucero: Writing – review & editing, Writing

– original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lizbeth Soledad Falcón-González:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Monserrat Ovando Franco:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Sergio Revah:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.121414.

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