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Botanical filters for the abatement of indoor air pollutants

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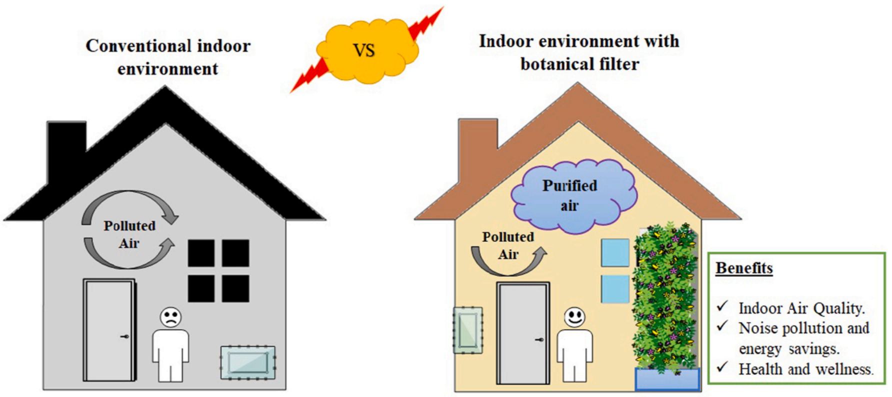
HIGHLIGHTS

- Indoor air pollution is associated with detrimental public health problems.
- Active botanical filters are an effective biotechnology for indoor air purification.
- NASA initially proposed botanical systems to cope with indoor air pollutants.
- Well-designed botanical filters effectively purify indoor air at low operating cost.

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays, people spend 80–90% of their time indoors, while recent policies on energy efficient and safe buildings require reduced building ventilation rates and locked windows. These facts have raised a growing concern on indoor air quality, which is currently receiving even more attention than outdoors pollution. Prevention is the first and most cost-effective strategy to improve indoor air quality, but once pollution is generated, a battery of physicochemical technologies is typically implemented to improve air quality with a questionable efficiency and at high operating costs. Biotechnologies have emerged as promising alternatives to abate indoor air pollutants, but current bioreactor configurations and the low concentrations of indoor air pollutants limit their widespread implementation in homes, offices and public buildings. In this context, recent investigations have shown that potted plants can aid in the removal of a wide range of indoor air pollutants, especially volatile organic compounds (VOCs), and can be engineered in aesthetically attractive configurations. The original

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Abbreviations: BFs, Biofilters; BTEX, Benzene, toluene, ethylbenzene and xylene; BTFs, Biotrickling filters; EBRT, Empty bed residence time; EPA, Environmental Protection Agency; GAC, Granular activated carbon; HVAC, Heating, ventilation and air conditioning; IAQ, Indoor Air Quality; MBRs, Membrane Bioreactor; MEK, methyl ethyl ketone; N/A, not applicable; NASA, National Aeronautics and Space Administration; OSHA, Occupational Safety and Health Administration; PM, Particular matter; ppm, Parts-per-million; ppb_{v}, Volumetric parts-per-billion; ppm_{v}, Volumetric parts-per-million; RH, Relative humidity; SPRE, Single pass removal efficiency; T, Temperature; TCE, Trichloroethylene; TVOCs, Total volatile organic compounds; TSP, Total suspended particulate matter; VICs, Volatile inorganic compounds; VOCs, Volatile organic compounds; WHO, World Health Organization.

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investigations conducted by NASA, along with recent advances in technology and design, have resulted in a new generation of botanical biofilters with the potential to effectively mitigate indoor air pollution, with increasing public aesthetics acceptance. This article presents a review of the research on active botanical filters as sustainable alternatives to purify indoor air.

1. Introduction

Clean air is a vital necessity for humans and natural ecosystems. Indoor air quality in houses, schools, offices, or any public and private building, where people spend most of their lifes, plays a key role in people's health and well-being (World Health Organization, 2010). People in developed countries spend approximately 90% of their time indoors, where the concentrations of some pollutants can be 2 to 5 times higher than typical outdoor concentrations. According to the World Health Organization (WHO), air pollution and human exposure to low-quality air are nowadays the most critical environmental threats to public health worldwide. In 2013, the WHO reported that 5.5 million premature deaths worldwide could be attributed to air pollution, this pollution being considered the fourth greatest risk factor (World Bank and Institute for Health Metrics and Evaluation, 2016). Likewise, the US-Environmental Protection Agency recently reported that people who live and work in buildings made of man-made materials inhale more than 300 pollutants every day (EPA, 2021a).

This environmental and health problem affects all people and to a large extend those who are more susceptible to the adverse effects of pollution, such as the elderly, the very young or those suffering from respiratory or cardiovascular diseases (EPA, 2021b). Indoor air pollutants have significant health impacts (Table 1), including triggering or worsening respiratory problems such as asthma and allergies. Volatile organic compounds (VOCs) and tobacco smoke often cause irritation of eyes, nose and throat. Prolonged exposure to indoor air pollution can induce headaches, fatigue and impaired cognitive function. Additionally, indoor air pollutants are associated with cardiovascular problems and long-term health effects such as cancer and even premature death.

Air pollution is not only a health risk, but also entails a huge economic burden. Hence, air pollution causes multiple diseases and even death, leading to the loss of productive labor and thus reducing production and income. This loss of revenue amounts to hundreds of billions of dollars annually, which represents a severe burden for developing countries (World Bank and Institute for Health Metrics and Evaluation, 2016).

Under the Directive 2010/31/EU (European Parliament, 2010), EU Member States have committed to constructing nearly zero-energy buildings by the end of 2020 and improving energy performance during major renovations of existing buildings or retrofitting of building elements. These new designs devoted to energy savings involve sealed, insulated and airtight constructions that reduce ventilation rates, which will lead to increased indoor air pollutant concentrations (Broderick et al., 2017).

Indoor air pollutants include particulate matter (PM), biological pollutants (spores, bacteria, fungi, etc.), physical agents (noise, electromagnetic waves, humidity, temperature) and over 400 different chemical compounds, mainly VOCs like formaldehyde, BTEX (benzene, toluene, ethylbenzene and xylene) and volatile inorganic compounds (VICs) such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2) and ozone (O_3) (Luengas et al., 2015). The sources of indoor contaminants can be occasional (human metabolism, cooking, application of cleaning and disinfestation products, etc.) or permanent (adhesives, paints, building materials, furniture, electronic devices, etc.), while outdoor pollutants intrusion from industry, road traffic, etc. also contributes to background indoor air pollution (Hubbard et al., 2005; SCHER, 2007).

Different organizations have established general Indoor Air Quality (IAQ) standards for key indoor air pollutants (Table 1).

The best strategy to improve IAQ is prevention at source. For instance, some initiatives have been carried out to reduce exposure to one the most prominent particulate pollutant, asbestos, which has been used in the past in a variety of building materials. In this context, the European Directive 99/77/EC restricted harmful construction materials and products containing hazardous components like halogenated pesticides. Another mitigation action that has been successfully implemented in many countries is the ban on smoking in public and workspaces. However, prevention is only possible when the sources are

Table 1
Exposure limits and health effects for the main indoor air pollutants (Adapted from EPA, 2021a, 2021c, 2021d, 2021e, 2021b; Marta Morales et al., 2010; New Jersey Department of Health, 2015, 2016a, 2016b; OSHA, 2011a, 2011b).

Pollutants	Exposure Limit			Health Effects
	WHO	EPA	OSHA	
CO_2	–	–	5000 ppm (8981632 μg/m^3) (8 h)	At high levels, CO_2 concentration in the blood increases, causing symptoms ranging from headache to loss of consciousness and even death.
CO	10 ppm (11432.65 μg/m^3) (8 h)	9 ppm (10289.39 μg/m^3) (8 h)	50 ppm (57163 μg/m^3) (8 h)	Suffocation, fatigue, angina, impaired vision, reduced brain function, headaches, nausea and death.
NO_2	0.1 ppm (187.78 μg/m^3) (1 h)	0.053 ppm (99.52 μg/m^3) (24 h)	1 ppm (1878 μg/m^3) (15 min)	Irritant that affects the mucosa of the nose, throat, eyes and respiratory tract, and increases bronchial reactivity in some asthmatics.
Ozone	120 μg/m^3 (8 h)	0.08 ppm (156.73 μg/m^3) (8 h)	0.1 ppm (196 μg/m^3) (8 h)	Alterations in respiratory function responses.
Benzene	2.3 μg/m^3	5 μg/m^3 (civil year)	1 ppm (3188 μg/m^3) (8 h)	Irritation of eyes, skin, nose and throat. It can cause headache, dizziness, nausea, vomit and leukemia.
Toluene	260 μg/m^3 (1 week)	–	200 ppm (752163 μg/m^3) (8 h)	Effects on the central nervous system.
Formaldehyde	100 μg/m^3 (30 min)	–	0.75 ppm (919 μg/m^3) (8 h)	Irritation of the skin, nose, eyes and throat. Exposure to high levels may cause different types of cancers.
Xylene	4800 μg/m^3 (24 h)	10 ppm (43330.61 μg/m^3)	100 ppm (433306 μg/m^3) (8 h)	Effects on the central nervous system.

known, which makes it technically and economically difficult to fully prevent indoor air pollutants at all times (Guieysse et al., 2008; Luengas et al., 2015).

Therefore, there is an urgent need to develop and optimize environmentally friendly technologies for *in-situ* indoor air purification, since physical-chemical technologies typically entail high investment and operation costs. The field of physicochemical technologies for purifying indoor air involves methods such as mechanical and electronic filtration, adsorption and UV photolysis. Mechanical filtration is based on the forced circulation of air through a fiber-rich medium, effectively trapping particulate pollutants. A renowned example is the High-Efficiency Particulate Air (HEPA) filter, which supports an outstanding capture efficiency of 99.97% for particles measuring $\geq$0.3 μm. While upfront costs for these filters are reasonable, their maintenance involves regular filter replacements (Dubey et al., 2021). In the electronic filtration realm, the methodology is grounded in attracting negatively charged particles to oppositely charged plates. The most representative commercial devices utilizing this principle are Ionic and Electrostatic purifiers, which require more capital and higher operating costs than their mechanical counterparts. Their efficiency typically fluctuates between 14.5% and 67.7% depending on the particle size (Zeng et al., 2020). On the other hand, adsorption operates by entrapping volatile pollutants on the surface of specific materials like activated carbon or zeolites. Maintaining their efficiency requires periodic material replacements or regeneration, thereby increasing operational costs. The efficiency of VOC adsorption is variable and a function of the nature of the pollutant. Removal efficiencies higher than 90% have been recorded for BTEX compounds using activated carbon (Chen et al., 2005; Guieysse et al., 2008; Jo and Yang, 2009; Luengas et al., 2015). Finally, UV photolysis can degrade VOCs and microorganisms using ultraviolet radiation, although its high operational costs often challenge the economic sustainability of the process. The state-of-the-art of physical-chemical technologies for indoor air pollutants was recently summarized elsewhere (González-Martín et al., 2021). In the context of indoor air purification, botanical filters have emerged as a promising alternative combining interior design aesthetics and an effective VOC removal. Their effectiveness covers a broad spectrum of pollutants, with special emphasis on VOCs. The initial cost of botanical filters may seem equal to or even higher than some traditional methods. However, the multiple benefits they offer, from improving mental health to modulating humidity, reinforce their appeal. This review papers aims at presenting and discussing the fundamentals and recent advances of botanical filters as a platform for indoor air purification.

2. Biotechnologies for air purification

Biological technologies for air purification rely on microorganisms or plants that use gaseous pollutants as a source of energy or carbon for cell growth and maintenance. Plants, bacteria, microalgae and fungi can degrade common indoor air pollutants. For instance, bacteria typically exhibit high growth and pollutant biodegradation rates, high tolerance to toxicity, and require a neutral pH and high water activity to maintain an active metabolism, making them more efficient in removing hydrophilic air pollutants. In contrast, fungi are more tolerant to low moisture contents, low pH, and nutrient-limited conditions, and are more suited to biodegrade hydrophobic pollutants (Kraakman et al., 2021). Finally, plants can absorb pollutants through their roots and break them down into less harmful compounds through metabolic processes such as photosynthesis and cellular respiration. This method can be particularly effective in removing VOCs and other hydrophobic pollutants and is typically referred to as phytoremediation. Microalgae typically exhibit a greater capacity for light absorption and carbon sequestration than plants. Both organisms use light to perform photosynthesis, during which they convert H_2O and CO_2 into oxygen and biomass. However, due to their simpler cell structures and higher light utilization efficiency, algae are much more efficient in this process than plants. Thus, algal photobioreactors may represent a viable solution for indoor environments with high CO_2 levels (Soreanu and Dumont, 2020; Wang et al., 2023).

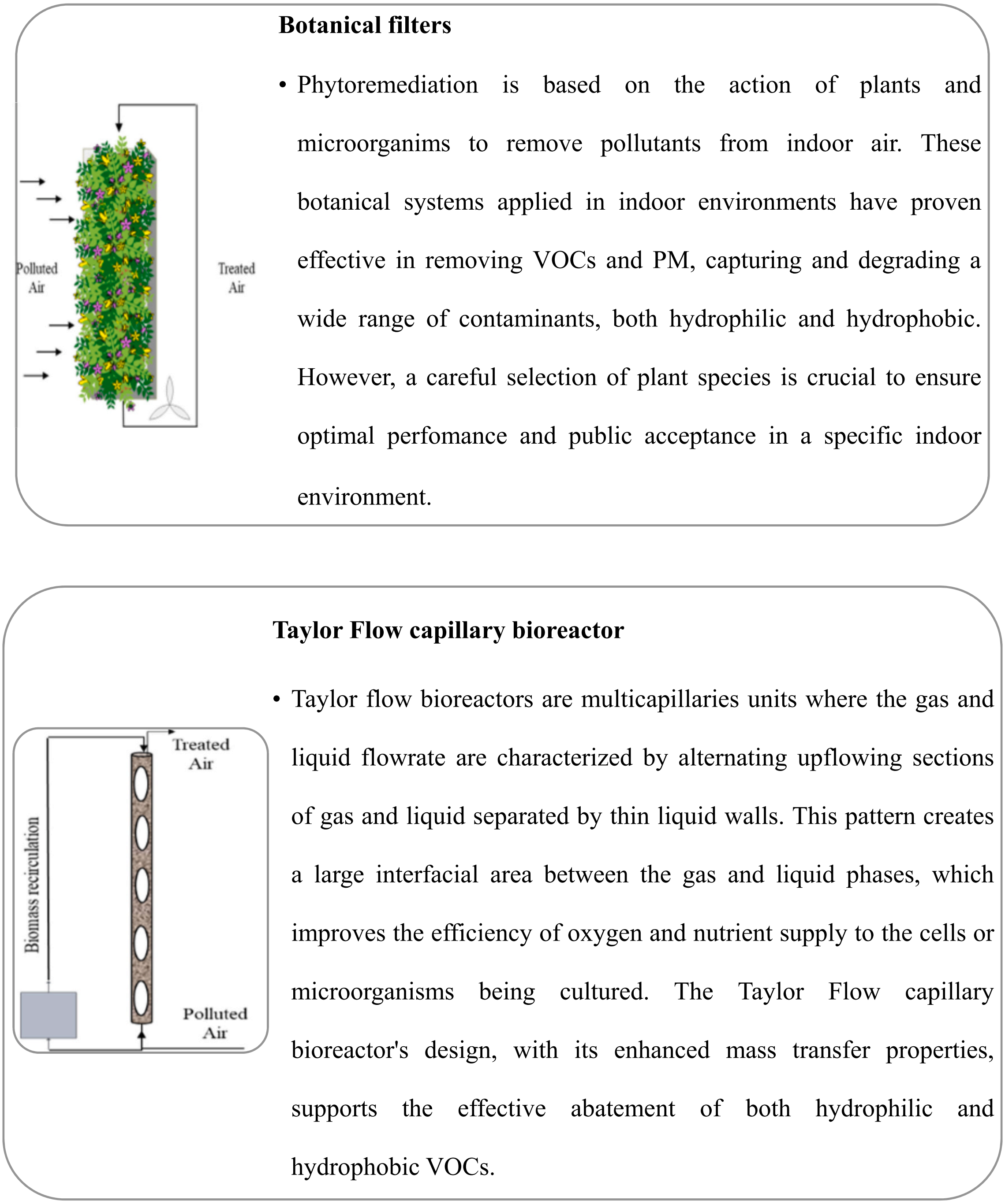
In this context, biological treatments with great functional versatility and robustness are necessary to address the random introduction of new sources of indoor air pollution and the fluctuating pollutant concentrations. These biotechnologies are described in more detail in Fig. 1 (González-Martín et al., 2021; Kraakman et al., 2021, 2023; Soreanu and Dumont, 2020). Botanical filters have emerged in the past years as a cost-effective technology to mitigate indoor air pollutants, based on their multiple biocatalytic mechanism and their aesthetic acceptance.

3. Botanical filters to mitigate indoor air pollution

The National Aeronautics and Space Administration (NASA) originally proposed botanical systems in the 1984 as a treatment alternative for indoor air pollutants, during a research program targeting the development of "Biological life support systems" for long-term habitation in outer space. This initial research demonstrated the ability of potted plants to remove a wide variety of VOCs. Further research at the Mississippi National Space Technology Laboratory developed a biological air purification system for closed environments such as space stations and energy efficient homes using houseplants (Wolverton et al., 1984).

Based on this initial work carried out by NASA, further research in this area has been focused on improving indoor air quality using a wide variety of potted plants, referred to as passive systems. This research was recently compiled by P. J. Irga et al. (2018) and Matheson et al. (2023).

Passive botanical systems are based on the diffusion of air pollutants through the botanical components, without any active mechanism to direct the contaminated air to plants or their substrates (Pettit et al., 2018a). These systems have demonstrated significant reductions of VOCs in the range of 10–90% withing 24 h in sealed chambers (Llewellyn and Dixon, 2011). For instance, Aydogan and Montoya (2011) tested different substrates such as growth stone, expanded clay, and activated carbon with various potted plants (*Epipremnum aureum, Hedera helix, Dieffenbachia Compact, and Chrysanthemum morifolium*) and achieved removal efficiencies ranging from 81 to 96% for formaldehyde in 24 h at a concentration of 1.63 ppm_v. Indoor air biotreatment using potted plants has been extensively studied and several investigations have been devoted to optimize the environmental and operating parameters (i.e. type of plant, configuration, light, etc.). For instance, Hörmann et al. (2017) reported that the initial concentrations of toluene and 2-ethylhexane (14.6 and 20 mg m^{-3} respectively) were reduced to 1 and 9.5 mg m^{-3} in 48 h in a chamber with a total volume of 240 L containing *Dieffenbachia maculata* and *Spathiphyllum wallisii* plants. Overall, the removal of VOCs in passive systems was typically investigated in assays where a concentration of contaminants is introduced into a small sealed chamber containing potted plants, which represents a process far from reality. In addition, there is a controversy about the level of activity of the microbial populations responsible for pollutant biodegradation when exposed to fluctuating concentrations of VOCs. For these reasons, investigations of passive systems have evolved into active botanical systems where the polluted air is mechanically introduced into the plant-based biofilter. These active biotreatment systems typically use fans to enhance the pollutant removal capacity and expose the microbial community inhabiting the systems to a constant flow of contaminants (Kraakman et al., 2021; Pettit et al., 2018a). A typical configuration for these systems is to grow on a vertical wall (Green Wall). The interest in active green walls to improve indoor air quality has rapidly increased in the last decade along with the public awareness about the relevance of indoor air quality. The common goal of the most recent investigations in the field is to demonstrate that botanical filters can be used not only for indoor decoration, but are also functional for the elimination of different air pollutants by controlling environmental and operational variables such as temperature, airflow, lighting and



Botanical filters

- Phytoremediation is based on the action of plants and microorganims to remove pollutants from indoor air. These botanical systems applied in indoor environments have proven effective in removing VOCs and PM, capturing and degrading a wide range of contaminants, both hydrophilic and hydrophobic. However, a careful selection of plant species is crucial to ensure optimal perfomance and public acceptance in a specific indoor environment.

Taylor Flow capillary bioreactor

- Taylor flow bioreactors are multicapillaries units where the gas and liquid flowrate are characterized by alternating upflowing sections of gas and liquid separated by thin liquid walls. This pattern creates a large interfacial area between the gas and liquid phases, which improves the efficiency of oxygen and nutrient supply to the cells or microorganisms being cultured. The Taylor Flow capillary bioreactor's design, with its enhanced mass transfer properties, supports the effective abatement of both hydrophilic and hydrophobic VOCs.

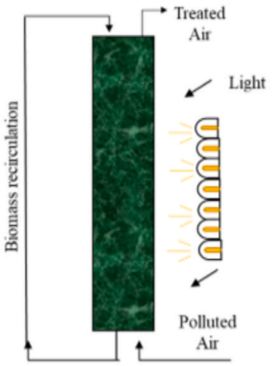
Fig. 1. Air purification biotechnologies.

substrate, among others. Table 2 summarizes recent works investigating the capacity of these plant-based botanical filters configured as green walls for indoor air purification.

The optimization of the capacity of botanical biofiltration systems entails the treatment of the largest contaminated air flowrate per unit of volume, with satisfactory removal efficiencies and long-term plant viability. In this context, the air flow treated and the residence time of the air in the biofilter are key parameters in the design of botanical filters (Irga et al., 2018). Typical residence times in these systems, according to research, range from 10 s to 2 min.

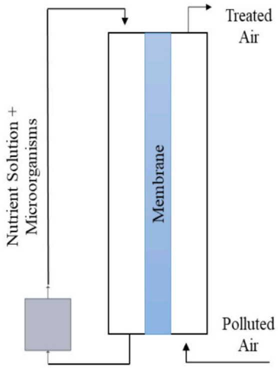
Studies on active botanical filters have focused on exploring the influence of various operational and design parameters to optimize their performance and efficiency for indoor air purification. Important parameters that have been investigated include plant species selection, contaminant types and concentrations, airflow rates, filter design and control techniques. These studies have highlighted the importance of selecting plant species with high pollutant removal efficiency and rapid growth rate to maximize filtration capacity. Yang et al. (2009) reported a classification of plants based on their total removal efficiency for certain VOCs. The plants belonged to different types of families and were classified into superior, intermediate and poor abatement categories. *Syngonium podophyllum, Chlorophytum comosum, Spathiphyllum wallisii, Epipremnum Aureum, Nephrolepis exaltata, Philodendron scandens* and *Ficus lyrate* rank among the plant species most commonly used in biofilters. At this point, it is worth mentioning that there are contradictory data on the air pollutant removal efficiency of plants, and some plants

Microalgae reactor



- Photobioreactors with algae can be a viable solution to decontaminate indoor environments with high CO_2 levels, since microalgae fix CO_2 using light as an energy source and release O_2 into the ambient air during the photosynthesis process. In addition, photobioreactors can absorb and biodegradabe hydrophilic compounds like formaldehyde and methanol based on its aqueous nature. Their potential to degrade hydrophobic pollutants, such as alkanes and polycyclic aromatic hydrocarbons, is more limited due to mass transfer limitations.

Membrane Bioreactor (MBRs)



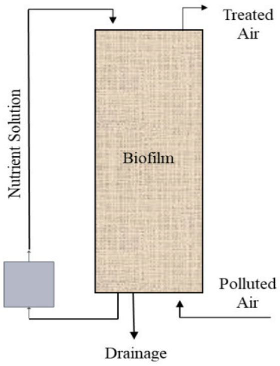
- MBRs rely on the physical separation of the indoor air and the liquid phase contanining the microbial comunity. A nutrient solution containing microorganisms capable of degrading pollutants is continuously circulated on one side of the membrane, while the contaminated air circulates on the other side, typically in a counter-current flow configuration. Over time, a biofilm of microorganisms may become attached to the aqueous side of the membrane. Pollutants diffuse through the membrane and are subsequently biodegraded by the microorganisms present in either the biofilm or the bulk cultivation medium. MBRs efficiently capture hydrophilic or hydrophobic VOCs as a function of the nature of the membrane material.

Fig. 1. (*continued*).

classified with a poor or low elimination potential in some studies have shown high pollutant elimination percentages at laboratory level. On the other hand, researchers have also evaluated different indoor air pollutants, VOCs, PM, benzene and formaldehyde at different concentrations being typically selected as model indoor air pollutants.

Typically, air pollutant removal is reported as single pass removal efficiency (SPRE). The SPRE is the proportion of a target contaminant that is filtered by the biofilter during each pass through a filtration

Biofilters, Bioscrubber and biotricking filters



- In biofilters (BFs) microorganisms are immobilized in a packed media (organic and inorganic), irrigation is intermittent, and moisture and nutrients are retained by the biofilm and packed media. Bioscrubbers consist of two separate units, where contaminants are initially transferred to the recirculating aqueous phase in a packed bed absorption unit or mist chamber from the gas phase, and finally biodegraded in a second unit where microorganisms grow in suspension. Biotrickling filters (BTFs) are standalone units with an inorganic packed media supporting biofilm growth, with a continuously irrigated nutrient solution. Biotrickling filtration and bioscrubbers are very efficient in removing hydrophilic VOCs, whereas BFs are more suitable for the elimination of hydrophobic VOCs.

Fig. 1. (*continued*).

system. In these systems, the percentage of pollutant removal is considered high above 50% and reaching up to 80–90% over 24 h. The majority of the experiments have been conducted at laboratory scale using small sealed chambers (<1 m^3).

Darlington et al. (2001) found that the highest removal rates were observed at faster fluxes (0.200 m s^{-1}) in an active botanical filter. This could be due to the uniform distribution of VOC concentrations throughout the biofilter depth. This design was one of the first to use a green wall, significantly reducing the space required for pots, housing a large number of plants in a fabric mesh with potentially greater phytoremediation. This green wall design consisted of three main components: a moss bioscrubber, a region for hydroponically grown plants and an aquarium. The bioscrubbers were composed of four fiberglass air chambers (1.2 × 2 × 0.2 m) lined with porous, constantly wetted lava rock. The authors evaluated the capacity of the green wall to abate toluene, ethylbenzene and xylene at concentrations ranging from 60 to 80 ppb$_v$. This experiment was located on the first floor of the Canada Life Assurance headquarters building in Toronto (640 m^3). Later, this system was adapted by Mallany et al. (2002) to include plants in the green façade to increase phytoremediation potential and foster the aesthetic benefits of this technology.

3.1. Mechanisms of indoor pollutant removal in plants

Plants can remove pollutants by stomatal uptake (gas pollutants get absorbed through stomata on plant leaves, where they dissolve in water and enter the plant's system), absorption (pollutants can be absorbed directly into the plant tissue through the leaf surface and transported to the roots through the plant's vascular system) and adsorption (pollutants can be adsorbed onto the surface of the plant leaves, stem, and root surfaces) (Yang et al., 2009). Most indoor air pollutants, especially VOCs, are removed in the root zone of the plants, while foliage is responsible for approx. 10% of pollutant removal (Kim et al., 2008). Microbial communities inhabiting the substrate and rhizosphere play a key role in the degradation of VOCs, with the pollutants diffusing directly into the potting mix and being absorbed by bacteria, which then metabolize them as a carbon and energy source (Irga et al., 2018).

Botanical biofiltration is a complex, symbiotic process wherein plants and microorganisms collaborate to remediate airborne contaminants. The green plants, central to this ecosystem, contribute mainly by providing "food" to microbial communities present in the rhizosphere through root exudates. However, their significance does not overshadow the role of microorganisms, which, in association with their plant hosts, can influence plant growth, development, and overall phytoremediation efficiency. In the botanical biofiltration matrix, five primary mechanisms coexist simultaneously: 1) rhizosphere biodegradation spearheaded by microorganisms. Indeed, microorganisms form biofilms on plant roots and the surface of the substrate, which can uptake and degrade a range of organic contaminants, 2) phytoextraction by the plant from the liquid medium, 3) stomatal uptake directly from the air, 4) phytodegradation within plant tissues, and 5) phytovolatilization, which involves pollutant evaporation either directly from leaves or mediated by plant transpiration (Lee et al., 2021). This intricate interplay highlights the relevance of both plant and root-associated microorganisms in the effective operation of botanical biofilters. According to the literature, the most abundant microorganisms in the rhizosphere are bacteria, followed by fungi, protozoa and algae. Bacteria such as Pseudomonas, Enterobacter, Azotobacter, Alcaligenes, Arthrobacter,

Table 2

Summary of experimental studies investigating the potential of active botanical filters for indoor air purification.

Experimental System	Air flow	EBRT	Plant species	Pollutants	Starting Concentration	Removal rate/ efficiency	Environmental conditions	Reference
Chamber: 50 L Biofilter: 0.25 m^2	0.8 L s^{-1} 2.3 L s^{-1} 3.9 L s^{-1} 5.5 L s^{-1}	62.5 s^{-1} 21.7 s^{-1} 12.8 s^{-1} 9.1 s^{-1}	*Epipremnum aureum* *Syngonium podophyllum* *Chlorophytum comosum* *Peperomia obtusifolia* *Pilea cadierei* *Aglaonema treubii*	Formaldehyde	0.3–2.0 ppm$_v$	47.1–99.9%	T: 24.6 ± 0.9 °C RH: 55 ± 10% Illumination: 248 ± 11 lux	Abedi et al. (2022)
Chamber: 216 L Biofilter: 0.25 m^2	3.8 ± 0.2 m^3 h^{-1}	203.0 s^{-1}	*Spathiphyllum wallisii*	Cigarette-derived VOCs and all size fractions of PM	Full cigarette over 8 min	TVOCs: 43.3% TSP: 34.4%	T: 23.0 °C RH: 60–65%	Morgan et al. (2022)
Testing room: 24 m^3 Biofilter: 0.05 m^2	0.2 m^3 s^{-1}	120.0 s^{-1}	*Sansevieria trifasciata*	PM$_1$ PM$_{2.5}$ PM$_{10}$ Formaldehyde Acetone	2.9–3.0 mg m^{-3} 2.9–3.0 mg m^{-3} 3.6–3.7 mg m^{-3} 123.0–148.0 mg m^{-3} 9.5–12.0 mg m^{-3}	Over 8 h: 140–250 μg m^{-3} 147–257 μg m^{-3} 212–455 μg m^{-3} Over 24 h: 46.0–69.0% 31.0–61.0% TVOC: 40.0–65.0%	T: 30.0–35.0 °C RH: 60–62% Illumination: 10 ± 3.6 μmol PAR m^2 s^{-1}	Permana et al. (2022)
Chamber: 441.792 L Biofilter: 3.25 L with 16 openings for plants.	N/A	N/A	*Nematanthus glabra* *Schefflera arborícola* *Nephropelis exaltata bostoniensis* *Nephrolepis cordifolia*	PM$_{10}$ PM$_{2.5}$	N/A	53.5 ± 16.0% 48.2 ± 14.7%	T: daytime: 18–18.5 °C; night: 21.5–22.5 °C RH: day: 62–65% night: 65–70%	Abdo and Huynh (2021)
Chamber: 0.24 m^3 Biofilter: 0.05 m^3	540.0 m^3 h^{-1} 259.2 m^3 h^{-1} 162.0 m^3 h^{-1}	1.6 s^{-1} 3.3 s^{-1} 5.3 s^{-1}	*Epipremnum Aureum*	PM$_{2.5}$ PM$_{10}$ VOCs	18.0–25.0 mg m^{-3}	54.5 ± 6.0% 65.4 ± 9.3% 46.0 ± 4.0%	T: 25.0 ± 2 °C RH: 60 ± 10% Illumination: 300 lux	Ibrahim et al. (2021)
Chamber: 0.128 m^3 Biofilter: felt-based module 0.18 m^2	N/A	N/A	*Spathiphyllum wallisii* *Philodendron hederaceum* *Ficus pumila* *Tradescantia pallida* *Chlorophytum comosum*	TVOCs n-hexane Formaldehyde	TVOCs slightly over 3.0 mg m^{-3}	76.0–92.0%	T: 15.7–26.8 °C Illumination: 6828 lux	Suárez-Cáceres and Pérez-Urrestarazu (2021)
In-situ outdoor: roadside in Sydney, Australia. Biofilter: 1 × 20 m^2. Dimensions of modules: 0.25 m^2	186.7 m^3 h^{-1} 269.3 m^3 h^{-1}	N/A	*Westringia fruticose* *Myoporum parvifolium* *Strobilanthes anisophyllus* *Nandina domestica*	NO$_2$ O$_3$ PM$_{2.5}$	Outdoor concentrations	71.5% 28.1% 22.1%.	Irrigation: ~11 L of water every 2 days.	Pettit et al. (2021)
Biofilter in - situ outdoor: 25 L	N/A	N/A	Grass or moss	PM$_{2.5}$ PM$_{10}$	N/A	78.5% 47.0%	Environmental conditions	Elkamhawy and Jang (2020)
Chamber: 1 m^3 Biofilter: 15 L	5.5 m^3 min^{-1}	10.9 s^{-1}	*Sansevieria trifasciata* *Chlorophytum comosum*	PM$_{2.5}$ Formaldehyde Acetone Benzene Xylene	980.0–999.0 μg m^{-3} 120.0–150.0 ppm$_v$ 127.0–145.0 ppm$_v$ 15.0–35.0 ppb$_v$ 30.0–70.0 ppb	80.0–90.0%	T: 30.0–32.0 °C Illumination: 12/12 h day/night	Siswanto et al. (2020)
Chamber: 144 L	N/A	N/A	*Ruscus hyrcanus* *Danae racemosa*	Benzene Toluene Ethylbenzene Xylene	10.0 μL L^{-1} 20.0 μL L^{-1} 20.0 μL L^{-1} 50.0 μL L^{-1}	8.5 mg m^{-3} h^{-1}. cm^2 22.6 mg m^{-3} h^{-1}.cm^2 17.3 mg m^{-3} h^{-1}.cm^2 86.7 mg m^{-3} h^{-1}.cm^2	N/A	Fooladi et al. (2019)

(*continued on next page*)

Table 2 (*continued*)

Experimental System	Air flow	EBRT	Plant species	Pollutants	Starting Concentration	Removal rate/ efficiency	Environmental conditions	Reference
Chamber: 216 L Biofilter: 0.25 m^2, with 16 circular compartments for plant insertion.	14.9 L s^{-1}	14.5 s^{-1}	*Chlorophytum orchidastrum* *Nematanthus glabra* *Nephrolepis cordifolia* *Schefflera arboricola*	Benzene Ethyl acetate TVOCs	4.2 ± 0.1 ppm$_v$ 4.0 ± 0.1 ppm$_v$ ~35.0 ppb$_v$	45.5–59.5% 32.4–91.2% No significant differences	T: 23.7 ± 3.6 °C RH: 68.1 ± 16.0% Illumination: 90 ± 10 μmol m^{-2} s^{-1} (4860 ± 54 lx)	Irga et al. (2019)
Residential room: 8.75 m^2 and total volume of 22.70 m^3 Biofilter: 1.5 m^2	Residential room: 2 fans with a flow rate of 320.0 m^3 h^{-1}, no HVAC.	255.4 s^{-1}	*Chamaedorea elegans* *Epipremnum aureum* *Ficus lyrata* *Neomarica gracillis* *Peperomia obtusifolia* *Spathiphyllum wallisii* *Syngonium podophyllum* *Nephrolepis exaltata* *Scheffera arboricola*	TVOCs PM	0.0–120.0 ppb$_v$ 400.0 μg m^{-3}	Residential room: TVOC and PM concentration by 72.5 %	T: 20.0–24.0 °C	Pettit et al. (2019c)
Classroom: 40.07 m^2 and a volume of 120.2 m^3 Biofilter: 9 m^2	Classroom: 283.5 m^3 h^{-1} and HVAC system.	1526.3 s^{-1}		TVOCs PM	0.0–120.0 ppb$_v$ 400.0 μg m^{-3}	Classroom: TVOC concentration by ~ 28.0% and PM by 42.6%		
Chamber: 216 L Biofilter modules: 0.25 m^2 contained 16 holes from which plants grown	0.6 m^{3}min^{-1}	21.6 s^{-1}	*Syngonium podophyllum*	Ethanol Acetone Benzene Cyclohexane Ethyl acetate Hexane Isopentane Isopropanol Toluene	1.3 × 10^{-5} mol of each gaseous VOCs	96.3% 72.7% The rest of the chemicals ranging from 19.8% to 96.3%	Illumination: 6 μmolm^{-2}s^{-1} T: 21.0 °C RH: 41.6%–55.1%	(Pettit et al., 2019a)
Total reactor internal volume: 0.9 m^3	N/A	N/A	*Spathiphyllum wallisii* *Syngonium podophyllum*	NO	1.1 ± 0.1 ppm$_v$	381.2–242.6 m^3 h^{-1} m^{-3} of biofilter substrate	Illumination: indoor light and ultraviolet. T: 22.0 °C	Pettit et al. (2019b)
				NO$_2$	6.7 ± 0.6 ppm$_v$	661.3–550.8 m^3 h^{-1} m^{-3} of biofilter substrate		
				O$_3$	7.3 ± 0.1 ppb$_v$	95.0–23.0 m^3 h^{-1} m^{-3} of biofilter substrate		
Chamber: 240 L.	100.0 ml min^{-1}	144000 s^{-1}	*Dieffenbachia maculata* *Spathiphyllum wallisii* *Asparagus densiflorus*	Toluene	20.0 mg m^{-3}	3.4–5.7 L h^{-1}m^{-2} leaf area	CO$_2$: 500 ppm$_v$ RH: 70%, T: 22.0 °C Illumination: 180 ± 10 μmol m^{-2}s^{-1} and dark	Hörmann et al. (2018)
				2-ethylhexanol	14.6 mg m^{-3}	2.0 L h^{-1}m^{-2} leaf area		
Chamber: 216 L Biofilter: 0.05 m^3 with 9 holes on the front face.	150.0 L s^{-1}	1.4 s^{-1}	*Epipremnum aureum*	TSP PM$_{2.5}$ PM$_{10}$	N/A	85.0% 75.2% 71.9%	N/A	Ibrahim et al. (2018)
Chamber: 1 m^3 Biofilter: 15 L	128.0 L min^{-1}	468.7 s^{-1}	*Zamioculcas zamiifolia* *Dracaena sanderiana* *Chlorophytum comosum* *Euphorbia milii* *Sansevieria kirkii,* *Sansevieria trifasciata*	Toluene	3.9 ± 0.8 mg m^{-3}	15.0–20.0%	Illumination: light (50 μmole PAR m^{-2} s^{-1}) and dark conditions (three cycles)	Treesubsuntorn and Thiravetyan (2018)
Chamber: 30.0 m^3. Biofilter: 15000 cm^2 in area	50.0 m^3 h^{-1}	36.0 s^{-1}	*Philodendron scandens* *Asplenium antiquum* *Syngonium podophyllum*	2-butanone (methyl ethyl ketone; MEK)	33.9 ± 0.5 ppb$_v$	14.7 ± 0.3 ppb$_v$ 56.6 ± 0.9%	T: 21.5 ± 2 °C RH: 37.5 ± 2.5% Illumination: 2500 lux (40 μmol s^{-1} m^{-2})	Torpy et al. (2018)
Chamber: 216 L Biofilter: 0.25 m^2	N/A	N/A	*Chlorophytum orchidastrum*	PM$_{0.3\text{-}0.5}$ PM$_{5\text{-}10}$	19.9 μg m^{-3} 8.1 μg m^{-3}	45.8% 92.5%	N/A	Pettit et al. (2017)

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Table 2 (*continued*)

Experimental System	Air flow	EBRT	Plant species	Pollutants	Starting Concentration	Removal rate/ efficiency	Environmental conditions	Reference
with 16 holes on the front face from which plants grow			*Ficus lyrata* *Nematanthus glabra* *Nephrolepis cordifolia duffi* *Nephropelis exaltata bostoniensis* *Schefflera amate* *Schefflera arboricola*	TSP	142.2 $\mu g\ m^{-3}$	N/A		
Chamber: 0.216 m^3 Biofilter:32.5 L	3.8 L s^{-1} 7.5 L s^{-1} 11.3 L s^{-1} 15.0 L s^{-1}	57.6 s^{-1} 28.8 s^{-1} 19.2 s^{-1} 14.4 s^{-1}	*Chlorophytum comosum*	TSP PM_{10} $PM_{2.5}$	~700.0 g m^{-3}	53.3 ± 9.7% 53.5 ± 16% 48.2 ± 14.7%	T: 23.0 ± 0.1 °C RH: 55 ± 10% Illumination: 120 mol $m^{-2}s^{-1}$	Irga et al. (2017)
Chamber: 1.0 m^3 and impervious to VOCs	6.0 L min^{-1}	10000 s^{-1}	*Schefflera actinophylla* *Ficus benghalensis*	Toluene Xylene (*m,p,o*)	62.3–50.1 $\mu g\ m^{-3}$ 49.4–43.0 $\mu g\ m^{-3}$	13.3 $\mu g\ m^{-3}\ m^{-2}$ leaf area 7.0 $\mu g\ m^{-3}\ m^{-2}$ leaf area	N/A	Kim et al. (2016)

Notes: EBRT, Empty bed residence time; T, Temperature; RH, Relative humidity; TVOCs, Total volatile organic compounds; TSP, Total suspended particulate matter; VOCs, Volatile organic compounds; PM, Particular matter; $ppb_{v,}$ Volumetric parts-per-billion; $ppm_{v,}$ Volumetric parts-per-million; HVAC, Heating, ventilation and air conditioning; N/A, not applicable.

Azotobacter, Alcaligenes, Arthrobacter, Bacillus, Serratia and Rhisobium seem to support plant growth and to be able to effectively degrade VOCs and VICs (Irga et al., 2020; Soreanu et al., 2013).

Furthermore unpublished data from a botanical filter under operation in our laboratory revealed that when plants were removed from the system, the biofilter continued to degrade VOCs at removal efficiencies of 97.45 ± 1.39% for acetone, 69.27 ± 9.45% for toluene and 49.97 ± 14.66% α-pinene, which confirms that microorganisms play a key role in the purification of indoor air.

Given that the root zone is the main responsible for indoor air pollutant removal, reactor configurations that force the air to actively pass through this zone support the highest pollutant removal efficiency. This active filtration through mechanical ventilation, along with the vertical arrangement of the plants reducing the technology footprint, represent the main advances compared to the original biofilters developed by NASA (Fleck et al., 2020).

4. Construction of active botanical biofilters configured as vertical walls

There is a wide variety of active botanical biofilters designs, constructed with the following components (OVACEN, 2020).

4.1. Active components

In passive and active systems, the type of substrate supporting plant growth, its composition and depth determine the rate of pollutant removal and plant growth. The desired substrate must guarantee structural strength, oxygen access to roots, adequate water retention and the necessary nutrients (Pettit et al., 2018a). Different substrates have been used in botanical filters as packing material, such as coconut coir-based substrate (a natural and renewable resource produced from mature coconut husks with a water holding capacity of 41.0 ± 1.3% and an air-filled porosity of 53.3 ± 0.9%) (Pettit et al., 2018b), or a 50%:50% (v:v) substrate mix of active carbon and shale pebbles (Wang and Zhang, 2011). In addition, most of the companies that manufacture aesthetic vertical walls use geotextiles or rock wool as a substrate, as they are good water absorbers.

Within the spectrum of substrates discussed in literature, granular activated carbon (GAC) is particularly effective. Its extensive specific surface area is replete with both hydrophilic and hydrophobic adsorption zones tailored for diverse pollutants, a trait that enhances its efficacy in removing a variety of contaminants. In applied settings, botanical filters can be constructed with a synergistic combination of substrates to provide an environment ideally suited for VOC elimination. Such a multifaceted substrate strategy not only targets an encompassing array of VOCs but also nurtures a dynamic microbial community, which is pivotal for optimal pollutant degradation (Matheson et al., 2023; Pettit et al., 2020). Table 3 shows the different types of substrates that can be used in botanical filters.

Pollutant removal rate varies according to the target pollutant and the plant species inhabiting the vertical wall. Yang et al. (2009) investigated the ability of 28 ornamental plants to remove five VOCs (benzene, toluene, octane, trichloroethylene and pinene). The plants were classified according to their removal efficiency into high, medium and low efficiency, concluding that the plant species supporting the highest removal efficiencies for all target pollutants were: *Hemigraphis alterna, Helera helix, Tradescantia pallida, Asparagus densiflorus* and *Hoya carnosa.* This study also revealed that multiple species could improve indoor air quality as a result of the varying removal efficiencies between plants. (Yang et al., 2009).

4.2. Structural components

Irrigation systems, waterproof membrane, air supply system and vertical wall structure are essential components to construct and maintain vertical green walls. Thus, the irrigation system can be divided into two main groups: i) systems with water recirculation, where the irrigation water trickling down through the vertical garden is collected in a tank, and pump back to the top of the vertical green wall, and ii) systems with one-pass irrigation, where the sprinkled water trickling down the vertical garden goes directly to the drain. These irrigation systems can be visualized in Fig. 2 (OVACEN, 2020).

In botanical filtration systems, the implementation of recirculating

Table 3
Type of substrate used in botanical filters.

Type of substrate	
Hydrophobic VOCs	Hydrophilic VOCs
Peat	Heather
Compost	Coconut fiber
Activated Carbon	Polyurethane foams
Wood chips	Ceramic materials
	Activated Carbon

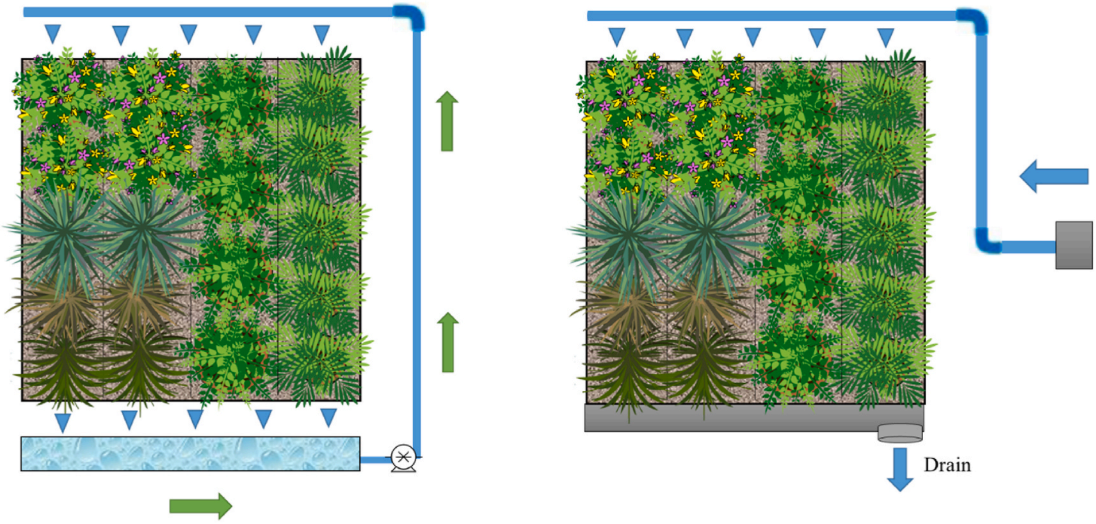

Fig. 2. Irrigation system. Left: System with recirculation. Right: System without recirculation.

and non-recirculating water supply strategies has significant implications. Recirculating systems are known for their water and nutrient savings, making them the best choice in water-scarce regions or where long-term cost-effectiveness is a priority. Although the initial costs of these systems can be high due to essential equipment, such as pumps and sensors, the long-term savings are remarkable. However, they require meticulous monitoring to mitigate the risks of toxin accumulation and pathogen proliferation. Irrigation by biotrickling systems promotes the dissolution of VOCs in the aqueous phase, enhancing the removal efficiency in botanical biofilters (Pettit et al., 2020). In contrast, non-recirculating, or drain-to-waste systems, while consuming more water, offer simplicity and consistent quality. By using fresh water and nutrients in each cycle, they minimize variables and reduce the risk of plant disease. Despite their simplicity, questions arise about their environmental impact due to the potential waste of water and nutrients. The optimal choice of the water supply system ultimately depends on the specific objectives, available resources and environmental considerations of the project.

Although data correlating purified air volume and wastewater production in a botanical filter has not been published, it is known that the main source of wastewater in these systems is the irrigation process, which depends on plant needs, air humidity and the efficiency of the trickling system. The operating configuration, especially when comparing recirculating and non-recirculating systems, greatly influences the wastewater profile. Singular Green, a company specialized in vertical wall construction and operation, has estimated that winter water consumption in a Mediterranean climate is approximately 1L m^{-2} day and summer consumption in the same type of climate is approximately 5L m^{-2} day in systems with recirculating water (Singular Green, 2023). The nature of the filter media and its moisture retention properties also play a key role in determining water retention versus wastewater generation. Other environmental factors, such as air humidity and temperature, can influence water supply and loss in these systems (Pettit et al., 2020).

The air supply in biofilters is usually provided by fans engineered to supply the air towards the planted side of the green wall, which diffuses through the substrate and leaves the system through the top surface of the system. On the other hand, the airflow is pumped through the substrate from the rear part and moves through the aerial part of the plants to finally mix with ambient air (Fig. 3) (Pettit et al., 2018a).

The volumetric airflow treated in botanical filters is an undefined characteristic that has not been consistently measured or compared among studies, which challenge a fair comparison of the performance of different filters reported in literature. A promising innovation is the

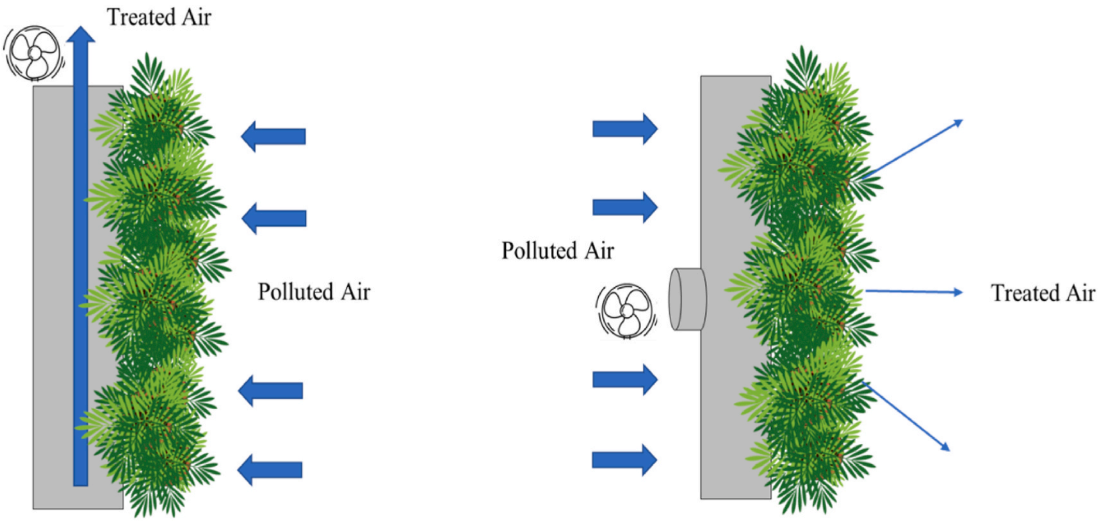

Fig. 3. Left: Airflow directed towards the front of the green wall. Right: Airflow directed from the rear section in an active green wall.

integration of botanical biofiltration with HVAC systems (Wang and Zhang, 2011), thus being more beneficial when applied *in-situ*.

4.3. Auxiliary elements

Wall separators, water evacuation systems, automatic irrigation devices and artificial lighting can be implemented into botanical biofilters to support a higher overall air purification performance.

5. Benefits of green walls

5.1. Indoor air quality

Some studies have found that chemicals such as formaldehyde and carbon monoxide can only be removed by plant leaves, while VOCs such as trichloroethylene (TCE), xylene, toluene, benzene and many other toxic carbonaceous chemicals can be removed by plant roots or by microorganisms living adhered to the roots (Wolverton et al., 1989). In this context, green walls can substantially improve indoor air quality. For example, a four-story building with a vertical garden façade filtered out 40 tons of harmful gases per year (Wolverton et al., 1989) and one square meter of vegetation cover generated the oxygen needed by one person throughout the year (Darlington et al., 2001) using little or no valuable space (Fig. 4).

5.2. Noise pollution, odors and energy savings

Plants and trees have been used for years as barriers against traffic and other types of urban noise pollution (Kotzen and English, 2009). Green walls installed outdoors can isolate noise, vibrations and reduce sound penetration. Indeed, the vegetal finish (plants + substrate) reduces noise by reflecting, refracting and absorbing acoustic energy.

For instance, a layer of vegetation can reduce noise pollution by up to 10 dB and lower the indoor temperature of a building by up to 5 °C in summer and maintain it in winter, thus generating significant energy savings (Singular Green, 2022). Botanical filters as indoor air purifiers are used in green building certifications to help make buildings sustainable, healthy, energy efficient and environmentally friendly.

These vertical plant installations are adapted to absorb gases such as VOCs and VICs, which are the main source of indoor odors. The rich microbial activity in the roots of the plants embedded in the substrate breaks down odor-causing organic compounds, while the dense wall structure captures particles that carry these odorous substances. In addition, some plants introduce pleasant fragrances, naturally covering unwanted odors and contributing to a fresher and more pleasant indoor environment. Although there is no specific research on this topic, green walls help improving the aesthetics and smell of indoor spaces.

5.3. Health and wellness

Green walls provide a substantial and spiritual connection to nature. A study conducted at Washington State University (Lohr et al., 1996) concluded that when plants are present in the workspace, workers were more productive (12% faster reaction times) and less stressed. In addition, gardens incorporated into hospitals have been shown to calm patients, improve their well-being and promote improved clinical outcomes, such as reduced analgesic intake and reduced pain medication and length of stay (Ulrich, 2002). These studies confirmed that green walls integrated in work and living spaces improves people's health and well-being as the simple fact of seeing plants in the environment provides a positive physiological and psychological response.

6. Limitations of botanical biofiltration

The key issue associated with active botanical filtration is the maintenance required for the persistence of healthy plants and associated microbial populations. The uptake of contaminants can compromise the health of planted species, which together with the specific requirements of each species becomes a crucial aspect for the development and maintenance of this novel biotechnology (Soreanu et al.,

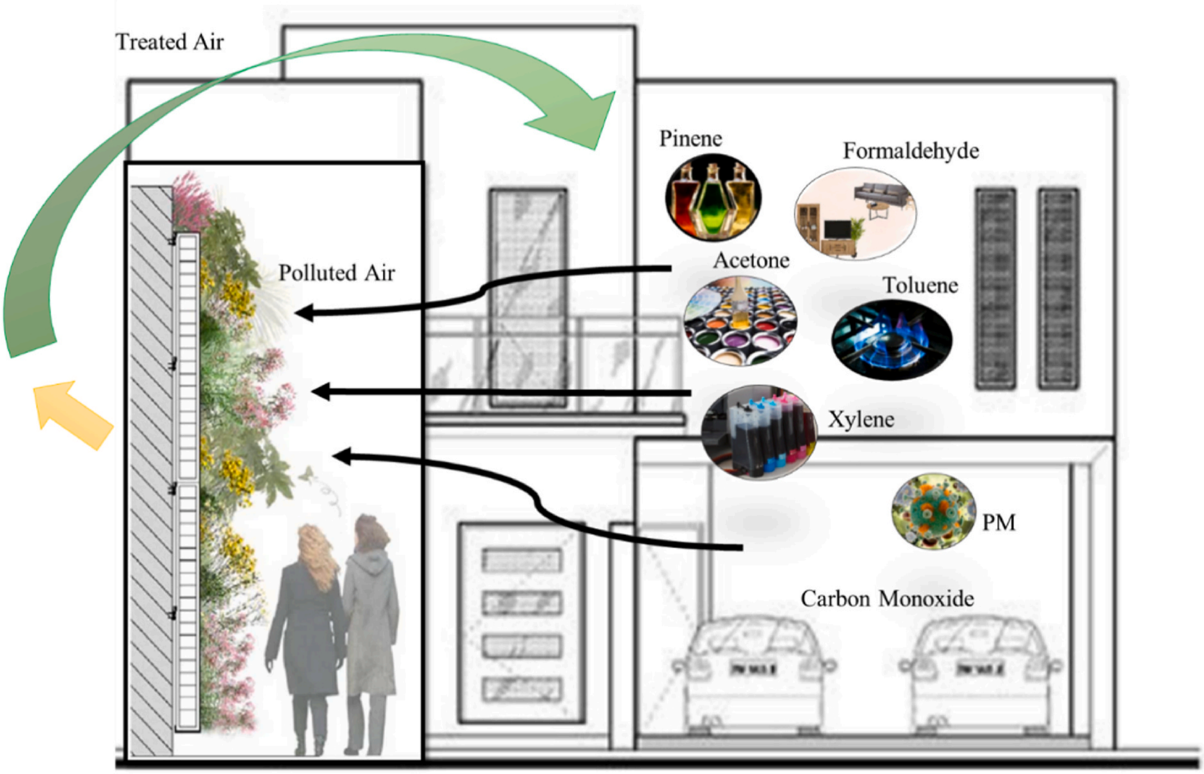

Fig. 4. Removal of major indoor air pollutants through a green wall.

2013). For instance, plants being vertically aligned require a time of adaptability to their new growth mode, requiring specialized irrigation systems because drainage must cover their needs. Although some studies have suggested that certain species are more efficient at phytoremediation of certain contaminants than others (Kim et al., 2010; Pettit et al., 2017; Torpy et al., 2014), it is likely that all plant species and their indigenous microflora exhibit significant pollutant removal capabilities, so the ability of plants to thrive in active botanical biofilter conditions is an equally important consideration as contaminant removal capacity.

The presence of an aerated and humid system with a large number of plants clearly presents the potential to increase the relative humidity of the indoor space (Guieysse et al., 2008). Wang and Zhang (2011) observed an increase in humidity of 17.7% in an office containing an active botanical biofilter. This increased relative humidity can promote mold formation and deterioration of building materials. In fact, humidity should be kept below 65% (Soreanu et al., 2013), which can be achieved through a balance of proper irrigation, airflow rates, and substrate selection, as these are all factors that can influence air humidity. Botanical filters for indoor air can be operated across the entire World, as the operating variables can be controlled. Although northern latitudes, characterized by limited solar irradiation and colder temperatures, pose specific challenges to biological systems outdoors, indoor botanical filters can be operated over the entire year. However, in order to take full advantage of their filtration capabilities, it is critical to select native or cold-tolerant plants and implement artificial lighting.

On the other hand, botanical filters can induce indoor spore contamination. For instance, Darlington et al. (2001) demonstrated that operating botanical biotrickling filters at a cool temperature, i.e., a few degrees below the indoor environment, prevented excessive humidity, promoted VOC removal and limited the likelihood of pathogen formation. To date, there are few studies of active botanical biofiltration that included microbiological evaluation (Darlington, 2000; Mallany and Darlington Alan, 2000; Wolverton and W.J.D, 1996), and none of these studies confirmed pathogen proliferation, when comparing total spores concentrations with the total spores concentration typically found in health indoor air environments. However, further microbiological research is needed before biofiltration can be used effectively in certain types of buildings and locations.

7. Examples of commercial botanical filters for indoor air

Today, botanical filters have become popular for improving indoor air quality and aesthetics. Interestingly, despite the market is gradually expanding, only a few systems have demonstrated a satisfactory and long-term removal efficiency for pollutants such as VOCs. Typically, green walls are not installed as a necessity to control indoor air quality, but for indoor landscaping and are popular in buildings, offices, shopping centers, etc. Green walls are installed primarily for aesthetics purposes and help aligning company branding with sustainability (Ambius, 2022). These structures are composed of vegetation attached directly to a wall or contained in a modular system, creating a natural cladding that can span from a few square meters to entire facades. In addition, green walls increase the value of a property (houses, buildings, businesses, etc.). Indeed, studies have shown that having plants in and around a property can increase real estate values by up to 15% (Weinmaster, 2009).

In fact, many buildings around the World have incorporated green walls into their design. Examples of green façades include the Musée du Quai Branly in Paris, which in 2004 incorporated 376 plant species into its 1800 m^2 façade, and the Corte Inglés shopping mall in Valladolid, whose 351 m^2 green wall was built in 2020 with outdoor plant species. There are also indoor green walls such as the central atrium of the University of Guelph-Humber, which has a 150 m^2 plant wall composed of more than 1000 plants of 100 different species, and the offices of the

Fig. 5. Examples of botanical filters. **A.** Musée du Quai Branly – Paris, France. **B.** Outdoor vertical garden in Corte Inglés - Valladolid, Spain. **C.** Biofilter of the University of Guelph's central atrium – Humber, Toronto. **D.** Singular Green Company – Alicante, Spain.

company Singular Green with 25 m^2 of plant area with multiple indoor plants (Fig. 5) (Paisajismo Digital, 2020; Singular Green, 2020; University of Guelph-Humber, 2020). These examples highlight the versatility and beauty of green walls. They represent an important step towards creating healthier and more sustainable urban environments. As cities continue to grow and face increasing environmental challenges, innovative and effective solutions such as active green walls for air quality management are increasingly necessary.

8. Conclusions

Botanical filters such as green walls and potted plants have shown promising results for the removal of indoor air pollutants. Recent studies have consistently demonstrated the ability of air-purifying plants to effectively remove various pollutants, including VOCs and PM, obtaining removal efficiencies higher than 50%, thereby enhancing the overall air quality in indoor environments. These systems are based on the natural ability of plants to absorb and metabolize pollutants through their leaves and roots, as well as the biocatalytic activity of the microbial community present in the substrate and rhizosphere. Certain plants, commonly used to decorate indoor environments, such as *Epipremnum aureum* (Pothos), *Syngonium podophyllum, Chlorophytum comosum*, *Spathiphyllum wallisii and Nephropelis exaltata bostoniensis* can support high rates of pollutant removal due to their unique physiological characteristics and high transpiration rates. In this context, understanding the specific pollutant-plant interactions can aid in selecting the most efficient plant species for filtration purposes.

The performance of active botanical filters implemented in green walls are ultimately determined by the air relative humidity, temperature, airflow, pollutant concentrations, type of plants, etc. These variables differ greatly among research studies, hindering the identification of the most effective design and operational conditions. Indeed, further research is needed to develop high-performance botanical filters combining VOC removal and aesthetic at laboratory scale and further scaling up. Future work should also focus on investigating the role of plant-microbe interactions in pollutant removal, and assessing the economic and environmental benefits of implementing botanical filters in various indoor settings.

Botanical filters, encompassing both aesthetic allure and wellness-enhancing properties, have attracted attention for their dual capability in phytoremediation and biofiltration. However, when targeting hydrophobic VOCs, the benchmarking of botanical filters performance against traditional biofiltration systems, namely biofilters (BFs) and biotrickling filters (BTFs), is still required. Over time, technological improvements on conventional BFs have resulted in a robust microbial degradation performance and consequently in a reliable efficiency when handling hydrophobic VOCs. An intrinsic advantage of BFs is their operation without a mobile liquid phase, beneficial for treating water-insoluble pollutants (Barbusiński et al., 2020). In contrast, BTFs, which are characterized by their compact nature and ability to treat high pollutant loads, leverage a liquid phase to solubilize and degrade VOCs, making them especially suitable for challenging applications where BFs might falter. However, despite their merits, BFs can face operational challenges, such as a poor moisture and pH regulation, alongside major concerns, such as medium clogging and deterioration (Vikrant et al., 2017). Considering the advantages and disadvantages, botanical filters provide multidimensional appeal, especially in populated areas while BFs and BTFs do not. These biotechnologies typically provide a high VOC removal performance. In conclusion, the selection of the optimal indoor purification biotechnology should be based on contaminant characteristics, operational considerations, space constraints and the broader set of desired outcomes.

CRediT authorship contribution statement

María Sol Montaluisa-Mantilla: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Pedro García-Encina:** Writing – review & editing, Supervision, Funding acquisition, Project administration, Resources, Visualization. **Raquel Lebrero:** Conceptualization, Visualization, Project administration. **Raúl Muñoz:** Supervision, Writing – review & editing, Funding acquisition, Project administration, Resources, Visualization.

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.chemosphere.2023.140483.

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