4.26 Can Plants Really Improve Indoor Air Quality?

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Glossary

BIAB Botanical indoor air biofilter composed of green plants, a porous root medium and hydroponic nutrient solution delivery to sustain the plants, and associated microbial communities in the root zone. The biofilter represents a complex, plant-based ecosystem that brings the contaminated indoor air stream into intimate contact with the contaminant-degrading microbes present in the rhizosphere.

biofiltration The filtration and metabolic breakdown of contaminant compounds, usual in soil or water but also indoor air.

phytoremediation Term used to collectively describe a multitude of mechanisms whereby green plants promote the capture and degradation of soil and groundwater contaminants.

PPM Potted plant microcosm, a term to describe the mini-ecosystem composed of a potted plant, the potting medium, and associated microbial organisms.

rhizosphere Root zone of plants in which roots access water and mineral nutrients and a broad spectrum of microbiological activity is undertaken by bacteria and fungi, both beneficial and pathogenic.

sick building syndrome Modern term used to describe the effects of tightly sealed (energy-efficient) buildings on atmosphere quality and human health. It includes both physiological and psychological responses to poor indoor air quality.

VOC Volatile organic compound, a common term in modern scientific literature, which includes the wide range of gaseous compounds that can emanate from paints, building materials, electronic components, and human activities and potentially accumulate in indoor spaces as contaminants.

4.26.1 Introduction

More than two centuries ago, while studying the properties of air, Joseph Priestley took particular note of the influence of different living things on air quality. He is credited for the discovery of oxygen and for demonstrating the necessity of gas exchange between living organisms and their surrounding atmosphere. Priestley famously demonstrated that a mouse could survive markedly longer inside a sealed vessel when it also contained an illuminated plant. In 1771 he wrote that "The injury which is continually done to the atmosphere by the respiration of … animals … is, in part at least, repaired by the vegetable creation." With these experiments, Priestley pioneered the research into the positive influence of green plants on the air quality of occupied indoor environments. He went on to have a profound influence on the foundations of modern chemistry and particularly the nature of atmosphere constituents and interactions with living organisms.

In modern times, indoor air quality (IAQ) has become a serious concern as buildings have been increasingly sealed in an effort to reduce energy consumption. Reduced ventilation and leakage rates lower the energy required to treat incoming air to ambient indoor conditions. This is most evident in areas of climatic extremes where the outdoor air (temperature and humidity) can vary significantly from indoor environments. However, a reduction in fresh air intake can also result in the accumulation of gaseous contaminants within the indoor environment, leading to a variety of occupant health concerns. Since urbanites spend in excess of 90% of their lives indoors, the quality of the ambient indoor environment can have serious implications.

Indoor air characteristically contains a large consortium of volatile organic compounds (VOCs), ranging widely in spatial and temporal concentrations [1, 2]. These contaminants arise from a wide variety of sources including building materials, cleaning

supplies, electronics, and occupant activities [3, 4]. The VOCs associated with poor-quality indoor air also range widely in physical properties such as solubility and biological activity. Single VOC concentrations are typically between 10^{-2} and 10^{2} μg m^{-3} and total VOC concentrations ([tVOC]) between 10^{2} and 10^{3} μ m^{-3} [1, 5]. Numerous mechanisms have been suggested whereby living plants and their associated microcosms could have the potential to improve IAQ. These mechanisms include

1. adsorption of gaseous contaminants and particulate (dust and bioaerosols) onto leaf surfaces [6–8],
2. absorption of gaseous contaminants through stomata and accumulation in various internal structures [9, 10],
3. degradation of gaseous contaminants through various metabolic pathways [9, 11, 12],
4. removal of CO_2 and production of O_2 through photosynthesis,
5. increasing humidity levels through leaf transpiration and evaporation from rooting media [8, 13], and
6. reducing airborne concentrations of dust and bioaerosols [8].

The purpose of this article is to examine a number of interpretations of the interactions between biological systems and IAQ and present a quantitative assessment and rationalization of the mechanisms involved. Further, the article sets out to address the level of impact these benefits might reasonably be expected to have within occupied environments and highlight recent advances in botanical biofiltration.

4.26.1.1 Impact of House Plants on CO_2/O_2 Balance in Occupied Spaces

The predominant indoor gaseous contaminant is carbon dioxide (CO_2), which is emitted every time we exhale. Background atmospheric CO_2 levels are currently about 400 ppm, while exhaled air is roughly 100 times higher (i.e., 40 000 ppm). It is not hard to see why CO_2 levels can quickly rise in tightly sealed, high-occupancy environments. Since elevated CO_2 concentrations have been linked with drowsiness and reduced productivity [14], most government regulations stipulate maximum allowable CO_2 concentrations of less than 1000 ppm higher than background levels [15]. Furthermore, since it is easily measured, the indoor CO_2 concentration is commonly used to indicate the potential for other gaseous pollutants to accumulate within the indoor environment. In fact, CO_2 is one of the main parameters used to determine ventilation rates in occupied spaces [4].

Green plants remove atmospheric CO_2 through the process of photosynthesis. The potential for plants to scrub CO_2 in the indoor environment is a common marketing tool used to sell foliage plants. However, upon closer examination of the key environmental variables, it seems unrealistic that potted plants would be capable of significantly reducing indoor CO_2. This is mainly due to low light levels in the indoor environment, which are often at or very near the photosynthetic compensation point of most common indoor plants [16, 17]. In addition, many potting mixes contain decomposing organic matter that produces CO_2. In fact, under low-light conditions, the 'potted plant microcosom' (PPM) can be a net producer of CO_2. Furthermore, the low level of gas exchange between the PPM and the air, relative to background air exchange rates, is insufficient to promote significant CO_2 reductions. This argument will be further elucidated in the following section on VOCs.

A corollary argument has been made that indoor plants can increase O_2 concentration in the indoor environment and thus contribute to the enhancement of air quality [18]. However, the process of photosynthesis exchanges CO_2 for O_2 in roughly molar equivalent rates. Even if plants could exchange 100% of the ambient CO_2 for O_2, this would have an insignificant effect on the much higher ambient O_2 concentration, which is roughly 210 000 ppm.

Clearly, the argument that indoor plants can have a significant impact on ambient CO_2 and O_2 concentrations is not realistic in most indoor environments.

4.26.2 Phytoremediation in the Indoor Environment

Phytoremediation is the term used to collectively describe a multitude of mechanisms whereby green plants promote the capture and degradation of soil and groundwater contaminants [9, 19]. There is a significant body of literature describing the potential for potted plants to capture, sequester, and/or biologically degrade various gaseous VOCs and other environmental contaminants from the indoor environment.

4.26.2.1 VOC Removal by the Potted Plant Microcosm: Static Chamber

Wolverton and his colleagues have been credited with pioneering this field of study, in conjunction with NASA's research on biological life support systems for space travel [20]. Their studies used static pull-down experiments, whereby small, sealed chambers containing plants were spiked with specific contaminants (formaldehyde, benzene, trichloroethylene (TCE)) and the headspace concentration was monitored over time [20–22] (Wolverton and Wolverton 1993). These studies positively demonstrated that potted plants could remove substantial amounts of gaseous VOCs in sealed chambers, with reductions ranging from 10% to 90% in 24 h.

It was initially believed that the foliage was the primary contributor to the VOC reduction [20]. It was later shown that the main mechanism for VOC reduction was rhizosphere microbial activity [7, 23, 24] (Wolverton and Wolverton 1993). The foliage played a minor role [10, 25, 26] and in some cases actually inhibited contaminant reduction by forming a boundary layer over the soil surface [22, 23, 27].

Many plant varieties have been investigated using the static pull-down method as a rapid-assessment technique to determine the potential interactions between plant variety and VOC species [12, 27, 28]. Most of these tests have used unrealistically high concentrations (i.e., 10–100 times higher than typical indoor [tVOC]) and very small chamber volumes (i.e., >0.5 m^3 per plant). Only the latest published studies have approached realistic indoor concentrations [12, 27].

4.26.2.2 Extrapolating Static Chamber Results

While the potential for the PPM to remove gaseous VOCs has been demonstrated, the static pull-down approach does not reflect realistic conditions in typical indoor environments in terms of contaminant concentrations or prevailing environmental conditions including ventilation rates. Despite this, many attempts have been made to extrapolate these results to estimate the numerical requirements for plants in specific indoor environments.

In their initial publication [20], Wolverton *et al.* calculated that roughly 70 spider plants were required for a modern, energy-efficient 1800 ft^2 home (0.42 plant m^{-2}, based on pull-down of formaldehyde). In a later publication that estimation was reduced by a factor of 3 by cross-referencing empirical pull-down data with US Environmental Protection Agency (EPA)-published mean [tVOC] (Wolverton and Wolverton 1993). More recently Wood, Orwell, and their colleagues have published numerous studies that utilize Wolverton's basic methodology to examine a number of different plant varieties, gaseous contaminants, and contaminant exposure regimes [7, 17, 24, 27, 29]. Yan-Ju *et al.* [12] calculated benzene removal rates in terms of leaf area for a variety of plants. In extrapolating the results of their chamber trials, they concluded that certain plants would take between 0.44 and 5.39 h to remove 150 ppb of benzene in a typical-sized room. A strong argument, based on simple first-order kinetic theory (elucidated by J. R. Girman, Chief of the Analysis Branch at EPA's Indoor Air Division), has been made against these claims [30]. Girman's calculations suggest that, based on the static pull-down results, the required plant density would be about 5 plants m^{-2} (680 plants per house), which is obviously far beyond reasonable practicality. Despite this discrepancy, the belief that simple potted plants can significantly improve IAQ continues to persist in scientific [7, 12, 27, 28] and popular literature. For example, a short video presentation by Kamal Meattle [18] (2009 TED Conference) has recently been given widespread exposure on the Internet. This video describes how 1200 potted plants comprised of three varieties are all that is required to "grow all of the fresh air" in an entire 4600 m^2, 300-occupant facility. However, aside from a brief reference to Wolverton's two-decade old work, there are no systematic, quantitative assessments given to support the claim that these plants significantly improved measurable aspects of IAQ.

4.26.2.3 PPM Field Trials

Wood *et al.* [17] attempted to empirically quantify the difference the PPM might have in a real-world setting. They compared the [tVOC] in various single-occupant offices containing 0 (reference), 3, or 6 plants. A broad-spectrum ppbRAE portable gas detector was used to measure [tVOC], calibrated in isobutylene equivalent units. This device cannot differentiate between gaseous contaminants; however, it is capable of measuring realistic indoor [tVOC] in real time. They also characterized the VOC profile of the air using 3M™ organic vapor monitors (OVMs) followed by subsequent analysis by gas chromatograph/mass spectrometer (GS/MS). Their results showed 47–69% lower [tVOC] in offices containing plants, when reference offices were above 100 ppb. They concluded that the PPM could improve IAQ in real-world settings and that a minimum threshold [tVOC] of about ~100 ppb is required to induce the biological contaminant reduction mechanism. It should be noted that this concentration is an order of magnitude lower than it is commonly believed necessary to support biological degradation [31, 32]. In their follow-up lab trials, Orwell *et al.* [27] demonstrated induction of VOC removal at initial [tVOC] concentrations as low as 200 ppb. However, they did not verify their previous hypothesis by examining initial [tVOC] less than 100 ppb.

Guieysse *et al.* [32] highlighted the challenges in inducing and maintaining the degradative capacity of any biological indoor air treatment system at typical indoor [tVOC]. However, they determined it was possible to biologically degrade VOCs at typical indoor concentrations.

4.26.3 Gas Exchange between the PPM and Its Surroundings

The level of gas exchange between the bulk indoor air stream and various components of the PPM is critical to understanding the potential mechanisms for contaminant removal in occupied spaces. However, to date, no attempts have been made at directly quantifying gas exchange between the PPM and its surroundings.

In order to have significant levels of contaminant removal, the rate of gas exchange between the PPM and the surrounding air must compare favorably with other contaminant reduction mechanisms within the environment (e.g., ventilation). However, the indoor air stream is reasonably still, with mean air velocities of only 2–20 cm s^{-1} for ventilation rates between 0.5 and 5 air changes per hour (ACHs) [33, 34]. Therefore, large boundary layers will surround the PPM. For example, at 10 cm s^{-1}, the leaf boundary layer for typically sized indoor plant leaves is between 4 and 7 mm [35, 36]. This means that diffusion, which is an inherently slow process, will have a significant role in gas exchange. This role is magnified with the understanding that VOC degradation occurs predominantly inside the rhizosphere, which is physically isolated from the air stream by the surface layers of potting media and the aerial portions of the plant.

It has been suggested that transpiration, which draws air into the rhizosphere to replace the volume of water taken up by the roots, naturally promotes convective gas transfer to the rhizosphere. However, foliage plants only transpire between 0.2 and

$0.7\ l_{(water)}\ m^{-2}{}_{(leaf)}\ d^{-1}$ [13, 37]. At saturation most potting soils contain about 25% water by volume. Therefore, the convective force due to transpiration could only draw a maximum of $0.25\ l_{(air)}\ l^{-1}{}_{(soil)}\ d^{-1}$. Hence, with respect to the total air volume in an occupied environment, the convective force of transpiration will have an insignificant impact on gas exchange.

Furthermore, if there were an effective mechanism to enhance gas exchange between the air and the rhizosphere, a concurrent release of water vapor from the soil would significantly raise ambient humidity levels and rapidly dry out the potting medium. However, this did not happen in either of the recent studies by Kohlrausch *et al.* [13] and Wood *et al.* [17]. Rapid water loss from the soil would also have a deleterious effect on microbial activity.

Clearly, the interpretation of the mechanisms involved in the interactions between the PPM and the indoor aerial environment (through modeling or empirical determinations) has not yet been conclusive.

4.26.3.1 The PPM as a Biofilter: A Best-Case Scenario

In order to achieve the level of contaminant reduction (47–69%) reported by Wood [17], the best-case scenario in terms of promoting gas exchange would be if the PPM were operating as a biofilter. Biofilters utilize pressure a differential to actively force a contaminant stream through a bed of microbially active media. Biofiltration is a time-proven technology with applications in many industries that produce concentrated waste-gas streams. However, it is not widely recognized as a potential technology for improving IAQ [31, 32] mainly because of ultralow contaminant concentrations and relatively high treatment volumes.

Based on the published room sizes and air-handling characteristics, the total volume of air that passes through each room ranged from 180 to 400 $m^3\ h^{-1}$. Therefore the PPM would have to treat a minimum of between 84.6 and 276 $m^3\ h^{-1}$, assuming 100% removal efficiency (RE) to achieve the reported reductions in ambient [tVOC]. This agrees well with the simulation by Guieysse *et al.* [32], which determined a volumetric flow of *c.* 400 $m^3\ h^{-1}$ would be required at 80% RE to realize a 90% reduction in [tVOC] in a 100 m^3 room that is ventilated at 3 ACH. Assuming a soil depth equivalent to the pot diameter, these volumetric air flows correspond to velocities through the soil matrix of between 5.56 and 40.8 $cm\ s^{-1}$ (i.e., gas residence times (GRTs) between 0.185 and 2.04 s). These GRTs, in turn, correspond to differential pressures between 5 and 40 $cm_{(water)}$, based on data from coarse media biofilters of similar depths [38]. These values are in line with conventional biofilters, which utilize blowers to create the pressure differential across a packed bed of a porous substrate (e.g., compost). However, the PPMs in the literature are sitting in the open with very little forced air passing across the soil surface and no mechanism for creating the necessary pressure differential between the top and the bottom of the pots.

The concept of using forced-air systems to promote convective gas exchange in the rhizosphere has had considerable attention, and various patented designs are currently commercially available including the following:

1. The Bel Air system, by Matthieu Lehanneur (http://www.mathieulehanneur.com, last accessed 5 July 2009).
2. Eco-planter, a device currently produced and marketed in Japan by Actree Corporation in collaboration with Wolverton (http://www.actree.co.jp/eco_planter.html, last accessed on 5 July 2009). PhytoFilter Technologies has the exclusive US license to the Eco-planter technology (http://www.phytofilter.com, last accessed 5 July 2009). The Eco-planter is described as having air flow rates as high as 1870 $m^3\ d^{-1}$.
3. US Patent #5277877, January 1994, describes a 'room air purifier' consisting of a blower, a lower water bath, and a depth of soil (that may contain plants), and a means of maintaining the soil moisture content. It is suggested that this device will be capable of treating between 400 and 500 $m^3\ d^{-1}$.

However, none of these systems is capable of promoting significant rates of gas exchange while also adequately addressing water loss. Acceptable indoor temperature and relative humidity levels range from 18 to 20 °C and 30% to 60%, respectively. With respect to this range, there is the potential for every cubic meter of air that is treated to remove from 3.5 to 15.6 g of water from the rhizosphere. On average, a liter of water will be lost for every 88 m^3 of air treated. Hence, the Eco-planter would lose between 6.6 and 29.2 $l\ d^{-1}$ while the unit described in US Patent #5277877 would lose between 1.4 and 7.8 $l\ d^{-1}$, yet it is described as only needing weekly water additions. Therefore, the lower water bath would have to be at least 80 l in volume.

These calculations are supported by empirical water-loss data that have been collected on similar systems operating in an environment having mean temperature of 25 °C and relative humitity (RH) of 40%. These systems had a mean water loss of $11.5\ g_{(water)}\ m^{-3}{}_{(air)}$, as determined gravimetrically and by data-logging thermohygrometers located in the inlet and outlet air streams (Llewellyn and Darlington, 2006 unpublished internal technical note).

It would be virtually impossible to create a stand-alone PPM that could operate effectively at these rates of water loss without a continuous source of water resupply. Furthermore, the water would have to be of very high purity; otherwise, dissolved salts would rapidly accumulate in the rhizosphere, inducing salt-related stress in the microbial community and the plants.

4.26.3.2 Active Botanical Biofiltration

Several studies have addressed the shortcomings of the potted plant approach and have assessed complex, plant-based ecosystems that bring the contaminated indoor air stream into intimate contact with the contaminant-degrading microbes present in the rhizosphere [39–45]. This technology effectively hybridizes the positive attributes of PPM and biofiltration approaches to contaminant removal, resulting in a botanical indoor air biofilter (BIAB).

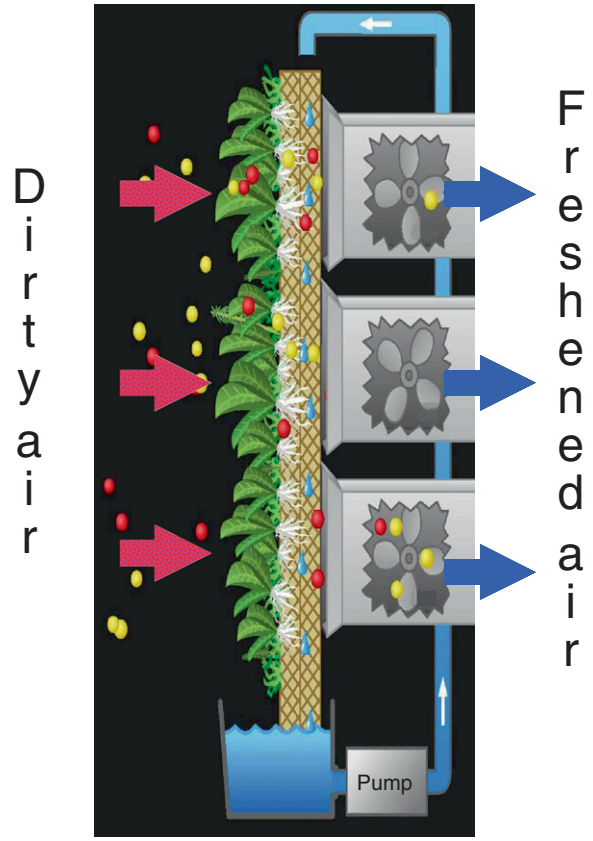

Figure 1 Schematic of botanical indoor air biofilter design, taken from http://livebuilding.queensu.ca/green_features/biowall.

The basic design (**Figure 1**) consists of plants rooted into a thin (~5 cm), stable, and very porous medium that is oriented in the vertical plane. Water flows gravimetrically from the top of the biofilter and is recirculated. Fans located in a plenum behind the biofilter draw air horizontally through the rooting medium and circulate the exhaust air back into the indoor environment. Air velocities range from 0.01 to 0.5 m s^{-1}, resulting in GRT from 0.1 to 2 s, all with extremely low pressure differentials.

These systems have undergone over 15 years of focused research and development and have been well characterized in the literature. BIAB technology has been extensively tested for contaminant removal and many other aspects of design and operation in a variety of configurations ranging from benchtop to full scale (e.g., >100 m^2).

The laboratory test environment utilized a customized gas sensing and emitter system that permitted automatic sampling from up to eight locations as well as simultaneous feedback control of ambient concentrations of up to four surrogate contaminants. With this design, the exhaust of six separate biofilter modules was sampled once per hour while maintaining tight control on the ambient concentrations of surrogate VOCs. This arrangement permitted the design of statistically relevant experiments with replication.

Many different VOCs have been tested with this system including: ketones (acetone, methylethylketone and methylisobutylketone), alcohols (ethanol, butanol), BTEX (benzene, toluene, ethylbenzene, o-xylene and p-xylene), halogens (trichloroethylene, dichloromethane and tetrachloroethylene), limonene and pinene. Ammonia and carbon monoxide have also been tested, using alternate gas sensors (Richard et al. 2002; Munz et al. 2002).

Depending on the experiment, each VOC concentration was controlled anywhere between 20 and 300 ppb (detection limit <5 ppb). Rather than maintaining stable concentrations, most experiments had varied concentrations, typically ranging from 25 to 100 ppb, in a controlled, diurnal profile.

Many experiments have been carried out investigating the effects and various aspects of BIAB design and operation on VOC removal. These include

1. the effect of temperature and airflow [39, 44, 45],
2. different plant varieties and planting densities [47, 48],
3. different media substrates [45], and
4. nutritional aspects [40, 49].

In all cases where BIABs have been challenged with surrogate VOCs using this system, they showed rapid acclimation (rates dependent on specific VOC), generally reaching steady-state removal efficiencies in 5–10 days. Depending on the circumstances,

Figure 2 Example of a typical botanical indoor air biofilter installation, located in the atrium of the University of Guelph-Humber building, Humber College, http://www.guelphhumber.ca/, photo courtesy of Nedlaw Living Walls Ltd.

steady-state elimination capacities have ranged from 0.15 to 4 g m^{-3} h^{-1} for ketones and 0.08 to 1.6 g m^{-3} h^{-1} for BTEX [39, 40, 42, 44, 45, 48, 49].

Ultralow ambient VOC concentrations (i.e., <10 ppb) have also been tested, using a pre-concentration system with the gas chromatograph (GC) [49]. In this trial, 8 out of 12 biofilters showed acclimation to mean toluene concentrations of <5 ppb. Post acclimation, the biofilters showed mean RE of 30%, corresponding to a mean elimination capacity of 0.035 g m^{-3} h^{-1}. When considering the low VOC concentrations and very short GRT, the elimination capacities of BIAB systems compare favorably to conventional biofiltration systems [31].

A commercial venture (www.naturaire.com) has developed over the last decade to design and market BIAB systems. Numerous botanical biofiltration systems are now actively cleaning the air in a variety of commercial and institutional settings, all across North America. **Figure 2** shows an example of a typical BIAB installation, located in the foyer of an educational institution in Toronto, Ontario.

4.26.4 Effluent Quality

Since indoor air biofilters treat the air through recirculating it, effluent quality is of great significance. The two most important issues are humidification and the potential for contaminating the treated air with particulate and harmful bioaerosols.

Bioaerosol (including *Legionella* spp.) and particulate concentrations have been routinely monitored in laboratory experiments as well as field trials and commercial installations. While the potential certainly exists, BIABs have never been shown to significantly increase background bioaerosol or particulate concentrations [41, 50, 51].

There is no direct mechanism for current BIAB technology to manage water loss and subsequent effluent humidification. Commercial installations are connected to sources of high-purity water (e.g., distilled, deionized, reverse osmosis) to manage water loss. Excessive humidification has been typically managed with condensers located in the effluent stream. Another potential currently being investigated is directly cooling the recirculating water in the biofilter. This strategy also promotes increased aqueous solubility of gaseous contaminants. In some cases the additional humidity has been found to be beneficial to the indoor environment, especially in colder and dryer climates.

Both the issues of water loss/humidification and bioaerosol production are currently being addressed with a new design that integrates hydrophobic membrane technology with the conventional BIAB design. This new design places a physical barrier between the air stream and the biofilter matrix, effectively eliminating the potential for biocontaminating the effluent stream. Guieysse *et al.* [32] identified the potential for membrane systems to be used in IAQ applications; however, they cited a need to demonstrate VOC removal at realistic concentrations. Early designs of the hybrid membrane–botanical biofilter have shown acclimation to MEK and toluene at inlet concentrations varying from 60 to 180 ppb, with elimination capacities similar to other botanical biofilters [52].

However, these biofilters had very high differential pressures and did not adequately resist water loss. Subsequent designs, utilizing a different membrane composition, have shown similar VOC removal but at much lower differential pressures. In addition, the rate of water loss has been reduced by about 95% [53].

4.26.5 Conclusions

There is a generally accepted belief that potted plants can substantially improve IAQ; however, much of the evidence is to the contrary. The limited relevant empirical data does not agree well with basic gas transfer models (including humidity). Additionally, proponents of the PPM concept have not adequately examined potential mechanisms for gas transfer and contaminant removal that might support their conclusions. It would appear doubtful that the PPM concept could have significant impacts on the air quality in typical occupied spaces at realistic planting densities. There is evidence that biological systems can adapt to removing gaseous contaminants at typical indoor concentrations. The development of a botanical indoor air biofiltration system has shown the potential for plant-based ecosystems to remove substantial amounts of gaseous contaminants when the air stream is actively exposed to the rhizosphere. These systems are currently on the market. In addition, new designs are being developed to address potential effluent quality issues including water loss [54–56].

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