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Reducing indoor air pollution through applied botanical biofiltration

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SUMMARY
Increasing urban populations and behaviour associated with urban lifestyles has led to an increase in awareness of indoor environmental quality, especially maintenance and control of indoor air quality (IAQ). Potted plants, and more recently green walls, within indoor spaces, have increased in popularity in recent decades, not only for their aesthetic value but more recently for their proposed IAQ improvement potential. However, limitations are associated with the rate at which potted plants remove pollutants, rendering their practical efficiency negligible. Recent developments have fused the removal mechanisms of the plant foliage with biofiltration technology to create active green walls (botanical biofilters), which have proven to be an efficient means for the removal of gaseous pollutants. This article will provide; real-world examples of current *in situ* implementations of phytosystem technology, including laboratory prototypes, that demonstrate significant pollutant removal. Further, the synergistic plant-microbe interactions for air phytoremediation, with considerations related to the release of harmful microorganisms associated with indoor plants will be addressed. Finally, opportunities for enhanced phytoremediation by stimulation of plant-microbe interactions, from simple and practical steps to advanced genetic manipulations will be explored.

KEYWORDS
Volatile Organic Compounds, Phytoremediation, Botanical Biofiltration, Active Green Walls, Bioaerosols.

INDOOR AIR QUALITY

Air pollution exposure is ranked amongst the most significant health risk factors worldwide, and accounts for up to 5 % of the global disease burden. Rapid urbanisation has led to an increase in building occupation time, and due to energy saving building designs, a reduction in natural ventilation. In the absence of adequate ventilation, indoor spaces are prone to the accumulation of egregious indoor contaminants which give rise to a range of health issues such as “sick-building-syndrome” and respiratory discomfort. Common indoor contaminants include; volatile organic compounds (VOCs) from off-gassing from synthetic furnishings and cleaning products, particulate matter (PM) from cooking, solid fuel heating, smoking or dusting, and 'criteria' pollutants (CO, NO_2, O_3, SO_2 and CO_2) from heating, smoking, printers and photocopiers, and occupant respiration. Therefore, technologies that reduce occupant exposure to indoor pollutants are paramount to ensuring safe indoor environments.

Conventional technologies such as high-efficiency particulate air (HEPA) filters are often utilised in building heating, ventilation and air conditioning systems for pre-conditioning indoor air as well as stand alone desktop units for localised air purification. While these systems are effective for PM removal, they are incapable of gaseous pollutant filtration.

Alternatively, nature-based solutions are undergoing development to address the shortfalls in current indoor air remediation technologies, as well as contributing towards zero-emission building targets. The use of potted plants for air pollution mitigation was established in the late 1980s by NASA scientists who demonstrated significant reductions in ambient VOC concentrations from sealed chambers containing potted plants. Since then, over 200 plant species have been tested for their phytoremediation potential, and from these findings, active green infrastructure has been conceptualised.

ACTIVE GREEN WALLS

To increase the efficiency of nature-based air cleaning systems, Darlington *et al.* tested a plant-based system integrated into a building's air handling system that actively drew polluted air through the plant growth substrate and across plant foliage. This system used hundreds of plants supported in a fabric mesh and was first prototype active green wall system. The addition of active airflow contributes significantly to phytoremediation performance as contaminants drawn across plant foliage are absorbed into plant tissue through stomatal activity and exposed to air pollutant degrading epiphytic microbes or translocated to the root zone (Figure 1). However, the greater part of phytoremediation occurs when pollutants are drawn through the plant substrate and are exposed to rhizospheric microbial communities where they are metabolised or otherwise sequestered.

Commercial systems have subsequently been brought to market that have similar design components, including low-profile fans so their design might be uninhibited by the placement of air handling systems.

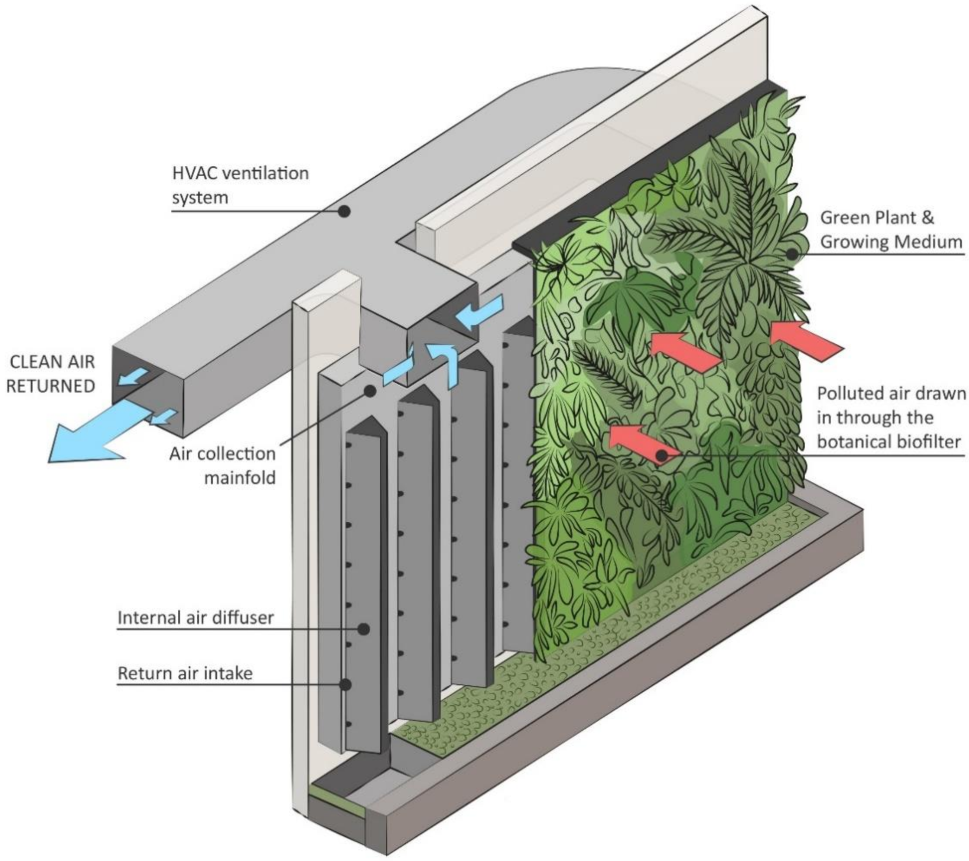

Figure 1: A phytosystem incorporating assisted (active) airflow via building ducting. Air is mechanically forced through the plant foliage, travels through the bioactive substrate, and then returns to the ventilation system through the back of the system. Image adapted from (Soreanu *et al.*, 2013)

Many aspects of green wall technology have been improved through scientific investigation. Liddy *et al.*, (2005) outlined the nutrient requirements for high plant density where sustained removal of a diverse VOC profile was dependent on available mineral nutrients. Recent studies (Pettit *et al.*, 2017, 2018a) have additionally been aimed at assessing substrate modifications for the removal of PM and VOCs, and to determine the most efficient plant species for PM removal in active green walls. These two studies found that both substrate composition and plant species selection play a vital roles in the removal of both PM and VOCs. The application of automated management is another area of current development. Liu *et al.*, (2018) investigated the usefulness of remote monitoring (Internet of Things technology) and cloud platforms to ease the spatial, temporal and financial challenges associated with the widespread deployment of green walls such as; maintenance labour, site accessibility, localised monitoring, and diagnostics.

COMMERCIAL PHYTOREMEDIATION TECHNOLOGIES

A study conducted by Chen *et al.*, (2005) reviewed 15 different air cleaning technologies, including a botanical biofilter. The filters were subject to testing in a full-scale steel chamber (~54 m^3) to calculate the single pass removal efficiency (SPRE) of 17 VOCs and the clean air delivery rate (CADR) of each filtration type. The study noted that the botanical biofilter prototype demonstrated significant removal of formaldehyde, acetaldehyde and *n*-hexanal, with a SPRE of approximately 20 %, however it was concluded that the CADR was not competitive with the other filters tested. Despite the prototype status of this technology, Chen *et al.*, (2005) concluded the botanical biofilter showed significant promise for further development. Liddy *et* *al.,* (2005) explored efficiency improvements through determining the effect of plant density and nutrient load on the phytoremediation of methyethylketone as a test VOC, within a partially sealed 65 m^3 room. The study utilised six botanical biofilters with a total surface area of 0.9 m^2, with a circulating nutrient solution. The study found that under low nutrients, high plant density had a negative effect on the removal of VOCs, however under high nutrient conditions, high plant densities were able to influence the microclimate of the rhizosphere microbial community such that VOC degradation significantly increased. More recently, a field-study conducted by Pettit *et al.,* (2018c) found that the installation of a small-scale active green wall reduced the concentrations of PM and VOCs to provide greater improvements to IAQ than that provided by the building HVAC system in a comparable time frame. The experiment was divided into two field-studies; the first study consisted of two green walls (1.5 m^2 each), one with and one without active air flow, alongside potted plants for the removal of PM and VOCs. Each wall was tested within a 22.7 m^3 room, with no HVAC or mechanical ventilation. It was determined that the active green wall led to significantly lower concentrations of ambient total VOCs (TVOCs) throughout the experimental period. In the second study, a 9 m^2 active green wall was constructed to service a classroom (120.2 m^3), and was effective in reducing TVOC concentrations by ~28 % within a 20-minute period, which was again significantly more effective than the building HVAC.

The application of this research has led to the commercialisation of several phytoremediation systems. Internationally, large-scale implementations of green walls have become popular due to their IAQ benefits, and perceived aesthetic improvements (Medl *et al.*, 2017). Several manufacturers of green wall technology employ, or have employed, scientific research into the development of their systems, such as Nedlaw Pty Ltd (Canada), Junglefy Pty Ltd (Australia), Bravolinear Tech Ltd (Hong Kong) and Navaa Ltd (Finland).

Nedlaw is the proprietor of the 'original' green wall design produced by Darlington *et al*., (2001), and have constructed over 60 indoor green spaces. In the early 2000s, a prototype of the Nedlaw green wall system (42 m^2) was constructed and assessed in its ability to service a 640 m^3 room utilising 150 plant species and a rock bioscrubber to degrade pollutants. This system was displayed a CADR of m^3 h^{-1} per m^2 bioscrubber and, in terms of bioaerosols, this wall did not lower the air quality.

Junglefy Pty Ltd is a major supplier of green wall technology in Australia, with several large indoor walls in both public and private buildings, alongside several major outdoor green walls. The Junglefy Breathing Wall utilises a modular design, making the system easily scalable from small office systems (2 m^2) to large-scale center pieces for landmark buildings (120 m^2). The Breathing Walls consists of 0.25 m^2 modules containing 16 circular compartments for housing individual plants. A large body of work has demonstrated the effective removal of several VOCs, PM, and CO_2 by these systems. Additionally, the Breathing Wall is one of few commercial systems that has undergone *in-situ* bioaerosol assessments to ensure there is no risk of aerosolisation of bioparticles.

Bravolinear Tech Ltd (Hong Kong), has innovated upon existing green wall technology through the application of 'smart' technologies. The Bravolinear EnvoAir IoT Active Green Wall (IAG) has incorporated Internet of Things (IoT) and Cloud software to develop a user-friendly interface to monitor green walls, providing real time data on air quality in the room, as well as energy savings as the active component of the green wall is only initiated when air pollutants exceed a certain threshold. Further, maintenance and monitoring costs are reduced by creating an autonomous and adaptive system that is responsive to various stimuli and allows for remote adjustments such as changes to lighting, ventilation, and irrigation. This development is significant in that it allows for the placement of high-profile walls in areas that would be difficult to manually monitor such as building exteriors. Further, testing by Bravolinear has determined that EnvoAir contributes to indoor thermal regulation by reducing effluent air temperature by up to 2 ℃ (Figure 2). Whilst the potential of indoor green infrastructure for maintaining thermal comfort exists, comprehensive assessments of energy saving features provided by this technology requires further research.

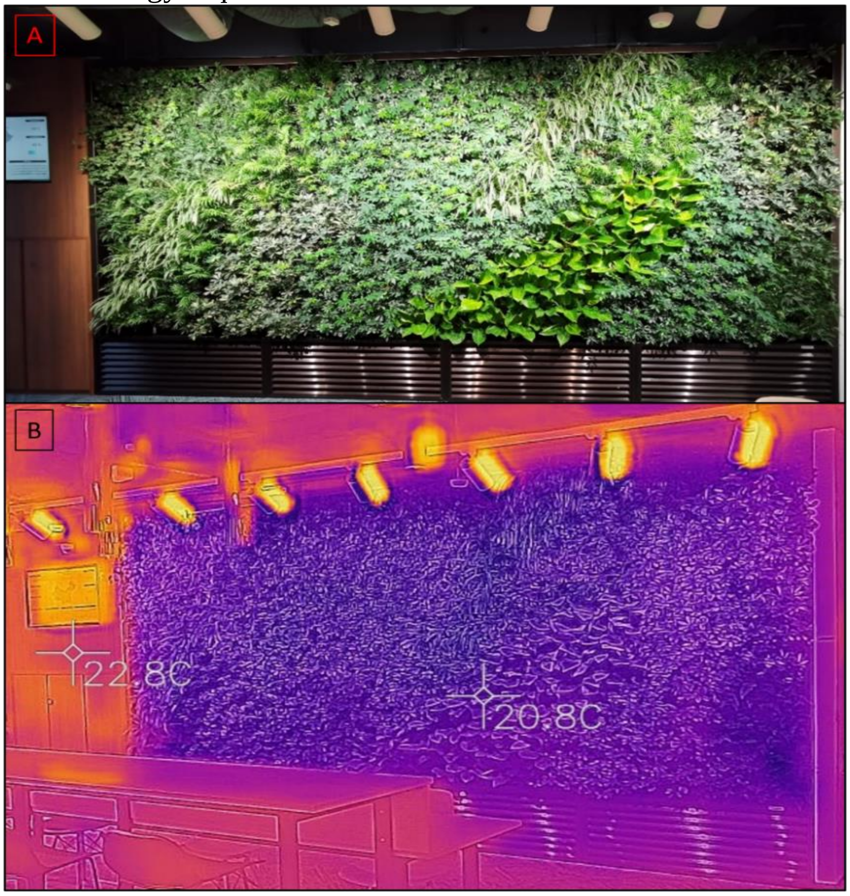

Figure 2: Bravolinear EnvoAir Active Green wall thermal regulation imaging (B). Source: *Used with permission of Bravolinear Tech Limited.*

While the installation of large-scale green walls has become increasingly popular amongst developers, the application of phytoremediation technology has not been limited to companies with large budgets and wall space. Nedlaw Pty Ltd and Junglefy Pty Ltd supply smaller scale phytosystem solutions to IAQ, however these products often require specific designs and, in some cases, infrastructure, such as irrigation.

A 'dynamic botanical air filtration system' (DBAF – 1.08 m^2) was developed by Wang and Zang (2011) to complement HVAC filtration supplied to a commercial space (265 m^3). This system was able to demonstrate a SPRE of 91.7 and 98.8 % for toluene and formaldehyde respectively from the airstream. Further testing over 300 days indicated that the system has potential to reduce heating energy by up to 30% and cooling by 3%per year in a temperate climate. This system utilised a single plant species for ease of maintenance and control of the rhizospheric microbial community, and a planting bed that included granular activated carbon to which some of its removal efficiency may be attributed. This system had a CADR of 898 m^3 h^{-1} per m^2 DBAF root bed, suggesting that it could be both a viable addition to HVAC systems and an effective standalone device.

Torpy *et al.,* (2018a) describe the commercial "Navaa One" (Navaa Ltd, Jyväskylä, Finland) phytoremediation system that utilises both botanical components and a biotrickling filter for the sustained removal of VOCs. Unlike Nedlaw and DBAF systems, the Navaa One is freestanding, and can hold 63 individual plants in a vertical plane 1.5 m^2 in area. This system utilised both an inorganic growth substrate to sustain plant growth, and activated carbon for additional VOC removal. The system draws air in through the front face, where it is filtered through both plant foliage and substrate before entering a return duct at the top of the system. In this study, the system demonstrated a CADR of 18.9 $m^3 h^{-1}$ per m^2 for the removal of 2-butanone, with a SPRE of 56.6 ± 0.9 % over replicated eight-hour test periods (Torpy *et al.*, 2018). Additional experimentation conducted by Mikkonen *et al.*, (2018) demonstrated that plant selection contributed less to VOC removal efficiency than substrate composition, which is indicative of abiotic or microbially-mediated VOC removal.

SYNERGISTIC PLANT-MICROBE INTERACTIONS

The rhizosphere is a 1-3 mm deep area immediately surrounding the outside surface of plant roots that is occupied by microbial communities. However, rhizospheric bacteria, those which drive the metabolic degradation of contaminants, can also exist in the exorhizosphere (extending beyond the 3 mm region) or the endorhizosphere (within the root's intercellular spaces). However, in the field of IAQ phytoremediation, the rhizosphere typically refers to all belowground microbial interactions.

The belowground plant-microbe relationship is complex, where plants communicate with rhizospheric bacteria through root exudate chemical signaling (Bais *et al.*, 2006), and may interact with the complex organic and inorganic environment surrounding them. The composition of growth substrates, including soilless growth substrates generally utilised by botanical biofilters, has an effect on the composition and function of rhizobacteria. By reducing environmental pressures associated with competing bacterial species, symbiotic plant-microbe relationships may favour those bacteria which are capable of utilising readily available carbon sources, including ambient VOCs, for sustained bacterial growth. In these systems it has been demonstrated that microbial populations rapidly adopt a VOC degrading profile in concert with the varying concentrations of single, or mixed, VOCs to which they are exposed (Mudiyanselage, 2019). The adaptability of these systems to the removal of varying concentrations of VOCs has led to a growing interest in the manipulation of microbial communities for heightened phytoremediation.

OPPORTUNITIES FOR ENHANCED PHYTOREMEDIATION

Currently, active green wall systems have achieved removal efficiencies that rival those of many contemporary methods, however the full potential of these systems is yet unrealised. There are several avenues of research that show promise for increased performance, one of which is the development of selectively enhanced microbial communities and genetically manipulated (GM) organisms.

Stimulation of rhizospheric communities for the enhanced phytoremediation of environmental contamination is a well-studied field, however there is currently little literature on the development of microbial biostimulants or GM plants/microbes for air phytoremediation. Biostimulation (BS) is the process by which enhanced bacterial communities are identified and artificially administered to a biological system for enhanced phytoremediation. This technique presents some challenges. Further research is required to identify a generalised indoor microbial community best suited for ambient concentrations of indoor pollutants. Currently, BS requires elevated concentrations of pollutants to sustain the stimulated communities and prevent the loss of the key metabolic pathways.

Genetic modification (GM) may address the shortcomings of BS and may involve both GM plants to provide enhanced selectivity for specific microbes, and GM bacterial communities with more diverse phytoremediation profiles. GM is a well characterised technique for the phytoremediation of heavy metals, but little research on GM plants or microbes for air phytoremediation has been performed. Two promising avenues of research include the CRISPR-mediated expression of plant growth promoting hormones and root exudate genes, and the design and application of more competent plant-growth promoting rhizobacteria (PGPR) (Basharat *et al.*, 2018).

CONCLUSIONS

The application of green infrastructure is becoming a prominent aid to the reduction of indoor air pollution associated with urban living. Whilst most components of air phytoremediation systems require further research and development, these systems have demonstrated strong air cleaning potential. Further investigations into plant selection, airflow systems, substrate composition and the manipulation of plant-microorganism interactions are pressing areas for future studies. Additionally, the implementation of low-cost sensors and IoT technologies are promising developments that will likely facilitate accurate real-time assessments of air cleaning performance *in-situ*.

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