

USING PLANTS AND SOIL MICROBES TO PURIFY INDOOR AIR: lessons from NASA and Biosphere 2 experiments

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The Biohome, a sealed chamber facility created by NASA in the late 1980s to investigate interior plants' ability to purify the air.
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Bill C. Wolverton is an American scientist who joined the NASA in 1971 as head of the Environmental Research Laboratory at the Mississippi Test Facility (now known as the John C. Stennis Space Center). There, he mainly studied phytoremediation for confined spaces, - the application of biotechnologies to treat wastewater, derived for land-based pollution treatment. As early as 1989, he studied at NASA the ability of plants to absorb several chemical compounds. After the publication of NASA's Clean Air Study report in 1990, he left NASA and launched his own research structure, Wolverton Environmental Services, which is still studying the topic of phytoremediation.

Mark Nelson is an American scientist, who served as Director of Space and Environmental Applications for Space Biospheres Ventures, which created and operated Biosphere 2, an Earth system science research facility located in Oracle, Arizona. He was a founder of the Institute of Ecotechnics, a U.K. and U.S. non-profit organization, which consults to several demonstration projects working in challenging biomes around the world. He is head of Wastewater Gardens International which has implemented ecological constructed wetlands, a technology used in Biosphere 2, in 14 countries.

Phytoremediation is the process by which plants and their root microbes remove contaminants from both air and water. Those purifying properties have been discovered within the frame of space habitation experiments: in the 1980s, scientists at the John C. Stennis Space Center shed light on interior plants' ability to remove volatile organic chemicals (VOCs) from tightly-sealed chambers. Further investigation, including the construction of a dedicated facility, Biohome, led to scientific breakthroughs and helped understand how to maximize interior plants' ability to purify the air. The experiment showed that indoor plants were able to remove VOCs that were continuously off-gassed in a closed system, thanks to the combined action of plant leaves and root microbes (by metabolization, translocation and/or transpiration).

Concurrently, the experiments led by Mark Nelson on Biosphere 2 demonstrated that high levels of crop productivity and maintenance of soil fertility can be maintained while biofiltration of the air is also achieved. The implications of the Biosphere 2 research on plant/soil biofiltration are that efficiency of trace gas removal depends on the populations of soil microbiota capable of metabolizing them.

Both experiments conclude that plant biofiltration is a promising technology that can help solve widespread global problems caused by air pollution. These solutions have a wide scope of application, and they require far lower capital investment and have lower operating costs than competing technologies. As such, they should be far more widely applied, especially within indoor areas.

INTRODUCTION

The earth is a dynamic, living planet with an evolving biosphere which has transformed the planet. The interaction of plants and microbes plays an important role in balancing the earth's ecosystems: in the simplest terms, plants and microbes act as the 'lungs' and 'kidneys,' continually filtering and disposing of impurities and waste products. We understand these functions in nature, yet many have a difficult time envisioning these same processes filtering the air and water within our built spaces.

Although humans yearn to stay connected to nature, many spend as much as 90 % of their time indoors where the air quality is often far from ideal, and indeed sometimes worse than outside. We have now introduced more than 85,000 synthetic chemicals into the environment and many off-gas toxins that become trapped within our buildings. Synthetic materials, equipment and digital devices also release trace gases. In order to conserve energy, modern buildings are tightly-sealed. As a result, a build-up of this variety of outgassing sources including airborne microbes and volatile organic chemicals (VOCs) often leads to poor indoor air quality (IAQ). Indoor air pollution is now rated among the top five threats to human health.

Aiming at improving IAQ, building engineers continually recommend increasing ventilation rates in an effort to purge the air. Most buildings bring in fresh air through an outside duct and mix it with re-circulated air. However, ventilation has four inherent problems: energy efficiency is compromised; outside air is often heavily polluted; outside air must be heated or cooled for human comfort; we can question how environmentally responsible it is to inject indoor air pollutants into the outside environment. Plant and soil-based systems, in part derived from systems designed for futuristic outer space exploration, can be part of the answer, bringing us back to fundamental processes that sustain life on earth. Two pioneer and decisive experiments investigated the capabilities and properties of such systems in the 1980's: the NASA's Biohome project and the Biosphere 2 project.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA) RESEARCH AND THE BIOHOME PROJECT

After the successful moon landing in 1969, NASA initiated programs to sustain life during long-term space habitation. Scientists at the John C. Stennis Space Center (SSC) took part in research to develop a 'Closed Ecological Life Support System'. NASA has within its charter that it should also seek applicability here on earth, such as treating environmental pollution. SSC scientists developed and installed constructed wetlands, now termed phytoremediation systems, to treat both domestic and industrial wastewaters at the facility. These plant-based systems have successfully treated wastewater for more than forty years, twice the average lifespan of conventional mechanical systems and saved NASA millions of dollars in operational costs¹.

In 1980, SSC scientists first discovered that interior plants could remove VOCs from sealed test chambers. NASA

first published its findings in 1984²³. To further investigate these findings, NASA constructed a 'Biohome' made entirely of synthetic materials and engineered to achieve maximum air and energy closure. The interior space was subdivided into a one-person habitat and a bioregenerative component whose basic functions were air purification and wastewater treatment⁴.

Due to its synthetic building materials and furnishings, it was assumed that outgassing of VOCs would create IAQ issues. Upon entering the facility, most people experienced burning eyes and throat and respiratory problems.

Common interior foliage plants growing in commercial potting soil were placed throughout the living quarters to evaluate their ability to remove VOCs. Additionally, they placed one experimental fan-assisted planter containing a plant growing in a mixture of soil and activated carbon. Air quality tests before and after the placement of plants by mass spectrometer/gas chromatograph analyses revealed that nearly all of the VOCs were removed. Moreover, one no longer experienced burning eyes or other classic symptoms of 'sick building syndrome' (SBS) when entering the Biohome. This was the first 'real world' application of interior plants for alleviating SBS.

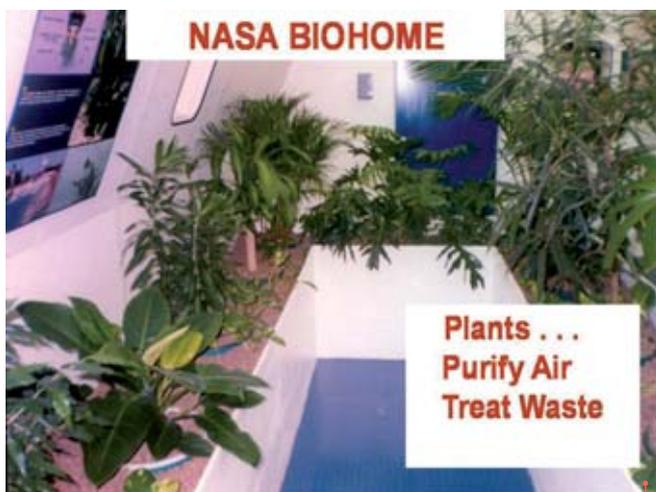
Technology termed 'phytoremediation' utilizes plants and their root microbes to remove contaminants from both air and water. During the early 1990s, studies sought to determine the mechanisms plant ecosystems utilize to remove VOCs from sealed chambers. The NASA studies employed only a one-time injection of VOCs into the test chambers. Questions arose whether plants could remove VOCs that were continually off-gassed from synthetic materials as commonly occurs in an indoor environment.

1 Wolverton, B.C. and J.D. Wolverton, *Growing Clean Water – Nature's Solution to Water Pollution*, Dolphin Press, 2001.

2 Wolverton, B.C., R.C. McDonald and E.A. Watkins, Jr., Foliage plants for removing indoor air pollutants from energy-efficient homes, *Economic Botany* 38(2), 224-228, 1984.

3 Wolverton, B.C., R.C. McDonald and H.H. Mesick, Foliage plants for the indoor removal of the primary combustion gases carbon monoxide and nitrogen oxides, *J. MS Acad. of Sci.*, 30:1-8, 1985.

4 Wolverton, B.C., A. Johnson and K. Bounds, Interior landscape plants for indoor air pollution abatement, NASA/ALCA Final Report, Plants for Clean Air Council, Mitchellville, Maryland, 1989.



Interior view of the Biohome. © Bill Wolverton



Plexiglas test chamber used in the experiments conducted by Wolverton Environmental Services, Inc. © Bill Wolverton

To answer this issue, Wolverton Environmental Services, Inc. (WES) conducted extensive studies^{5,6}. They had constructed two Plexiglas test chambers. Scientists placed two sections of interior paneling comprising urea-formaldehyde resins into each chamber. A lady palm (*Rhapis excelsa*) was added to one chamber while the other chamber, serving as a control chamber, did not contain a plant.

The lady palm and its soil removed formaldehyde that continuously off-gassed from the paneling sections. Temperature influenced the rate at which formaldehyde off-gassed from the paneling. The greater the temperature, the more rapidly formaldehyde was released. There was no removal of formaldehyde in the control chamber.

The lady palm showed no ill effects after extended exposure to formaldehyde. In fact, the lady palm increased its ability to remove formaldehyde as its exposure time increased. These studies indicated that plant root and soil microbes had rapidly adapted to the presence of formaldehyde and had contributed significantly to the chemical removal process. Further studies sought to determine the extent of plant root and soil microbe involvement in the removal of chemicals. Formaldehyde and xylene were introduced individually into sealed chambers containing plants having either exposed potting soil or soil covered with sterilized sand. The studies showed that 50 to 65 % of VOC removal could be attributed to root and soil microbes.

Due to the presence of microbes in the rhizosphere⁷, interior plants are not damaged when exposed to high concentrations of VOCs but continue to improve their ability to remove chemicals over time. The root/soil microbes rapidly adapt and grow in number, producing new generations of microbes that are even more effective in using the chemicals as a source of food and energy. Scientists at the University of Sydney, Australia, later conducted similar studies and obtained comparable removal efficiency⁸.

These findings added to studies show that both the plant leaves and root microbes contribute to the removal of VOCs from the indoor environment. It has been well-documented that plant leaves can absorb, metabolize and/or translocate certain VOCs to the root microbes where they are broken down. Studies show that 90 percent of these

Plant leaves and root microbes contribute to the removal of VOCs from the indoor environment

substances are converted into sugars, new plant material and oxygen. Scientists at the GSF-National Research Center for Environment and Health in Germany, produced the most definitive study yet on this phenomenon. They used radioactive carbon tracers to follow how the spider plant (*Chlorophytum comosum L.*) was able to break down and destroy formaldehyde⁹.

The other mechanism plants employ to move air down to their root system is transpiration. While moving water up from their roots to their leaves, a small convection current is created pulling air down to the root zone. Through this process, a plant not only moves atmospheric gases such as oxygen and nitrogen to its root zone, but also airborne chemicals. Because of this action, generally a plant with a high transpiration rate is more effective in its VOC removal capacity¹⁰.

All of the initial NASA interior plant studies were with plants grown in commercial potting soil. To go further, WES has sought to build upon their pioneering research and has concentrated its studies upon the use of hydroculture rather than potting soil. Indeed, hydroculture offers several advantages for use in the indoor environment (uses no soil, reduces over-watering and spillage, reduces risk of growing molds, reduces the need to transplant, plants take only the moisture they need).

WES hydroculture studies show that plants emit substances from their leaves that reduce the number of molds and bacteria in the ambient air even though further studies will further elucidate these mechanisms. Indeed, these studies suggest that plants grown in hydroculture are 30 to 50% more effective in removing airborne chemicals than plants grown in potting soil.

The NASA project and further development by WES also led to the creation of a High Efficiency Planter Filter, whose commercial applications (portable plant-based air filters) indicate they are as much as 50 to 100 times more effective in removing VOCs from the indoor environment than regularly potted plants. These air filters employ a mechanical fan to pull air down through highly adsorptive substrate in which an interior plant is grown. The substrate traps any airborne contaminants, where microbes in the rhizosphere break them down into components that serve as a source of food and energy for themselves and their host plant. Because microbes rapidly adapt to become more efficient with exposure, a bioregenerative or self-cleaning filter is created. These products are highly effective in VOC removal in small, confined spaces such as office cubicles or specific rooms within a living space.

5 Wolverton, B.C. and J.D. Wolverton, Plants and soil microorganisms – removal of formaldehyde, xylene and ammonia from the indoor environment, *J. MS Acad. of Sci.*, 38(2):11-15, 1993.

6 Wolverton, B.C. and J.D. Wolverton, Interior plants: their influence on airborne microbes inside energy-efficient buildings, *J. MS Acad. of Sci.*, 41(2):99-105, 1996.

7 The rhizosphere is the narrow region of soil that is directly influenced by root secretions, and associated soil microorganisms known as the root microbiome.

8 Wood, RA, et al., 'Study of absorption of VOCs by commonly used indoor plants,' proceedings of Indoor Air '99, 1999, 2:690-694.
Wood, RA, et al., 'Potted plant growth media: interactions and capacities in removal of volatiles from indoor air,' *J of Environ. Hort. and Biotechnology*, 2002, 77(1):120-129.
Wood, RA, MD Burchett, et al., 'The potted-plant microcosm substantially reduces indoor air VOC pollution; I. Office Field Study,' *J of Water, Air and Soil Pollution*, 2006, 175(1-4): 163-180.
Torpy FR, Irga PJ, Moldovan D, Tarran J, Burchett MD (2013) Characterization and biostimulation of benzene biodegradation in the potting-mix of indoor plants. *Journal of Applied Horticulture* 15(1): 10?15.

9 Giese, M., U. Bauer-Doranth, C. Langebartels and H. Sandermann, Jr., 'Detoxification of formaldehyde by the spider plant (*Chlorophytum comosum L.*) cell suspension cultures,' *Plant Physiology*, 1994, 104:1301-1309.

10 Wolverton, B.C., *How to Grow Fresh Air*, Penguin, New York, 1997; first published in the United Kingdom as *Eco-Friendly Houseplants*, Weidenfeld & Nicolson Ltd., London, 1996; now translated into 16 languages

BIOSPHERE 2 PROJECT

In the meantime, Space Biosphere Ventures investigated a similar phenomenon within the Biosphere 2 facility in Oracle, Arizona: originally designed as a new type of laboratory for studying basic processes of our global biosphere and the interplay of its internal mini-biomes, Biosphere 2 not only enabled detailed studies of self-organization and adaptation of its internal biomic areas and precise measurements of ecological dynamics including air, nutrient and water cycles; but was also a testbed for developing eco-technologies and ways of integrating required technologies with a living world to prevent damaging impacts¹¹.

When the Biosphere 2 project began in the mid-1980s, concerns about indoor air quality problems increased due to the impact of far tighter sealed buildings and homes to prevent energy loss. Amongst the many challenges of creating a virtually materially closed environment was achieving regeneration and maintenance of healthy air and water. Two serendipities led the Biosphere 2 design team to plant/soil biofiltration as an ecological, low-cost approach for preventing trace gas build up. The first was that B.C. Wolverton, then with NASA Stennis Space Center, was already working with the project to adapt constructed wetlands to treat and recycle all our human, animal and workshop/laboratory wastes¹². Wolverton had also been one of the first to study the efficacy of plants

to improve indoor air quality showing that common houseplants could effectively remove typical indoor air contaminants such as volatile organic compounds¹³. The second was meeting Hinrich Bohn, a professor at the nearby University of Arizona, who came from Germany, a country where the technology had begun in the early part of the 20th century. He and his brother at the University of Connecticut continued research and development of this innovative approach, then called “soil bed reactors” Soil biofiltration is far more widely used in Europe, especially in Germany and the Netherlands, than in the United States. It is even considered best management practice for control of industrial malodor caused by pollutant gases¹⁴.

The method takes advantage of the immense population numbers and metabolic diversity found in soil microbiota. Increased soil organic matter increases its effectiveness, leading to the use of compost and amended soils. The range of potential pollutant trace gases amenable to control by soil biofiltration is large – though much research remains to be done. But limitations include the rule of thumb that soil biofiltration can only work on gases that burn in air (are capable of oxidation). Neither is the technology capable of treating extremely concentrated pollution loads. Soil biofiltration engineering includes maintaining optimal moisture content and operating temperature, choice of substrate for desired porosity, surface area and soil organic matter content¹⁵.

- 11 Nelson, M., T. Burgess, A. Alling N. Alvarez-Romo, W. Dempster, R. Walford, and I. Allen. 1993a. Using a closed ecological system to study Earth's biosphere: Initial results from Biosphere 2. *BioScience* 43(4): 225-236.
Alling, A. and M. Nelson. 1993. *Life Under Glass: The Inside Story of Biosphere 2*, Biosphere Press, Tucson, published also in Dutch (1993) and Japanese (Kdansha Press, 1997)
Nelson, M., 2018. *Pushing Our Limits: Insights from Biosphere 2*, University of Arizona Press, Tucson.
- 12 Nelson, M., Finn, M, Wilson, C., Zabel, B., van Thillo, M., Hawes, P., and R. Fernandez, 1999. Bioregenerative recycle of wastewater in Biosphere 2 using a created wetland: two year results, *Ecological Engineering* 13(1-4): 189-197.
Nelson, M., and Wolverton, B.C., 2011. Plants + Soil/Wetland Microbes and Food Crop Systems that also Clean Air and Water, *Adv. Space Research* 47(4):582-590.

- 13 Wolverton, B.C., Johnson, A., Bounds, K. Interior Landscape Plants for Indoor Air Pollution Abatement, NASA/ALCA Final Report. Plants for Clean Air Council, Davidsonville, Maryland, 1989.
Wolverton, B.C., McDonald, R.C., Watkins Jr., E.A. Foliage plants for removing indoor air pollution from energy-efficient homes. *Economic Botany* 38 (2), 224-228, 1984.
- 14 Bohn, H.L. 1972. Soil Adsorption of Air Pollutants. *J. Envir. Quality*, 1:372-377.
Bohn, H.L. 1975. Soil and Compost Filters of Malodorant Gases, *APCA* 25:953-955.
Bohn, H.L. and R.K. Bohn, 1986. Soil bed scrubbing of Fugitive Gas Releases, *J. Environ. Sci. Health A21:561-569*.
- 15 Nelson, M. & Bohn, H. (2011) Soil-based biofiltration for air purification: potentials for environmental and space life support application. *Journal of Environmental Protection*.



Test modules of closed ecological systems from the Biosphere 2 experiments. Construction for the project started in 1987 and the first mission began in September 1991. © Mark Nelson

To research the applicability of soil biofiltration for the project, a three-year research program was initiated. The first question was whether growing plants could be combined with soil biofiltration. To test this, seventy-two beds growing food crops equipped with air pumps to push greenhouse air up through the soils were tested at the Environmental Research Laboratory (ERL) at the University of Arizona. These studies demonstrated that there were no negative impacts on crop growth and productivity. In fact, yields were somewhat enhanced, probably because soils were well-aerated¹⁶.

Plant/soil biofiltration experiments in the Biosphere 2 Test Module studied rates of removal of injected trace gases such as ethylene, carbon monoxide, NOx, methane and technogenic gases like formaldehyde and toluene. This research coupled with similar tests using sealed aquaria at ERL examined the effectiveness of the technology and the impacts of factors such as flow rates, prior exposure of the soil microbiota to the specific trace gases and soil type and organic content of the soils^{17,18}.

Biosphere 2’s entire agricultural soil was engineered to function as a plant/soil biofilter as all the facility’s air could be pumped through the soil in about 24 hours if trace gas concentrations required countermeasures¹⁹.

The implications of the Biosphere 2 research on plant/soil biofiltration are that high levels of crop productivity and maintenance of soil fertility can be maintained while biofiltration of the air is also achieved, and that the efficiency of trace gas removal depends on the populations of soil microbiota capable of metabolizing them.

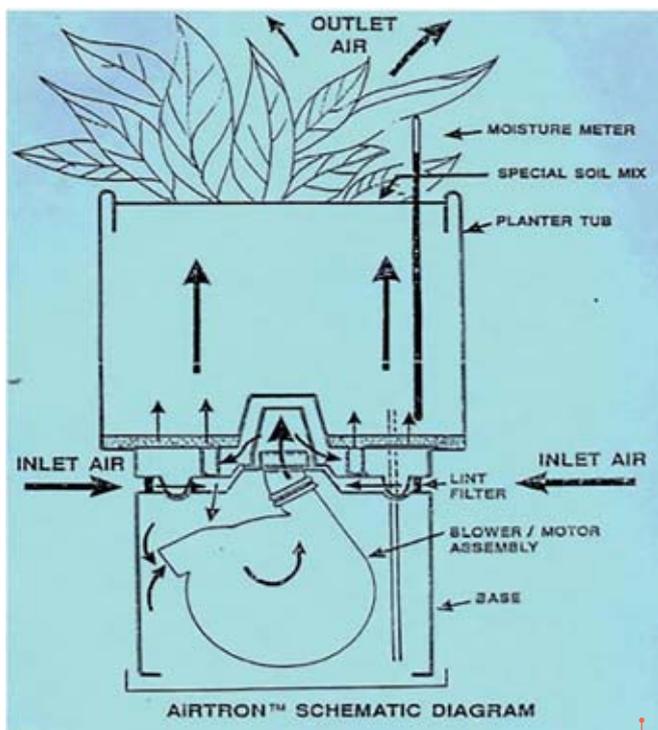
Since soil biofiltration was at the time limited to industrial pollutant gas applications, there was an opportunity to develop the technology for other applications, such as indoor air pollution. A commercial product called the “airtron” was developed by the Biosphere 2 project in the early 1990s. This device transformed what appeared to be an ordinary indoor house plant container into a plant/soil biofilter with the installation of an air pump below the planting soil which would force the air up through the soil, exposing its contaminants to soil/root microbes capable of detoxifying them.

16 Frye, R. J. and Hodges, C. N. 1989. Soil Bed Reactor Work of the Environmental Research Lab of the University of Arizona in Support of the Research and Development of Biosphere 2. In: Biological Life Support Technologies: Commercial Opportunities. NASA Conf. Publ. 3094. Pp 33-40.

17 Alling, A. & Nelson, M. (1993) Life Under Glass: The Inside Story of Biosphere 2. Tucson, AZ: Biosphere Press

18 Frye, R. J. and Hodges, C. N. 1989. Soil Bed Reactor Work of the Environmental Research Lab of the University of Arizona in Support of the Research and Development of Biosphere 2. In: Biological Life Support Technologies: Commercial Opportunities. NASA Conf. Publ. 3094. Pp 33-40.

19 Nelson, 2018, Pushing Our Limits: Insights from Biosphere 2



Schematic diagram of an “airtron” soil biofiltration unit developed by Biosphere 2 © Mark Nelson



Prototype unit used in the Mission Control building of the Biosphere 2 project. © Mark Nelson

OTHER RESEARCH

Extensive studies by WES as well as other scientists in Europe, Canada, India, Korea, Australia and Japan have provided scientific evidence that interior plants can help improve the air quality within energy-efficient buildings²⁰. Interior plants are more effective in removing harmful airborne pollutants in tightly-sealed buildings than in heavily ventilated buildings. No filtering device can effectively clean the air within a building when mechanical ventilation is constantly bringing in outside air. Outside air, especially in metropolitan areas, is often laden with pollutants. Additionally, a building is not energy-efficient if outside air is continually heated or cooled to a temperature range for human comfort.

Interior plants can help improve the air quality within energy-efficient buildings

In addition, research has shown that when workers are in close proximity to living plants productivity increases, morale improves and stress is reduced. Evidence collected during the past twenty years overwhelmingly supports the beneficial health effects of interior plants. Living plants also remove carbon dioxide and produce oxygen. These can be important functions when a large number of plants are placed within greenhouse roof gardens, sunrooms or atriums²¹.

CONCLUSION: LIVING IN HEALTHY INDOOR AREAS

These pioneering studies showed that plant and soil biofiltration can be an important bioremediation tool and a promising technology that can help solve widespread global problems caused by air pollution. Although the purifying power of plants has stirred controversy over the past years, the ability of plants to remove volatile chemical toxins under laboratory conditions and in airtight spaces is not doubted. Moreover, it requires far lower capital investment and has lower operating costs than competing technologies.

Like any technology, there are situations for which it will not be effective, such as highly concentrated air pollution, or for contaminants where slow reaction times would require unrealistic treatment time. However, there is enormous scope for the expanded use of this technology.

For space life support for extended human habitation, the technology is attractive because it produces many benefits since a food production unit can double as an air purifier, requires little maintenance and consumables and less energy than alternative approaches.

Plant/soil biofiltration also seems an ideal approach for dealing with indoor air pollution, because a rich soil has enough biodiversity to be able to naturally adapt to virtually whichever trace gases are being released within offices and homes. The transformation of indoor house plants, office green spaces such as atriums and even city vegetation, e.g. portions of parks, living walls or rooftop gardens, to also function as plant/soil biofilters can dramatically increase their ability to improve the air we breathe.

Large interior plantings are already commonplace in many public and commercial buildings. Trending within buildings at the moment are systems known by a variety of names, including green walls, living walls, bio-walls or vertical gardens. These systems are installed primarily for aesthetics. Very few take the concept a step further to employ the biological functions of plants and microbes to help improve IAQ. An exception is Takenaka Garden Afforestation, Inc., the largest interior plantscape company in Tokyo, which has developed an Ecology Garden[®], and Paharpur Business Center, Nehru Place Greens in New Delhi, India²².

The ultimate goal is to further plant-based air filtration technology whereby the air is treated for the whole building. The 'whole building concept' led to the development of modular planter systems that are much larger in scale, which allows a greater diversity of plants and can accommodate automatic watering systems. Most importantly, they may be connected to the building's heating, ventilating and air conditioning (HVAC) system²³ so that during the internal air-exchange process, the air circulates through various planter modules, stripping it of pollutants, before returning to the indoor environment. This process reduces the need for outside ventilation.

The need for further interest and investment into the 'whole building concept' is more and more essential. Plant/soil biofiltration is a quintessentially green technology, a wonderful example of ecological engineering that should be far more widely applied as we develop a more sustainable and regenerative relationship between our technosphere and our biosphere.

²⁰ Professor Margaret Burchett, University of Technology, Sydney, Australia (extensive research on plants and their ability to improve indoor air quality); Kozaburo Takenaka, Takenaka Garden Afforestation, Inc., Tokyo, Japan (Ecology Gardens for improving indoor air quality and patient/staff comfort in hospitals); Professor Tov, Fjeld, Agricultural University of Norway, Oslo, Norway (Plants for human health and well-being in offices); Kamal Meattle, The Paharpur Business Center, New Delhi, India (Interior plants for improving indoor air quality in office buildings); Professor Priscilla Pegas, University of Aveiro, Portugal (Interior plants for improving indoor air quality in classrooms).

²¹ Wolverton, B.C. and Kozaburo, Takenaka, Plants: Why You Can't Live Without Them, Roli Books, New Delhi, India, 2010.

²² Kamal Meattle, The Paharpur Business Center, New Delhi, India, Interior plants for improving indoor air quality in office buildings.

²³ Paharpur Business Centre and Software Technology Incubator Park. Heating, ventilating and air conditioning system.