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Plants + soil/wetland microbes: Food crop systems that also clean air and water

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Abstract

The limitations that will govern bioregenerative life support applications in space, especially volume and weight, make multi-purpose systems advantageous. This paper outlines two systems which utilize plants and associated microbial communities of root or growth medium to both produce food crops and clean air and water. Underlying these approaches are the large numbers and metabolic diversity of microbes associated with roots and found in either soil or other suitable growth media. Biogeochemical cycles have microbial links and the ability of microbes to metabolize virtually all trace gases, whether of technogenic or biogenic origin, has long been established. Wetland plants and the rootzone microbes of wetland soils/media also been extensively researched for their ability to purify wastewaters of a great number of potential water pollutants, from nutrients like N and P, to heavy metals and a range of complex industrial pollutants. There is a growing body of research on the ability of higher plants to purify air and water. Associated benefits of these approaches is that by utilizing natural ecological processes, the cleansing of air and water can be done with little or no energy inputs. Soil and rootzone microorganisms respond to changing pollutant types by an increase of the types of organisms with the capacity to use these compounds. Thus living systems have an adaptive capacity as long as the starting populations are sufficiently diverse. Tightly sealed environments, from office buildings to spacecraft, can have hundreds or even thousands of potential air pollutants, depending on the materials and equipment enclosed. Human waste products carry a plethora of microbes which are readily used in the process of converting its organic load to forms that can be utilized by green plants. Having endogenous means of responding to changing air and water quality conditions represents safety factors as these systems operate without the need for human intervention. We review this research and the ability of systems using these mechanisms to also produce food or other useful crops. Concerns about possible pathogens in soils and wastewater are discussed along with some methods to prevent contact, disease transmission and to pre-screen and decrease risks. The psychological benefits of having systems utilizing green plants are becoming more widely recognized. Some recent applications extending the benefits of plants and microbes to solve new environmental problems are presented. For space applications, we discuss the use of in situ space resources and ways of making these systems compact and light-weight.

Keywords: Constructed wetlands; Air purification; Bioremediation; Soil biofiltration; Indoor air pollution; Space bioregenerative life support

1. Introduction

The varied challenges of space agriculture include the probability that they will be housed within airtight environments to provide the environmental conditions necessary for growing plants and in circumstances where the loss of vital life elements, e.g. nutrients, atmospheric oxygen and carbon dioxide and water, would be both expensive to replace and potentially dangerous. Thus systems for recycling and ensuring full closure of biogeochemical cycles gain urgency.

Among the leading challenges is the maintenance of healthy atmospheric composition without buildup of trace

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gases which cause the now widespread "sick building syndrome." This is caused by the outgassing from materials, equipment and people in a tightly sealed structure designed to maximize energy efficiency by preventing loss of cooled and heated air (depending on season and climate). In spacecraft environments these issues have long been recognized since air analysis on early Skylab missions showed hundreds of trace gases (Nicogossian and Parker, 1982; Rippstein and Schneider, 1977; Hord, 1985). On Earth, indoor air pollution resulted from the tight-sealing of buildings to increase their energy efficiency. This has led to an unintended consequence: deterioration of indoor air quality. This mirrors the issues that space agriculture and human habitation in tightly sealed spacecraft, space stations and eventually lunar or planetary bases will face to a higher degree because space closure will need to be orders of magnitude tighter than Earth buildings to preserve precious breathable air and water.

The treatment and recycling of both nutrients and water in human waste products is another crucial area. With the need to supply water for by crew, in space agricultural systems provision must be made for safe, hygienic methods of returning sewage constituents so that plants can access their nutrient loads and the water be treated to levels appropriate to continued utilization.

This paper focuses on the ecotechnologies which both authors were involved with developing and researching – especially constructed wetlands for wastewater treatment and reuse; and technologies using green plants and soil microbes for air purification. Both methods offer striking synergies in a space agricultural application because they can result in the production of food and other valuable plant products in addition to their roles in ensuring air and water purification. These methods were in fact developed by the authors with bioregenerative life support as a primary application, but have significant benefits and future in environmental applications to solve pressing pollution problems in our terrestrial biosphere.

2. Constructed wetlands for wastewater treatment and water/nutrient reuse

The modern applications of constructed wetlands began primarily in Germany in the 1950s but have spread worldwide. The original insight was that natural wetlands serve as nutrient sinks and play a significant role in improving the quality of water. These ecological functions can be replicated in constructed wetlands, engineered systems sized for the quantity and quality of the wastewater to be treated, and the required quality of the treated water. Well-designed and maintained wetland systems show high levels of wastewater treatment and nutrient removal/utilization with the advantage of long-life for systems, minimal human management needed and applicability for small to much larger systems. Constructed wetlands usually exceed municipal standards for sewage treatment (Table 1) (Kadlec and Wallace, 2009; Kadlec and Knight, 1996).

One of the US constructed wetland pioneers was B.C. Wolverton working at the NASA Stennis Space Center in Mississippi. He demonstrated the efficacy of small constructed wetlands using both floating and emergent wetland plants for a range of treatment uses, from removing heavy metals and complex organic chemicals from industrial wastewater to the efficient treatment of residential wastewater. Wolverton initially worked with open-water surface wetlands, utilizing water hyacinth, and later developed systems with both free water surface and subsurface flow (Wolverton et al., 1975, 1983; Wolverton and Wolverton, 2001). Development of the constructed wetland technology was motivated by its potential usefulness in bioregenerative life support systems. Wolverton demonstrated the effectiveness of the technology in a "Bio-Home" pilot project (Fig. 1) at NASA Stennis Space Center along with plant systems for air purification (see below). In the Bio-Home all wastewater was treated within the tightly sealed building and reused for plant irrigation (Wolverton et al., 1989). The two authors' research intertwined when Wolverton served as a consultant for the Biosphere 2 project and helped adapt the constructed wetlands concept to the needs of this large closed ecological system. There two constructed wetlands systems, with floating and emergent (rooted) wetland plants, were housed in fiberglass containers, treated all human and domestic animal wastewater and the effluent from the workshops and laboratories inside Biosphere 2 (Nelson, 1999).

3. Food production and other benefits of constructed wetlands

Subsurface flow constructed wetlands offer numerous advantages when applied to space life support systems.

Table 1
Comparison of loading rates and removal efficiency of average North American surface and subsurface flow wetlands (Kadlec and Knight, 1996).

Parameter	Wetland system	In (mg/l)	Out (mg/l)	Removal %	Loading (kg/ha/d)
BOD	Surface flow	30.3	8.0	74	7.2
	Subsurface flow	27.5	8.6	69	29.2
TP	Surface flow	3.78	1.62	57	0.5
	Subsurface flow	4.41	2.97	32	5.14
TN	Surface flow	9.03	4.27	53	1.94
	Subsurface flow	18.92	8.41	56	13.19

Fig. 1. The Bio-Home at NASA Stennis Center which incorporated indoor constructed wetlands for wastewater treatment and reuse and plant/microbe systems for purifying the indoor air (http://www.sti.nasa.gov/tto/Spinoff2007/ps_3.html).

With wastewater never exposed, there is no malodor, no danger of accidental contact. These systems also are far more efficient than surface-flow wetlands, requiring just 20% of the area. Considerable research has also been done on the integration of food, fodder and other useful crops compatible with growing in the saturated water conditions of constructed wetlands (Wolverton and Wolverton, 2001; Nelson, 1999; Nelson et al., 2008a).

Root crops and uncooked greens like lettuce are not recommended for either planting in the constructed wetlands nor in further subsoil irrigation use of the treated effluent since normally constructed wetlands do not include a disinfection step. But crops such as bananas, papaya, rice, dwarf coconuts, several varieties of berry, etc. have been successfully grown in subsurface flow wetlands. In Biosphere 2, wetland plants such as canna edulis, water hyacinth and wetland reeds were harvested for use by domestic animals, such as goats, pigs and chickens (Nelson, 1999). In addition, food crops or other harvestable plants can be grown in areas irrigated with treated wastewater from constructed wetlands, benefitting from remaining nutrients. In those areas, root crops should be avoided unless a disinfection step is included, but choice is not limited to wetland-tolerant species (Fig. 2).

Other benefits are that constructed wetlands offer a low-energy solution for recycling wastewater and keeping nutrients in forms usable by plants. In Biosphere 2, the treated water from the constructed wetlands could be sent through a UV light sterilizer (which was not used since the biospherian crew's health was well-studied and there were no infectious diseases) and was then mixed into the irrigation supply for the agricultural system. Two constructed wetland systems treated all wastewater, domestic from the biospherian kitchens, laundry, showers and toilets and another treated liquid wastes from the domestic animals plus workshop and laboratory wastewater. Composting was done of domestic animal manure and inedible plant wastes. Treated water from the constructed wetlands was added to the irrigation supply for the Biosphere 2 agricultural area. Thus all nutrients were returned to the farm soils contributing to their sustainable long-term use (Nelson, 1997).

For ecological diversity, constructed wetlands offer habitat for beneficial insects, which were part of the Integrated Pest Management program in Biosphere 2, e.g. ladybugs. Constructed wetlands can also support beautiful flowers

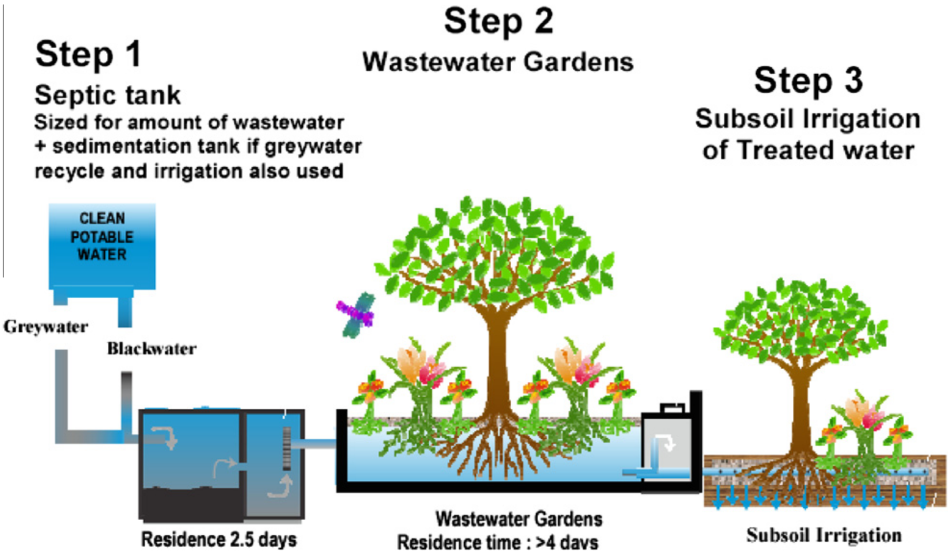


Fig. 2. Schematic of a subsurface flow constructed wetland followed by subsoil irrigation area where treated wastewater can be used for further irrigation of crops or other plants. A subsurface flow wetland typically has a gravel bed with 5 cm of dry gravel covering the wastewater, thus insuring no malodor or human contact occurs. It typically follows primary treatment in a septic or Imhoff tank or other sedimentation tank and a standpipe sets the height of sewage in the system and overflows to the final use area or collection for disinfection (if necessary) and further use of remaining water and nutrients (Nelson et al., 2008a).

(e.g. all Heliconia, many rose and hibiscus and decorative plants like lotus and papyrus can be grown) to enrich the space environment. In continued work after Biosphere 2, Nelson and colleagues have expanded the range of plants that can be utilized in tropical and temperate areas (Nelson et al., 2008a,b); www.wastewatergardens.com). All plants in a space life support system also help humidify the atmosphere through transpiration and cleanse the air of pollutants.

4. Growing clean air: the role of plant/rootzone microbial systems

Another lesser known capacity of plants and soil and root zone microbes is the ability to purify air of pollutants.

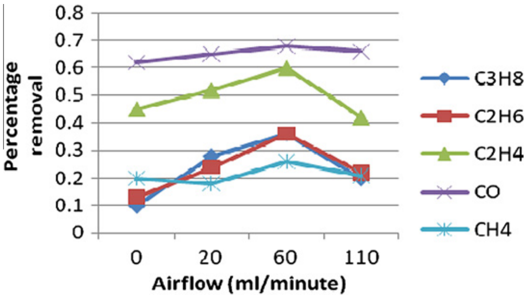
These approaches have been called "soil biofiltration" when focusing on the microbial component. A simple technology, invented in Germany in the early 1900s, was to pass the bad-smelling and pollutant-containing air exhaust from industrial, sewage treatment and other factories through soil or compost beds, originally called "soil bed reactors" (Fig. 3). This removes high percentages of the pollutant-load. Drs. H.L. Bohn and R.K. Bohn brought this technology approach to the United States starting in the 1970s. The technology is more widely used in Europe but currently is limited to industrial air quality improvement (Bohn, 1992; Bohn and Bohn, 1986; Bohn et al., 1980).

B.C. Wolverton was one of the first scientists to research the efficacy of plants themselves at removing air pollutants. His research, started in the 1970s at NASA Stennis Space Center, showed that many common houseplants could be very effective at removing typical pollutants of indoor air such as Volatile Organic Compounds, released by synthetic materials (Wolverton et al., 1984, 1985; Wolverton and Wolverton, 1993, 1996). This research became of increased importance as the oil embargo and rising energy prices helped spark a move towards tightly sealed buildings, with sharply reduced ventilation, to minimize energy losses of heated and cooled air. This has led to the problem known as sick building syndrome as toxic and irritant trace gas compounds built up inside energy-efficient homes and offices (Wolverton et al., 1989).

Through the serendipity that Hinrich Bohn was teaching at the University of Arizona, this approach was introduced to the designers and researchers working on Biosphere 2. Buildup of trace gases was seen as one of the greatest dangers in the facility as the engineering proved to be as airtight as intended, under 10% per year. Therefore a research program was initiated by Biosphere 2 at the project's research and development center and at support facilities of the Environmental Research Laboratory of the University of Arizona. Experiments demonstrated that soil bed reactors could also function as crop-producing soils; since the aeration provided by the air being pumped up through the soils insured they remained well-aerated (Frye and Hodges, 1990; Nelson and Dempster, 1996). A soil-bed reactor supporting plants was also installed for research purposes inside the Biosphere 2 Test Module (Alling et al., 1993). These tests also demonstrated the efficacy of such soil filters for removal of contaminants of concern such as methane, ethylene, carbon monoxide, toluene, formaldehyde (Frye and Hodges, 1990; Wolverton, 1997;

Table 2

Removal percentage as a function of airflow for selected trace gas compounds CO (carbon monoxide), CH_4 (methane), C_2H_4 (ethane), C_2H_6 (ethylene) and C_3H_8 (propane) at the University of Arizona soil biofiltration testing facilities in preparation for the Biosphere 2 experimental facility (after Frye and Hodges, 1990).



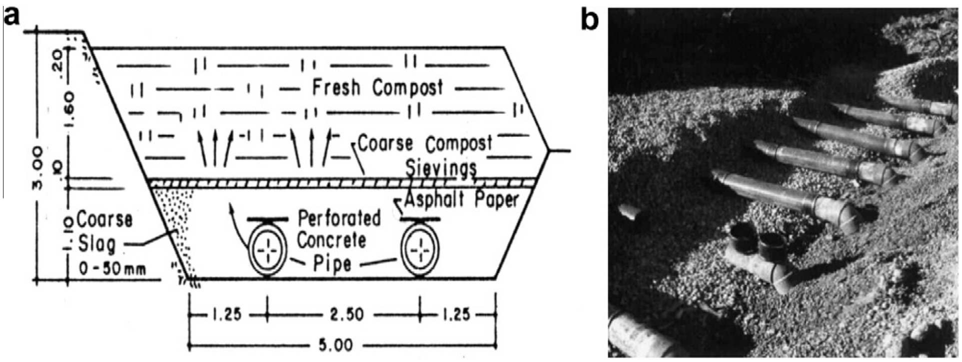


Fig. 3. Schematic of a biofilter using compost and compost sieving (a) and photo of aerator pipes leading into a soil or compost biofilter (b) (Mathsen, 2004).

Nelson and Dempster, 1996). Table 2 illustrates trace gas removal, showing how rates of removal (in percentage of concentration of the trace gas) increase as microbial populations increase, then decline along with the reduction in the atmospheric concentrations of the trace gases. The entire soil-based agricultural system of Biosphere 2 was engineered with ducting and air pumps from a technical basement below the farm, so that the entire volume of Biosphere 2's air could be pumped through the soil in a day (Nelson et al., 1994).

Biosphere 2 demonstrated effective control of all trace gases through passive adsorption by the abundant soils and microbial/plant biomass of the facility. The one exception in Biosphere 2 during the closure experiments 1991–1994 (though there may be other trace gases in the global biosphere) was nitrous oxide which is largely controlled because of its degradation in Earth's stratosphere by short wavelength sunlight and atomic oxygen. It was also found in Biosphere 2 sponsored research that there was an initial increase in carbon dioxide from the activation of the air pumps in a soil biofiltration unit (since soil is normally at 5–10 times the concentration of ambient air). Since maintenance of acceptable carbon dioxide levels was a prime operational concern during Biosphere 2's closure experiments and the absence of any significant rise in any technogenic or biogenic trace gases (with the exception of nitrous oxide) precluded use of the soil bed reactor system during either of the two closure experiments. Passive soil biofiltration through the deep soils of Biosphere 2 undoubtedly played a major role in keeping trace gases under sufficient control (Nelson and Bohn, 2010).

In the Bio-Home at NASA's Stennis Space Center, an experiment in closed ecological systems, Wolverton designed plant filters for air purification which made the facility habitable by its effective removal of the plethora of VOCs and other out-gassing from the synthetic materials from which it was made (Wolverton et al., 1989). Wolverton invented an indoor planter fitted with carbon filters and pumped air movement through the microbe-rich rooting media (expanded clay, etc.) which effectively makes them plant + soil microbial air filters (Fig. 4(a)). His later design, called the Ecoplanter, is currently marketed in Japan.

A few years later, at Biosphere 2, a similar device was developed, called an Airtron to make an indoor planter a mini-soil bed reactor by installation of an air pump to circulate air through the soil. Its effectiveness was demonstrated in small closed system experiments where trace gases were deliberately input (Fig. 4(b)). Wolverton has calculated that addition of the air pump to the planter increases air purification by some 50–200 times in VOC and other trace gas removal over just the passive filtration of air by plants and their associated root zone microbes (Wolverton, 1997).

5. Assessing and reducing risk factors of pathogens in soil and wastewater treatment

For both space and environmental applications, it is important to both assess potential health hazards of these technologies and indicate ways they can be mitigated or eliminated.

Wastewater (sewage) has the potential to include human pathogens (helminthes, viruses, bacteria, etc.). There have been cases of disease transmission of such pathogens by the physical contact of humans and irrigation of crops with improperly treated and non-disinfected sewage. Such concerns are avoided by subsurface flow wetlands which keep sewage away from people and in contact only with the rootzones of plants (Reed et al., 1995). This underlies the prohibition of growing root crops or leafy vegetables in constructed wetlands or in the subsoil irrigation with treated water from the systems. In space applications, as in Biosphere 2, it is unlikely the crews will have any infectious diseases since they will be medically screened, but for additional safety, a UV light disinfection system can be added. Irrigation should be limited to subsoil or other approaches which preclude human contact. Crops which are carried high above the wetland or irrigated surface, such as fruits, or which are cooked prior to consumption, e.g. rice, grains

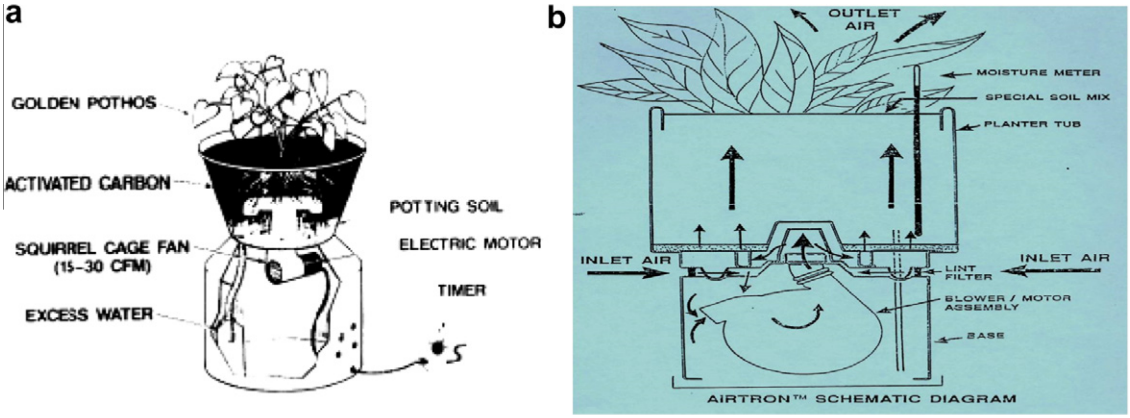


Fig. 4. (a) Schematic of a plant/root zone microbial air purification device (Wolverton et al, 1989). (b)The indoor planter/air purifier "Airtron" derived from research for Biosphere 2 (Space Biospheres Ventures, Oracle, AZ, 1994) (Nelson and Bohn, 2010).

and cooked vegetables, offer further protection as pathogens are destroyed by the heat of cooking.

The concern with soil biofiltration is that there may be pathogens in the soil which might become airborne or come into contact with people. The first thing to realize is that the likelihood of any pathogen movement due to the operation of a small airpump operating from the bottom of the soil bed is quite low. To further minimize this risk, a fine mesh or weedmat materials can cover the soil surface and/or a layer of heavier material (e.g. gravel or crushed stone) or sterile soil can cover the living soil further below.

To attempt to eliminate pathogens from the soil is more complicated as the number of potential soil pathogens in quite large. One approach would be to take soils from as healthy environments as possible. Many of the pathogens in soil are a result of untreated sewage and these can be precluded by knowing the history of the candidate soils. There are some emerging technologies which are being used to screen or treat potential pathogens (e.g. Linderman and Davis, 2008). For example, RNA magnification techniques offer the possibility of being able to exclude soils with pathogens prior to use. One proposed method is to combine polymerase chain reaction (PCR) with an enzyme immunoassay (EIA) to test soils for the presence of pathogens. Such approaches would screen for a wide variety of pathogens, require far less time than the culturing of indicator species and could screen for non-culturable pathogens (e.g. Sachse and Frey, 2002; Sabat et al., 2000).

Other possibilities include replacing soils with soil-like substrate and inoculating them with a diversity of important soil microbial types (Ushakova et al., 2005). Such a “synthetic” approach might start with sterilization of soils or soil media, then addition of selected microbial species. The incorporation of hyper-thermophillic composting might be another way to preclude pathogens which would not survive the high temperatures used to turn organic wastes into high-nutrient additions to the soil (Kanazawa et al., 2008).

6. Applications of these technologies in space life support systems

In space bioregenerative life support systems, such systems can be made light-weight and compact to minimize mass. Constructed wetlands might use alternative media for orbiting or spacecraft environments and for early lunar/planetary applications until in situ resources can be utilized. For example, instead of gravel and soil, e.g. polypropylene beads or other synthetic materials which give the needed porosity to hold water and surface area for microbial colonization. “Airtrons” or other versions of air-pump planters might utilize ceramic beads, perlite, polymer fibers or other lightweight soil-substitutes which can support microbial populations.

Both these technologies might be incorporated as part of the planned area for food production with suitable engineering modifications. Constructed wetlands could supply rice or fruit crops as part of the diet while also functioning as sewage treatment and water improvement. Plants + soil biofiltration could be used for any candidate space crops and give an additional reason for the inclusion of soil since its presence in the life support system would add air-purification capabilities even if only through passive filtration of the air volume.

The higher concentrations of carbon dioxide in the soil environment make its occasional flushing which occurs with the activation of soil biofiltration another tool in atmospheric dynamics management as crop yields increase with higher than ambient CO_2 levels.

7. Environmental applications of constructed wetlands and plants/microbes for air and water purification

7.1. Constructed wetlands

The spread of constructed wetlands for sewage treatment has been continuing both in the developed world and more recently in developing nations. The feature that such systems are also very effective water recycling approaches for both gray and blackwater and conserve potable water by using lower-quality water have become more important because of the realization of current and long-term water shortages worldwide (Kadlec and Wallace, 2009).

But the potentials of constructed wetlands are still quite large. The technology represents one of the few wastewater treatment systems which is either carbon-negative since the plants/soils/microbial biomass sequester carbon, or at least far less carbon positive, since these systems do not require the extensive machinery (solids pumps, aerators, stirrers, etc.), chemical additives used in operation of conventional

Table 3

Comparison of conventional mechanical vs constructed wetlands (here called Micro-Agro by Wolverton) for a town sewage system serving 2000 residents. The data illustrates the far lower maintenance costs of constructed wetlands and their far lower energy requirements. In this case, electrical usage is only 1% that of conventional treatment plants (Wolverton and Wolverton, 2001).

	Construction cost	Annual operation and maintenance cost	Annual electricity use (cost)
Comparable costs			
Obsolete mechanical system	\$600,000 (1974 Cost)	\$55,000	498.665 KWH (\$30,000)
Modifications to obsolete system	\$660,000	\$55,000	1.066.667 KWH (\$64,000)
New mechanical system	\$1,200,000	\$55,000	997.330 KWH (\$60,000)
New Micro-Agro™ system	\$550,000 (including land acquisitions)	\$5,000	9.974 KWH (\$600)

Courtesy: Southeast Mississippi Resource Conversation and Development Council.

sewage treatment plants. Typical centralized sewage treatment systems are not only very expensive in capital and maintenance costs, but have high fuel/electricity consumption in pump stations and mechanized processes in the sewage plant (see Table 3). In addition, there can be significant water resource conservation as significant greening/landscaping can be accomplished with the constructed wetlands and final subsoil irrigation with the treated wastewater. This replaces the use of potable water (and fertilizers) ordinarily used for greening around buildings and homes.

Constructed wetlands are also far more resilient approaches than centralized sewage and less susceptible to disruption by flood, storm and loss of electrical power infrastructure which happens in many natural disasters. They can be sized from individual houses to large industrial or city-sized systems. For example, Wolverton Environmental Services designed a hybrid, part free water surface and part subsurface flow, constructed wetlands to treat 7500 m^3 of sewage per day covering 8.8 ha and serving a town population of some 14,000 people (Wolverton and Wolverton, 2001).

Choice of plants and engineering/sizing adaptations can make them suitable for a wide variety of climates and types of pollutants, from residential sewage to industrial wastewaters. Constructed wetlands are also being explored for bioremediation of generalized pollution problems, such as pollution of rivers and other surface waters (Table 4).

Research and experimentation to discover the full range of plants which can be used in constructed wetlands can lead to the inclusion of productive plants, e.g. wetland trees for fuel or timber; fiber, medicinals, cut flowers and food. The field is still dominated by a monoculture approach which uses reeds or cattails since the paradigm for most engineers is just sewage treatment and not multi-benefits including ecological diversity, beauty and habitat/food for birds and animals (Fig. 5).

The inclusion of constructed wetlands inside houses and buildings has been done in a few instances, including systems designed by Wolverton. Centralized sewage treatment followed by “disposal” is an outmoded and expensive approach. Use of constructed wetlands for on-site treatment and reuse, and incorporation in and around buildings offers another way of increasing the green-ness, environmental health and enjoyment of modern buildings.

7.2. Plant + microbial air purification

In contrast, plants and soil biofiltration technology has only seen a very limited application – mainly in parts of Europe and to a lesser extent in the US. Its spread for the purposes it was originally invented – odorous industrial and sewage facilities – is just the start of how it can be used for environmental benefit.

While there are several commercial houseplant + air-pump systems on the market, this technology could be integrated with the infrastructure of houses, buildings and industrial facilities. Modern office buildings frequently now include green atrium areas with trees or other attractive plantings; and a recent move has been to include “living walls” of greenery. These could be greatly augmented in their air-purification effectiveness by making them active soil biofiltration units as well. This could also be done in houses by making attached greenhouse planting beds so the air could be pumped through the soil; or in planters under skylights, under south windows and/or with supplemental lighting.

Such systems might also be used for improvement of urban air quality through incorporation of air-pumping under portions of existing parks or in future urban greening efforts, e.g. rooftop gardens. Applications for uptake of methane from landfills have already been designed, but

Table 4
Illustration of industrial chemical removal from river water by constructed wetlands (here called rock/reed filters) with 24 h residence time (Wolverton and Wolverton, 2001).

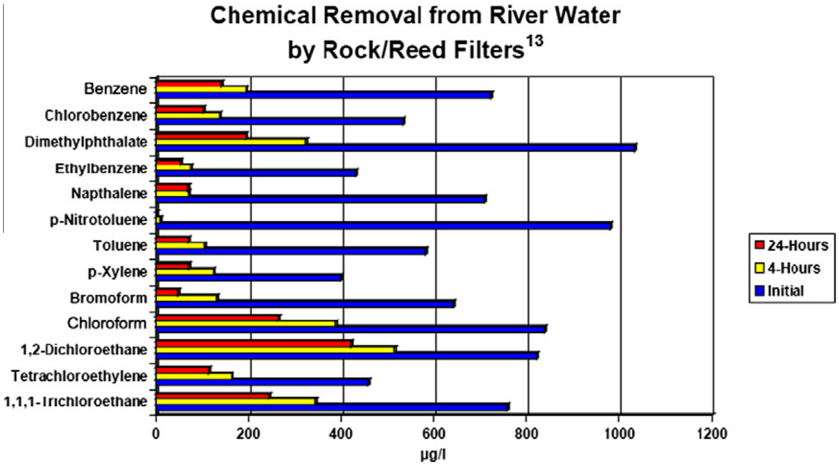


Fig. 5. Photos showing diversity and beauty of wetland plants in subsurface flow wetlands in (upper right) Bali, Indonesia; (upper left) Cape Eleuthera, the Bahamas; (bottom right) New Mexico, USA and (bottom left) Temacine, Algeria (Nelson et al., 2008a).

without planting which would increase the environmental and air-quality benefits (Park et al., 2004).

Since plants + soil biofiltration systems respond to changes in pollutants without need for human intervention, they lend themselves to a wide range of application while and serve as an ecological risk-abatement for new kinds of trace gases of the future.

Both these technologies have much to offer to a world seeking to evolve into more sustainable ways of living with and in the biosphere.

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