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Living Machines for Bioremediation, Wastewater Treatment, and Water Conservation

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CONTENTS

Abstract This chapter describes the application of Living Machines, which are advanced ecologically engineered systems (AEES), which use natural abilities of living organisms to break down macromolecules and metabolize organic nutrients typically found in wastewater and polluted water bodies. The choice of any natural bioremediation strategy depends upon the nature and characteristics of the environment polluted, the nature of the pollutants, and the availability of the biological agents. This chapter focuses on the application of bioremediation approaches in the remediation of polluted water ecosystems, i.e., rivers, lakes, and estuaries. Fourteen case histories are presented for introduction of practical applications of Living Machine in bioremediation, wastewater treatment, and water reuse. The technology provides opportunities for environmental and water resources education, showcasing its water reuse advantages with broad applications in water shortage areas, such as California, Nevada, and New Mexico.

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Key Words Living Machines • Advanced ecologically engineered systems • AEES • Living organisms • Bioremediation • Biological agents • Wetland cells • Wastewater treatment • Water reuse • Water shortage • Case histories • Water conservation • Aquaculture.

NOMENCLATURE

PCB	Polychlorinated biphenyls
PAH	Polycyclic aromatic hydrocarbons
EPA	Environmental Protection Agency
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
NAS	National Academy of Sciences
AEES	Advanced ecologically engineered systems
SFS	Surface flow systems
FWS	Free water surface
EFB	Ecological fluidized beds
TSS	Total suspended solids
NH_4^+	Ammonium
NH_3	Ammonia
HFR	Horizontal flow reedbed
VFR	Vertical flow reedbed
PRS	Pond and reedbed system
$CBOD_5$	Carbonaceous 5-day biochemical oxygen demand
TKN	Total Kjeldahl nitrogen
NO_3^-	Nitrate
TN	Total nitrogen
HRT	Hydraulic retention time
VOC	Volatile organic compounds
SBR	Sequencing batch reactor
UV	Ultraviolet
TP	Total phosphorous

1. INTRODUCTION

1.1. Ecological Pollution

Ecosystems comprising estuarine environments, marine shorelines, terrestrial environments, freshwater, groundwater, and wetlands are heavily polluted directly or indirectly by human activities such as mining operations, discharge of industrial wastes, agrochemical usage, and long-term applications of urban sewage sludge in agricultural soils, oil spills, vehicles exhausts, and bilge oil as well as anthropogenic organic pollutants. These activities introduce into the various ecosystems a diverse array of pollutants including heavy metals, volatile organic compounds, nitro-aromatic compounds, phenolic compounds, xenobiotic chemicals (such as polychlorinated biphenyls (PCB), polycyclic aromatic hydrocarbons (PAHs), and pesticides), and high nutrient-loaded wastewater [1-7]. In the environment these pollutants pose great health risks to both human and wildlife. The adverse effects of various pollutants depend on their chemical nature and characteristics. For instance, PCBs, PAHs, and pesticide residues owe their toxicity to being recalcitrant, which means they persist in the environment for many years. Organophosphate-based pesticides have been demonstrated to exhibit neurotoxicological properties as well as being associated with the pathology and chromosomal damages associated with bladder cancer [8]. Heavy metals, on the other hand, pose the greatest health risk because of the difficulty associated with removal from the environment, which arises from the fact that they cannot be chemically or biologically degraded, making them (heavy metals) ultimately indestructible [2].

When it comes to water, the situation becomes more serious since both the quantity and the quality of freshwater present major problems over much of the world's continents. Freshwater lakes and rivers are polluted by oil spills as well as less satisfactorily treated effluents that come from various processing industries [9]. In addition, groundwater pollution is increasingly becoming widespread because of uncontrolled waste deposits, leakages from petrochemical tanks, and continued percolation of untreated sewage, agrochemicals, and other pollutants in the aquifers. Notably, over the last several hundred years, humans have begun living in higher and higher densities, leading to high volumes of sewage output in small geographic areas. This high density of sewage has led to the need to treat the wastewater in order to protect both humans and ecosystem health. Besides, fruits, vegetables, olive oil processing, and fermentation industries also generate solid waste and wastewater which is nutrient rich. Such wastewater has high biochemical oxygen demand (BOD), (which is a measure of oxygen consumption required by microbial oxidation or readily degradable organic and ammonia), chemical oxygen demand (COD) [9], and is usually acidic (low pH). These wastes often find their way into freshwater bodies (rivers and lakes) where they cause eutrophication (the process of becoming rich in nutrients), which triggers explosive algal blooms. Owing to exhaustion of micronutrients, toxic products or disease, the algal population eventually crashes. The decomposition of the dead algal biomass by heterotrophic microorganisms exhausts the dissolved oxygen in the water, precipitating extensive fish skills and septic conditions. Even though eutrophication does not go to this extreme, algal mats, turbidity, discoloration, and shifts of fish population from valuable species to more tolerant but less value forms represent undesirable eutrophication changes [10]. Besides, it is estimated that between 1.7 and 8.8 million metric tons of oil are released into the world's water every year, of which more than 90% is directly related to human activities including deliberate waste disposal [11, 12]. For example, marine oil spills emanating from large-scale spill accidents have received great attention due to their catastrophic damage to the environment: (a) the spill of 37,000 metric tons (11 million gallons) of North Slope crude oil into Prince William Sound, Alaska, from the Exxon Valdez in 1989 led to mortality of thousands of seabirds and marine mammals, a significant reduction in population of many intertidal and subtidal organisms, and many long-term environmental impacts; (b) minor oil spills and oil contaminations from nonpoint source discharges (e.g., urban runoff and boat lodge) pollute rivers, lakes, and estuaries. As a matter of fact, the US Environmental Protection Agency National Water Quality Inventory reports nonpoint source pollution as the nation's largest source of water quality problem [13, 14], with approximately 40% of surveyed rivers, lakes, and estuaries not clean enough to meet basic uses such as fishing and swimming [12].

1.2. Bioremediation Strategies and Advanced Ecologically Engineered Systems (AEES)

In order to address these environmental/ecological pollution concerns, several bioremediation (natural or biological remediation approaches) strategies have been devised. For example, to address pollution of the environment by sewage and wastewater, an assortment of technologies including septic systems in rural areas and sewage treatment plants in urban have been developed. The purpose of these systems is to remove pathogens, solid waste, and organic carbon from the water. Some also remove nutrients such as nitrogen and phosphorus which normally cause eutrophication in aquatic systems [15]. There are, however, some problems with the current systems for sewage treatment. Septic tanks in particular do not effectively remove nutrients and many larger treatment plants generally rely on chemical treatment to remove some nutrients. Notably, phosphorus removal has largely relied on chemical precipitation. Although nitrogen removal primarily relies on microbiological processes, methanol is often added to stimulate the removal of nitrate. Treatment plants also typically use chemicals such as chlorine or ozone to remove pathogens. Another difficulty of conventional wastewater treatment is the large energy input required. A more fundamental problem with conventional wastewater treatment is its failure to take advantage of the potential resources embodied in wastewater. The nutrients in wastewater are an important resource that is currently going unused. By changing the way wastewater is processed, it is possible to take advantage of these resources [15].

Several biologically based technological systems, which are currently being developed as alternatives to conventional systems include, (a) the widely studied use of natural or constructed wetlands to treat wastes (discussed in Sect. 3.4) and (b) the use of a hybrid between sewage plants and wetlands. The use of a technology based on biological systems, microorganisms and plants (bioremediation/phytoremediation), known as advanced ecologically engineered systems (AEES), is beginning to emerge as promising technology, particularly as a secondary treatment option [12]. Specifically, these advanced ecologically engineered systems (AEES) use natural abilities of living organisms to break down macromolecules and metabolize organic nutrients typically found in wastewater and polluted water bodies. The major advantages of using AEES technology include the following: (a) it is less costly, (b) it is less intrusive to the contaminated site, and (c) it is more environmentally benign in terms of its end products [12]. However, the choice of any natural bioremediation strategy goes hand in hand with the nature and characteristics of the environment polluted, the nature of the pollutant(s), and the availability of the biological agent(s). It is not the aim of this chapter to exhaust all aspects of application of bioremediation technology. However, this chapter dwells on the application of bioremediation approaches in the remediation of polluted water ecosystems, i.e., rivers, lakes, and estuaries.

2. LIVING MACHINES: AS CONCEPT IN BIOREMEDIATION

As already pointed out above (Sect. 1), water bodies are on a daily basis being contaminated with waste and therefore the availability of clean and safe drinking water on Earth is continually reducing. Besides, the chemical methods aimed at mitigating the problem introduce other residual pollutant as a result. On the other hand, bioremediation, which uses biological systems to mitigate the problem, has proven to be a more effective and safe way of restoring the ecosystem to its natural state. Ecological studies have, for long, revealed that nature has an inbuilt system to restore itself and thereby sustaining its continuity. It is the tilting of the balance in nature that always leads to undesirable consequences. In a typical ecosystem, different populations interact, whereby some of them benefit positively from the interactions while others may be negatively affected by the interactions [10]. For example, possible interaction between micro- and macropopulations can be recognized as negative interactions (competition and amensalism), positive interactions (commensalisms, synergism, and mutualism), or interactions that are positive for one but negative for the other population (parasitism and predation).

In simple communities, one or more of the above interactions can be observed. However, in a complex natural biological community, all of these possible interactions will probably occur between different populations concurrently [10]. Another important aspect emerging from ecological studies is the observation that positive interactions (cooperation) predominate at low population densities and negative ones (competition) at high population densities. As a result, there is an optimal population density for maximal growth rate [10]. In a natural ecosystem a balance always exists whereby different populations interact either positively or negatively until equilibrium is established. In other words, natural population can act as "Living Machines" in keeping the ecosystems habitable by every community member population. Living Machines as concept evolves around the utilization of different biological (microbial, plants, and animals) systems to decontaminate the environment of pollutants that are, on a daily basis, released as a result of various human activities. Carefully studied biological systems are selected and their metabolic and growth requirements evaluated. Then different community populations that cooperate in their interaction are given particular tasks, after which the product is used by yet another set of cooperative community populations. As the pollutant gets depleted, the populations likewise reduce in sizes. However, the engineered ecosystems (Living Machines) should have systems that reduce the population via the natural food chain. Therefore, instead of population downsizing through death, prey–predator relations/interactions are introduced. These keep the sizes of the various populations at optimal and thus maintain the performance of the systems. In other words, these systems differ from a typical natural ecosystem in as far combining a variety of natural processes in a structured manner, which artificially accelerate wastewater purification [16]. The term Living Machines describes technologies that employ living organisms of all types and usually housed within a casing or structure made of extremely lightweight materials and powered primarily by sunlight. A typical Living Machine comprises a series of tanks or constructed ponds teeming with live plants, trees, grasses, and algae, koi and gold fish, tiny freshwater shrimps, snails, and a diversity of zooplanktons as well as bacteria [16]. In North America, the brothers Eugene Odum and Howard T. Odum laid out the conceptual framework for the practical concepts of ecological designs, and over the last three decades, these concepts have been transformed into part of the science called "ecological engineering" [17].

Ecological engineering is defined as *the design of sustainable ecosystems that integrate human society with its natural environment for mutual benefit*. It involves creating and restoring sustainable ecosystems that have value to both humans and nature. In so doing, ecological engineering combines basic and applied science for the restoration, design, and construction of aquatic and terrestrial ecosystems. Two major goals are achieved, namely, (a) the restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbances and (b) the development of new sustainable ecosystems (Living Machines) that have both human and ecological value [18]. It is engineering in the sense that it involves the design of the natural environment through quantitative approaches, which rely on basic science, a technology whose primary tool is the self-designing ecosystem, and it is biology and ecology in the sense that the components are all of the biological species of the world [18].

The designing of Living Machines explores the chiefly two of nature's attributes, namely, self-organization and self-designing capacities of ecosystems. Self-design and the related attribute of self-organization are important properties of ecosystems that require clear understanding in the context of creation and restoration of ecosystems. Self-organization, defined as *the property of systems in general to reorganize themselves given an environment that is inherently unstable and nonhomogeneous*, is a property that applies very well to ecosystems. This is so because in any ecosystem species are continually being introduced and deleted, while species interactions, e.g., predation, mutualism, etc., bring about change in dominance, as well as changes in the environment itself. Since ecological engineering often involves the development of new ecosystems as well as the use of pilot-scale models such as mesocosms to test ecosystem behavior, the self-organizing capacity of ecosystems remains an important concept for ecological engineering. Besides, self-organization develops flexible networks with a much higher potential for adaptation to new situations. It is for this reason that it is desirable for solving many of the ecological problems. Therefore, in the construction of Living Machines whereby biological systems are involved, the ability of the ecosystems to change, adapt, and grow according to forcing functions and internal feedbacks is most important [18].

On the other hand, self-design, which is defined as the *application of self-organization in the design of ecosystems*, ensures the continual presence and survival of species in ecosystems after their introduction by nature or humans. As a matter of fact, self-design is an ecosystem's function in which the chance introduction of species ensures continuous sustainability of the system. The ecologically engineered system may be further augmented by multiple seeding of species, which would speed the selection process during the process of self-organization [19]. In the context of ecosystem development, self-design means that if an ecosystem is open to allow "seeding" of enough species and their propagation through human or natural means, the system itself will optimize its design by selecting for the assemblage of plants, microbes, and animals that is best adapted for existing conditions. The ecosystem then "designs a mix of man-made and ecological components in a pattern that maximizes performance, owing to its ability to reinforce the strongest of alternative pathways that are provided by the variety of species and human initiatives" [19].

By applying these biological systems as the driving force, several living technological innovations have been designed [17]. Living Machines or AEES are primarily designed as either tank-based systems for treatment of point-source waste or floating systems placed on existing bodies of water that receive nonpoint source pollution [17]. Besides, ecological technologies are also useful in food production through waste conversions, architecture and landscape design, and environmental protection and restoration. It is thus clear that this technology is very advantageous to the conventional pollution management technologies.

2.1. *Advantages of Living Machines*

Living Machine technology offers a number of advantages over conventional treatment processes:

(a) Living Machines use no chemicals and are thus less costly than conventional treatment plants. For example, in northern climates, some lagoon systems freeze over, making it necessary to find extensive storage space for wastewater until the warm discharge season. However, Living Machines can be small enough to be placed in a greenhouse near the source of the pollutant (sewage, wastewater from processing industries, agro-wastewater, etc.) for year-round treatment. Besides, the constant supply of treated effluent water is of such a high standard that it can be used for horticulture and aquaculture production in addition to being recycled to non-potable use such as toilets [16].

(b) Living Machines have sensitive response systems. As such, a sudden influx of toxic pollutants, for example, is quickly obvious when snails move out of the water onto branches of leaves. In a conventional system it can take days to chemically measure toxicity. The levels of other indicators such as acidity can be determined by the color of the tails of certain species of fish. If these are integral part of the system, it saves both time and money [16].

(c) Owing to their cleanliness and lack of odor, Living Machines may be integrated into buildings, providing an aesthetic dimension while at the same time reducing energy requirements. Consequently, they are amenable to various designs that not only provide a quality-working environment but are also an attraction to visitors [16]. Such systems serve as direct examples of human processes that are harmonious and symbiotic with natural systems.

(d) They are easy to operate and maintain, i.e., the caring for a Living Machine such as a Restorer is less labor intensive since the operator works with living and growing ecologies, rather than with bags or tones of chemicals (15; 19).

(e) Living Machines are capable of absorbing or resisting "shock loads" in the waste stream. They owe this capacity to the fact that they are natural and biologically diverse systems, yet they are also mechanically simple. Typical examples are the Lake Restorers. Restorer Technology is borrowed from an analogous component in nature called the floating island. Like the floating islands, Restorers are an assembly of engineered ecologies incorporated into floating rafts. As the storm blows on the lake, the “Island” or Restorer migrates around with the changing wind. As this is done, the diverse ecologies of plant micro- and macroorganisms decontaminate the lake, thereby restoring the water back to acceptable health standards. In doing all this, any shock load is being resisted [16].

(f) These systems are modular and can be made in various designs to meet the needs of a growing business or community. This means that the operations and efficiency of the Living Machines can be easily enhanced and improved without excessive costs involved. New Living Machines are already a third smaller than earlier. As the systems are refined and in some cases miniaturized, it will be possible to integrate them in different ways to support human population without destroying the rest of nature [16].

(g) Since most ecosystems are primarily solar-powered systems, they are self-sustaining. Therefore, once an ecosystem (Living Machine) is constructed, it is able to sustain itself indefinitely through self-design with only a modest amount of intervention.

(h) Living Machines have the ability to self-design. The engineer provides the containment vessels that enclose the Living Machine and then seed them with diverse organisms from specific environments. Within the Living Machine the organisms self-design the internal ecology in relation to their prescribed tasks and the energy and nutrient streams to which they are exposed [20].

(i) Living Machines have the ability to self-replicate through reproduction by the vast majority of the organisms within the system. This means that, in theory at least, Living Machines can be designed to operate for centuries or even millennia. In Living Machines the intelligence of nature is reapplied to human ends. They are both garden and machines [20].

2.2. Limitations of Living Machines

In as much as Living Machines offer such versatile advantages, they are not without limitations:

(a) The reliance of Living Machines on solar power means that a large part of land or water is needed. Therefore, if property purchase (which is, in a way, the purchase of solar energy) is involved in regions where land prices are high, then ecological engineering approaches may not be feasible [19].

(b) Sometimes the species available may not be efficient in degrading very toxic and persistent, recalcitrant wastes. This may result in the persistence of such waste, and as a result pollution of such habitats and accompanying health impacts to flora and fauna persist.

(c) Inasmuch as the natural system is desirable, in some instances the rate of inflow is so high that it overshoots the natural rates of removal of the pollutants. This means that a longer residence time may be required to give nature ample time to do the task. Accordingly, a large piece of land may be required to set up the Living Machine, which may not always be available.

3. COMPONENTS OF THE LIVING MACHINES

3.1. Microbial Communities

The notion that microbial communities are the foundation of Living Machines is obvious. What is less obvious is the diversity in communities of microorganisms required, if the potential of ecological engineering is to be optimized. On the one hand, bacteria are considered as ubiquitous organisms that organize life on the planet. This is suggested to be through organization, not as distinct species as is conventionally understood in biology, but as unitary society of organisms with no analogous counterparts among other living organisms [21]. On the other hand, microbiology maintains that bacteria species have highly specific nutritional and environmental requirements and the ubiquity principle, which may work over long-term time frames, is inappropriate to the design of Living Technologies [21, 22]. In waste or intensive aquaculture, for example, if conditions are not right for nitrifying bacteria, e.g., not enough calcium carbonate as a carbon source, then Nitrosomonas and Nitrobacter will functionally disappear from the system. The only quick way to reestablish nitrification is through correcting the calcium carbonate deficiency and reinoculating the system with culture of appropriate bacteria. For their application in the design of Living Technologies, bacterial communities remain a vital component, but unfortunately they largely remained unexplored. Although some 10,000 species have been named and described and many important reactions characterized, the natural history and ecology of these bacterial species have been little studied and therefore their distribution and numbers remain obscure [21, 23]. Despite this limitation, the use of microorganisms in designing Living Technologies has proceeded in earnest. In their work with the system to degrade coal tar derivatives (PAHs), Margulis and Schwartz [23] inoculated the treatment systems with microbial communities from such diverse locations as salt marshes, sewage plants and rotting railroad ties, nucleated algae, water molds, slime molds, slime nets, and protozoa. While the bacterial communities provide a diverse array of metabolic pathways for the degradation of the pollutants, nucleated algae, water molds, slime molds, slime nets, and protozoa, which are less diverse metabolically than bacteria, are important for the efficiency of the system owing to their exceptionally diverse life histories and nutritional habits. For example, it has been shown that protozoans are important in removing coliform bacteria and pathogens from sewage as well as moribund bacteria thus improving the systems' efficiencies, while fungi are key decomposers in ecological systems [21]. Currently, the microbial communities are estimated to comprise about 100,000 species, many capable of excreting powerful enzymes from various metabolic pathways. Such heterogeneous microbial communities are efficient in the removal of organic matter from wastewater [21]. Fungi, however, tend to dominate in low pH and terrestrial soils than in aquatic environments. It may, therefore, be important that Living Technologies should incorporate soil-based acid sites linked to the main process cycles into their design.

3.2. Macro-bio Communities (Animal Diversity)

The macro-bio communities comprising various animal species are the regulators, control agents, and internal designers of ecosystems. Unfortunately, they are often little appreciated organisms. It has long been recognized that organisms from every phylogenetic level have a role in the design of Living Technologies and in the reversal of pollution and environmental destruction. For this reason, a search of the vast repository of life forms for species useful to ecological engineers is needed. Odum [24] empathized the need to find control species, meaning those organisms capable of directing living processes towards such useful end points including foods, fuels, waste recovery, and environmental repair. The potential contributions of animals to Living Technologies are therefore remarkable, yet their study has been badly neglected in Biology of Wastewater Treatment. For example, mollusks are not mentioned [25], and in the two-volume Ecological Aspects of Used Water Treatment, snails are mentioned only once and referred to as nuisance organisms [26, 27]. It has now been found that snails play a central to the functioning of Living Technologies. As a matter of fact, pulmonate snails, including members of the families *Physidae*, *Lymnaeidae*, and *Planorbidae*, feed on the slime and sludge communities. Snails also play a dominant role in sludge reduction, tank maintenance, and ecological fluidized bed and marsh cleaning. Ram's horn snails of the family Planorbidae, for example, graze and control filamentous algae mats that would otherwise clog and reduce the effectiveness of the diverse fluidized bed communities. Needless to say, some snails digest recalcitrant compounds. The salt marsh periwinkle, *Littorina irrorata*, produces enzymes that attack cellulose, pectin, xylan, bean gum, major polysaccharide classes, algae, fungi, and animal tissues as well as 19 other enzymes interactive with carbohydrates, lipids, and peptides [28]. Besides, snails can function as alarms in the Living Machines treating sewage. When a toxic load enters the Providence Sewage Treatment System, for example, the snails quickly leave the water column and move into the moist lower leaves of the floating plants above the water. Observing this behavior the operator then increases the rate of recycling clean water back upstream into the first cells. Consequently, performance losses are minimized due to the rapid behavioral response of these animals [21].

Virtually all phyla of animals in aquatic environments feed through some filtration mechanism. Bivalves, algivorous fish, zooplankton, protists, rotifers, insect larvae, sponges, and others are in this functional category [21]. They remove particles of approximately 0.1–50 μm from the water column. Bivalves are significant filterers. For example, mussels can retain suspended bacteria smaller than 1 μm. Efficiencies may reach 100% for particles larger than 4 μm [29]. Individual freshwater clams of the genera Unio and Anodonta filter up to 40 L/day of water, extracting colloidal materials and other suspended organic and inorganic particles. Removal rates of 99.5 % may be achieved [30]. Zooplankton such a microcrustaceans, on the other hand, can be employed to good effect in applied mesocosms. They feed upon particles 25 μm and smaller and their juvenile stages graze on submicrometer-sized particles. Since they can exchange the volume of a natural body of water several times per day, it is difficult to overstate their importance in ecological engineering [21]. In cells within the Living Machines, where fish predators are absent, their numbers are prodigious. Insects play pivotal roles in Living Technologies. Removed from predators in ecologically engineered systems, they proliferate and impact significantly on the water. For instance, chironomid larvae, which feed on sewage, may in turn be fed to fish with water quality improvement as an additional benefit [21].

Vertebrates play key roles in the functioning of Living Technologies. With an estimated 22,000 species, fishes are the most numerous and diverse of the vertebrates. In diet, behavior, habitat, and function, fish are extraordinarily diverse. Filter- and detritus-feeding fish are common to all the continents. The filtration rate of algivorous fish may be five orders of magnitude greater than their volume every day [21]. In theory it is possible for the total volume of a fishpond to pass through algae-filtering fish on a daily basis. There are edible fish species like the Central American characin, *Brycon guatemalensis*, which are capable of shredding and ingesting tough and woody materials. Members of the South American armored catfish family *Plecostomidae* may be used to control sludge buildup in waste treatment and as food in culture Living Technologies as well. Tilapia, *Oreochromis* spp., may be used to harvest small plants like duckweed and aquatic ferns. In several Living Machines minnows, including the golden shiner, *Notemigonus crysoleucas*, and fathead minnow, *Pimephales promelas*, feed on organic debris and rotting aquatic vegetation. They breed among rafted higher plants grown on the surface of the water. Excess minnows may be sold as bait fish. Therefore, research into the aquarium and ichthyologic literature will be valuable to ecological engineers [21].

3.3. Photosynthetic Communities

Ecological engineering was founded on recognition of the role of sunlight and photosynthesis. By way of contrast, algae and higher plants are seen in civil engineering as nuisance organisms to be eliminated physically and chemically from the treatment process. Contemporary intensive aquaculture takes a similar view. The ecosystem-based solar aquaculture developed at the New Alchemy Institute in the 1970s and its successors constitute an exception to this trend [21]. Algae-based waste treatment systems were pioneered by Oswald (1988) and Lincoln and Earle (1990) in the USA, Fallowfield and Garrett (1985) in the UK, Shelef et al. (1980) in Israel, and a host of scientists in China and India (Ghosh, 1991). In these systems floating higher aquatic plants are used in a variety of waste treatment approaches. For instance, the use of emergent marsh plants and engineered marsh-based systems for waste treatment has gained prominence and technical sophistication over the last few decades. Notably, employing plant diversity can produce Living Technologies that require less energy, aeration, and chemical management. Root zones are superb micro-sites for bacterial communities. There has been, for instance, observed enhanced nitrification in treatment cells covered with pennywort, *Hydrocotyle umbellata*, and water hyacinth, *Eichhornia crassipes*, as compared with comparable cells devoid of higher plants. Some plants sequester heavy metals. One such species of mustard, *Brassica juncea*, has been found to remove metals from flowing waste streams and accumulating up to 60 % of its dry weight as lead. Metals can subsequently be recovered from harvested, dried, and burned plants. Apart from metal sequestering, certain species of higher plants such as *Mentha aquatica* produce antimicrobial compounds or antibiotics that may kill certain human pathogens. Such plants are vital as components of the Living Technology design. Besides pollution reductions or mitigations, there is economic potential of plants from Living Machines. Flowers, medical herbs, and trees used in rhizofiltration in a waste treatment facility may subsequently be sold as by-products. For example, the Frederick, Maryland, Living Machine sewage treatment facility produces horticultural crops for the water gardening industry [21].

3.4. Nutrient and Micronutrient Reservoirs

Carbon/nitrogen/phosphorus ratios need to be regulated and maintained. A full complement of macro and trace elements needs to be in the system so that complex food matrices can be established and allowed to "explore" a variety of successive strategies over time. This will support biological diversity. In designing Living Machines, mineral diversity should include igneous, sedimentary, and metamorphic rocks. With a rich mineral base, they should support a wide variety of biological combinations and give the systems greater capacity to self-design and optimize. While mineral diversity provides the long-term foundation for nutrient diversity, in the near term microorganisms and plants require nutrients in an available form. If carbon is recalcitrant, or phosphorus in n insoluble state, or the NPK ratios are out of balance, or trace elements are missing, the ecosystems can become impoverished. There should, therefore, be a system to replenish the Living Machine of its vital nutrients. As a general rule, it is preferable that use is made of organic and rock-based amendments to correct imbalances and kelp meal for trace minerals and potassium [21].

4. TYPES OF LIVING MACHINES OR RESTORERS

4.1. Constructed Wetlands

Natural wetland systems have often been described as the "earth's kidneys" because they filter pollutants from water that flows through on its way to receiving lakes, streams, and oceans. For the reason that these systems can improve water quality, engineers and scientists construct systems that replicate the functions of natural wetlands. Constructed wetlands are accordingly defined as treatment systems or Living Machines that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality [31]. The concept of using constructed wetlands for the treatment of wastewater has evolved from years of observing the high water quality inherent to natural wetlands, despite contaminated effluent. This natural process has been simulated in constructed wetlands, which are designed to take advantage of many of the same processes that occur in natural wetlands, but accomplish them within a more controlled environment. Some of these systems have been designed and operated with the sole purpose of treating wastewater, while others have been implemented with multiple-use objectives in mind, such as using treated wastewater effluent as a water source for the creation and restoration of wetland habitat for wildlife use and environmental enhancement. Moreover, constructed wetlands also control pollutants in surface runoff, create wildlife habitat, and add aesthetic value [31, 32].

In general, these systems should be engineered and constructed in uplands and outside floodplains in order to avoid damage to natural wetlands and other aquatic resources, unless the source water can be used to restore a degraded or former wetland. The degree of wildlife habitat provided by constructed treatment wetlands, or sections of these wetlands, varies broadly across a spectrum. At one end of the spectrum are those systems that are intended only to provide treatment for an effluent or other water source, in order to meet the requirements of the Clean Water Act (CWA), and these provide little or no wildlife habitat. At the other end are those systems that are intended to provide water reuse, wildlife habitat, and public use, while also providing a final polishing function for a pretreated effluent or other water source. By harnessing and encouraging the complex ecologies present in these natural treatment systems, constructed wetlands can provide basic or advanced treatment for organic nutrient loads [31, 33]. There are many advantages of using constructed wetlands in treatment of water pollution. (a) Constructed wetlands provide simple, low energy, low-maintenance alternatives to conventional treatment methods. Accordingly, constructed wetlands can be integrated into a complete system including pretreatment, disinfection, and reuse. Options for reuse include subsurface irrigation, washdown water, toilet flushing, and industrial use. Besides, constructed wetlands can stand alone or function as an upgrade to conventional systems. (b) Constructed wetlands reduce residual wastewater sludges that typically require disposal and they are passive and exhibit reliable performance with minimal maintenance and operational costs, (c) they are simple to operate and simple to construct, (d) they can be operated year-round except in the coldest climates, and e) they can provide wildlife habitat, sites for wildlife observation, and environmental education.

There are two types of constructed wetlands [32]: subsurface flow system (SFS) and free water surface (FWS). Subsurface flow systems are designed to create subsurface flow through a permeable medium, keeping the water being treated below the surface, thereby helping to avoid the development of odors and other nuisance problems. Such systems have also been referred to as “root-zone systems,” “rock-reed filters,” and “vegetated submerged bed systems.” The media used (typically soil, sand, gravel, or crushed rock) greatly affect the hydraulics of the system. Free water surface systems, on the other hand, are designed to simulate natural wetlands, with the water flowing over the soil surface at shallow depths. Both types of wetlands treatment systems typically are constructed in basins or channels with a natural or constructed subsurface barrier to limit seepage. Constructed wetland treatment systems have diverse applications and are found across the USA and around the world. While they can be designed to accomplish a variety of treatment objectives, for the most part, subsurface flow systems are designed and operated in a manner that provides limited opportunity for benefits other than water quality improvement. On the other hand, free water surface systems are frequently designed to maximize wetland habitat values and reuse opportunities while providing water quality improvement [32].

The operations of constructed wetlands follow the same principle as other Living Technologies. Treatment of dissolved biodegradable material in wastewater is achieved through the synergistic work involving decomposing microorganisms, which are living on the exposed surfaces of the aquatic plants and soils, plants species, as well as various animal species. Decomposers such as bacteria, fungi, and actinomycetes are active in any wetland, breaking down dissolved and particulate organic material to carbon dioxide and water. This active decomposition in the wetland produces final effluents with a characteristic low dissolved oxygen level with low pH [32]. The effluent from a constructed wetland usually has a low BOD as a result of this high level of decomposition. Aquatic plants, on the other hand, play an important part in supporting these removal processes through such mechanisms as pumping atmospheric oxygen into their submerged stems, roots, and tubers. The oxygen is then utilized by the microbial decomposers attached to the aquatic plants below the level of the water. Plants also play an active role in taking up nitrogen, phosphorus, and other compounds from the wastewater. This active incorporation of nitrogen and phosphorus can be one mechanism for nutrient removal in a wetland. Some of the nitrogen and phosphorus is released back into the water as the plants die and decompose. In the case of nitrogen, much of the nitrate nitrogen can be converted to nitrogen gas through denitrification processes in the wetland [32]. While the use of wetlands is a promising idea, there are several potential obstacles. To be effective these wetlands require a large land area. In addition, wastewater added to wetlands must be pretreated to remove solids, reducing the energetic saving. Another problem is that in temperate climates these marshes exhibit reduced functionality for much of the year [32].

4.2. *Lake Restorers*

Restorers are an assembly of engineered ecologies incorporated into floating rafts. Restorer Technology is borrowed from an analogous component in nature known as the floating island, which is formed as dense mats of vegetation. Typically they are made up of cattails, bulrush, sedge, and reeds, which normally extend outward from shoreline wetlands. As the water gets deeper and the roots no longer reach the bottom, this vegetation uses the oxygen in their root mass for buoyancy, while the surrounding vegetation provides support that is crucial for retaining their top-side-up orientation. Moreover, the area beneath these floating mats is exceptionally rich in aquatic biota. Eventually, storm events may tear whole sections free from the shore. These resultant floating islands migrate around a lake with changing winds, occasionally reattaching to a new area of the shoreline, or breaking up in heavy weather [34].

Unlike the natural floating islands, Lake Restorers are construction that involves making rafts or wire cages that can float on water. They are then planted with different species of plants, which later provide habitats to various micro- and macroorganisms. Efficient airlift pumps and fine-bubble air diffusion systems incorporated in the design of Restorers add oxygen to the water as well as circulate water and nutrients over the Restorer's biological surfaces to stimulate the natural healing process. It is the complete body of water that treats itself. The resultant rafted floating ecologies can treat wastewater, assist in the upgrade of outdated and overloaded facultative lagoons, suppress algal growth, or help maintain the health of ponds and lakes. These diverse "floating islands" are installed in new or existing lagoons and ponds to provide a simple, robust, and beautiful method of treating waste and cleaning up polluted waters. The robustness of Restorers lies on the utilization of the widely recognized benefits of fixed biofilms to accelerate the natural processes found in a river, lake, pond, or constructed lagoon by:

(a) Introducing oxygen and circulation to the stressed environment that often lacks sufficient oxygen-rich surface areas necessary to maintain a balanced ecology
(b) Utilizing native higher plants and artificial media as biofilm substrate to support rich microbial, algae, and animal communities
(c) Acting as a chemostat and incubator by producing great volumes of beneficial microorganisms that flow into the surrounding water and feed on excess nutrients and organic pollutants
(d) Providing opportunities for benthic communities to establish themselves in the bottom areas that were once oxygen poor [34]

4.3. *Eco-Restorers*

Eco-Restorers, unlike Lake Restorers, are more expensive to construct yet less energy efficient to operate. These systems, many of which were originally built under the name "Living Machines," are ideal for situations either where there is very little land available or where a significant element of visitor interest and interpretation is required [34]. In 1995

Jonathon Porritt opened Europe's first Eco-Restorer System—a Living Machine*—at the Findhorn Foundation. This ecologically engineered plant is designed to treat sewage from the population of up to 300 people living at the Findhorn Foundation and provides a research and educational facility to promote this technology throughout Europe. Diverse communities of bacteria, algae, microorganisms, numerous species of plants and trees, snails, fish, and other living creatures interact as whole ecologies in tanks and biofilters. In this Living Machine system, anaerobically treated sewage flows into a greenhouse containing a series of tanks. These tanks contain species which breakdown the sewage naturally as it moves through. In many systems there are by-products of fish and plants being produced that can then be sold. Living Machines mirror processes that occur in the natural world but more intensively. At the end of the series of tanks, the resulting water is pure enough to be recycled. The technology not only is capable of meeting tough new sewage outflow standards but uses no chemicals and has a relatively inexpensive capital cost attached.

A typical design of an Eco-Restorer, using the Findhorn example, has five major components, which are housed in a single-span greenhouse, approximately 10 m wide by 30 m long. They comprise the anaerobic septic tanks, closed aerobic reactor, open aerobic reactors, the clarifiers, and the ecological fluidized beds (EFBs). This Living Machine at Findhorn receives about 60 m^3 wastewater per day for treatment. The raw wastewater is received in the first component of the system: the anaerobic septic tanks. Typically, three [3] anaerobic bioreactors are buried outside the greenhouse, and their function is to reduce significantly the organic material and inorganic solids in the wastewater. The absence of oxygen in the wastewater promotes the growth of anaerobic and facultative bacterial populations. After the anaerobic digestion, the effluent from the anaerobic tanks flows into a closed aerobic tank in the greenhouse. Air is introduced through fine-bubble diffusers to convert the wastewater from an anaerobic to an aerobic state. Gases from the closed aerobic tank pass through an air filter system to eliminate odors. After this treatment, the effluent moves the open aerobic reactors. The Living Machine at Findhorn has four aerobic tanks containing diaphragm aerators, and each is planted with plant species with large root masses on floating plant racks. The BOD and TSS are reduced at this stage and ammonia is nitrified. The primary function of the plants is to provide favorable environments for enhanced microbial activity. Bacteria and other microorganisms attach themselves to the large surface area of submerged plant roots. These attached biofilms contribute significantly to the treatment process. The secondary plant functions include nutrient removal, metal sequestering, pathogen destruction, and some control of gas exchanges. The main objective is to have a healthy and diverse sequence of ecosystems present. The wide variety of plant species filling ecological niches in the system is a key to the robust nature of natural treatment systems. The ecological network of species creates internal biological redundancies compared with a purely microbial system or a monoculture duckweed system. This gives the potential for improved efficiency and greater resilience. Despite the efficiency of both microorganisms and plants, the effluent from the open aerobic tanks still contains some un-degraded suspended solids. The solids kept in suspension in the aerobic tanks are removed in the clarifier. The clarifier is a settling tank with cone-shaped bottom. The suspended solids settle at the bottom of the tank and are returned to the anaerobic primary tanks. In the clarifier tanks you may see tiny water creatures such as

Cyclops living in the water. They perform an important part in both treatment and in creating a complex food chain. The clarified effluent now is set to enter a final phase of treatment by the ecological fluidized beds (EFBs).

The ecological fluidized beds in each train are filled with light rock media. For aerobic operation, airlift pumps raise the water from the bottom of the fluidized bed to the surface, where the water flows down through the bed. Recycle rates can be varied up to 100 times the flow rate through the component. The aerobic operation provides reductions in BOD and TSS and nitrification. For the anaerobic operation of the fluidized beds for denitrification, mechanical pumps circulate water up through the bed. The fluidized beds are planted and benthic animals graze the surface. The first fluidized bed is usually run aerobically to nitrify any remaining ammonia in the waste stream. The second fluidized bed can be run anaerobically to denitrify. The third and final fluidized bed is run for final denitrification and polishing. The underlying concept behind the design involves rapid flows of water by recycling through the media-filled zones. The key attributes of an ecological fluidized bed are stable high surface area microenvironment sites for bacteria, ultrarapid exchanges across biological surfaces, direct NH_4^+/NO_3^- uptake, nitrification and denitrification cycles, the support of higher plant life and root systems within the media and in the aquatic environments, and self-cleaning. The biology is managed as a balanced ecosystem. The levels of dissolved oxygen, and carbon to nitrogen ratios, as well as recycle rates and bioaugmentation, are adjusted with the overall objective of reducing levels of BOD, ammonia (NH_3), total nitrogen (TN), fecal coliform, and solids. Information on the efficiency of the Restorer system/Living Machine at Findhorn showed that the system treats sewage to advanced wastewater treatment (tertiary) standard. Specifically, biochemical oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen in water (TKN), ammonium (NH_4^+), nitrate (NO_3^-), and total phosphorous (TP) which were 250, 160, 40, 50, 10, and 7 mg/L, respectively, before treatment. After treatment, the effluent quality become 10 mg/L for BOD, TSS, and TKN, 2 mg/L for NH_4^+, 5 mg/L for NO_3^- and 5 mg/L for TP [34].

4.4. *Reedbeds*

Reedbeds are natural systems, which are ideal for treatments on small scale or where there are no land restrictions. They are cost-effective to install and simple and inexpensive to run. They do however take up larger areas of land than Restorers. Currently there are several different alternative designs: (a) horizontal flow reedbeds (HFR)—in this design the wastewater is fed in and flows slowly through the bed in a horizontal path below the surface until it reaches the outlet zone. Here, it is collected before leaving via the level control arrangement at the outlet. As it flows, the wastewater comes into contact with a network of aerobic, anoxic, and anaerobic zones. The reed rhizomes open up the bed to provide new hydraulic pathways. (b) Vertical flow reedbeds (VFR)—these systems are often used to reduce on-site sludge production. The sludge is added to the reedbed and is degraded in the oxygen-rich environment by the plant roots. (c) Pond and reedbed systems (PRS)—the pond and reedbed systems are individually designed, robust, and self-maintaining and can treat domestic, municipal, agricultural, and industrial wastewater to very high standards. They consist of a series of shallow outdoor ponds, fringed with various species of emergent plants, and are linked by areas of aggregate-filled constructed wetland. These systems can be built for as few as 5 and as many as 3,000 people. Land requirements are approximately 10 m^2 per person equivalent, depending on conditions [34].

5. PRINCIPLE UNDERLYING THE CONSTRUCTION OF LIVING MACHINES

As has been pointed out above (Sect. 2), Living Machines construction relies on the principles of ecology, and the resultant technological innovations, defined broadly as advanced ecologically engineered systems (AEES), are being considered for application to number of problem areas. Potential applications include a) the replacement of or provision of designs of ecological systems (ecotechnology) as alternatives to man-made/energy-intensive systems to meet various human needs (e.g., constructed wetlands for wastewater treatment); b) the restoration of damaged ecosystems and the mitigation of development activities; c) the management, utilization, and conservation of natural resources; and d) the integration of society and ecosystems in built environments (e.g., in landscape architecture, urban planning, and urban horticulture applications). These potential applications govern or offer a basis for the underlying principles for the construction of Living Technologies. Bergen and coworkers summarize these principles into five general principles to guide those practicing ecological engineering in any context or ecosystem [35]. There are specifically five principles governing the construction of Living Machines which are here below briefly explored.

5.1. Living Machine Design to Be Consistent with Ecological Principles

This principle emphasizes the importance of understanding the characteristics and behaviors of the natural systems. The designs accordingly produced with regard to, and taking advantage of, the characteristic behavior of natural systems shall be most successful. Also notable is the fact that when natural structures and processes are included and mimicked, then nature is treated as a partner in design and not as an obstacle to be overcome and dominated. This is because the capacity of ecosystems to self-organize is recognized and put into use. Mitsch and Jørgensen state that it is this “capability of ecosystems that allows nature to do some of the “engineering” and that ecological engineers participate as choice generators and as a facilitator of matching environments with ecosystems, but nature does the rest.” The key attributes of an ecosystem that allow for self-organization are complexity and diversity. Ecosystems can be complex structurally and in the temporal and spatial scales of processes. Significant ecological changes are often episodic, and critical processes, which occur at rates spread over several orders of magnitude, but clustered around a few dominant. Ecosystems are also heterogeneous, displaying patchy and discontinuous textures at all scales and do not function around a single stable equilibrium. They are rather defined by the functionally different states, which are created from the “destabilizing forces far from equilibria, multiple equilibria, and/or absence of equilibria define, and movement between states. These maintain structure and diversity of the ecosystems.” The structure and diversity produced by the large *functional space* occupied by ecosystems is what allows them to remain healthy or to persist. The large functional space required for sustainable ecosystems is directly at odds with traditional engineering design practices that create systems that operate close to a single, chosen equilibrium point. Another important characteristic of ecosystems is that the outputs of one process serve as the inputs to others. No waste is generated and nutrients are cycled from one trophic level to the next. In constructing Living Machines, this concept should be well understood. A final characteristic of natural systems is that they tend to function near the edge of chaos or instability. Designing systems to include ecological characteristics would, therefore, depart from common engineering practice. Designing for ecological rather than engineering resilience would mean encouraging diversity and complexity, while allowing systems to self-organize, mature, and evolve. How to design systems to perform like ecosystems and still function as desired is explored in the remaining principles [35].

5.2. Living Machine Design to Deal with Site-Specific Situation

The complexity and diversity of natural systems cause a high degree of spatial variability. While the ecological characteristics discussed above are generally applicable, every system and location is different. The second principle suggests that one has to gain as much information as possible about the environment in which a design solution ought to function. Furthermore, the spatial variability rules out standardized designs, which means that the solutions should be site specific and small scale. Standardized designs imposed on the landscape without consideration for the ecology of a place will take more energy to sustain. In addition, knowledge of the place also allows for more holistic designs. Such design takes into account both the upstream and downstream effects of design decisions. For upstream issues such as what resources must be imported and appropriated to create and maintain a solution are considered while for downstream the site-specific and off-site impacts of the design on the environment are considered. In addition to the physical context of a design, knowledge of the cultural context is important. Designs are more likely to succeed and to be accepted by the local community when the people who live in a place are included in the design process. They bring knowledge of the particularities of a place and are empowered through direct participation in shaping their environment. Attention to group dynamics and conflict mediation is important for successful stakeholder participation [35].

5.3. Living Machine Design to Maintain the Independence of Its Functional Requirements

Ecological complexity adds high and often irreducible levels of uncertainty to the design process. Even under conditions of certainty, the amount of relevant information in possession may be overwhelming and often unmanageable, yet it is desirous that the solutions are kept simple and workable. Under these circumstances a strategy for dealing with such uncertainty would be to set the *tolerances* on the design functional requirements as wide as possible. The third principle, which is a restatement of the first design axiom of Suh (1990), entails that the "functional requirements (FRs)," which are the specific functions that a design solution is required to provide, are satisfied, individually, by the "design parameters (DPs)." This means that the design parameters are the physical elements of the solution chosen to satisfy FRs. Therefore, best designs are those that have independent (not coupled) FRs and one and only one DP to satisfy each FR. Consequently, when modifying one DP affects more than one FR, then a design is described as being coupled. In these circumstances, wide tolerances on FRs can make the design essentially uncoupled. This is so because wide design tolerances allow a larger functional range for a system while the outputs remain within acceptable ranges. However, when interacting with ecological systems, the concept of functional independence becomes a lot less clear. This is so because ecosystems are complex with many levels of interconnection between components, which means that many elements of the system may be involved in more than one process. Since ecosystems can function and provide benefits to society without human intervention, the design FRs are incorporated or considered in any undertaking of Living Technology designs to satisfy unmet human needs. Therefore, the FRs for design follow from the statement of these needs, while the ecosystem processes that are in existence and their preservation needed while designing for unmet needs, act as constraints on design. Although the independence principle predicts that successful designs may be obtained when the FRs are kept uncoupled in the solution, in reality, however, it would be foolish not to take advantage of the multiple, coupled services an ecosystem can provide [35].

5.4. *Living Machine Design to Enhance Efficiency in Energy and Information*

The fourth principle follows from taking advantage of the self-organizing property of ecosystems. To let nature do some of the engineering means that the free flow of energy into the system from natural sources, primarily the Sun, should be put to maximum use. At the same time the energy expended to create and maintain the system directed, by design, from off-site sources, such as fossil fuels and large-scale hydroelectric sources, should be minimized. While utilizing free-flowing energy, however, it is important to follow where the energy would go without intervention, to make sure that it is not more critically needed downstream and that there is minimal adverse impact. This could be achieved by keeping the information content of the design to the minimum or simply stated making designs simple yet successful. For example, the energy input needed to restrict a stream channel to a confined space tends to be high and ultimately fails when a large flood occurs. A better design would recognize the expected variability in stream flows, and the system would be designed to withstand large variations in flow (wide tolerance) yet still maintain its ecological and engineering functions, i.e., minimizing information content. In this way the extra information required would be balanced by utilizing self-organization and wide tolerances. In other words, this can be considered as an up-front capital investment in diversity that would gain overall efficiency later through reduced energy requirements and a reduced risk of failure. Therefore, diversity provides insurance against uncertainty in addition to contributing to ecological resilience. In the case of an engineered wetland, for example, a wide range of species may be included in the initial construction, but natural processes are allowed to select those best suited for the imposed environment. Similarly, the first and second principles advocate an up-front investment in knowledge of the design context to minimize uncertainty and to allow less information to be transferred during design implementation [35].

5.5. *Living Machine Design to Acknowledge and Retain Its Values and Purposes*

The major goal of Living Technologies is the provision of ecologically oriented designs that would benefit both society and the natural environment. Moreover, most engineering codes of ethics state at least that engineers have a responsibility to serve and protect society. From an ecological engineering perspective, this code has been explicitly broadened to include the responsibility of sustaining the natural systems that support life. Regardless of specific ideology, however, design practices that acknowledge the motivating values and purposes would be more successful. Recall that the third principle recommends using wide tolerances under conditions of uncertainty. Consequently, it follows that a precautionary approach for ecological engineering is ought to be adopted at all times. A precautionary approach should act as a form of insurance against unpleasant surprises in the future. In Living Technologies innovations, classical engineering should be applied sparingly, and complex solutions avoided where possible. Furthermore, design solutions that are both fail-safe and safe-fail should be pursued to avoid catastrophic failures. As opposed to traditional fail-safe approaches, safe-fail solutions acknowledge that our original functional requirements for a design may not be met or that there may be unexpected results. Failure in this case is not catastrophic. Therefore, in selecting the design, alternatives that have the best worst-case outcome should be advocated for [35].

6. OPERATION OF LIVING MACHINES

The operationalization of the Living Machine technology relies on the incorporation of plants and animals in many of the same basic processes (e.g., sedimentation, filtration, clarification, adsorption, nitrification and denitrification, volatilization, and anaerobic and aerobic decomposition) that are used in conventional biological treatment systems. A typical Living Machine comprises six principle treatment components: (1) an anaerobic reactor, (2) an anoxic tank, (3) a closed aerobic reactor, (4) aerobic reactors, (5) a clarifier, and (6) “ecological fluidized beds” (EFBs) (Fig. 14.1a). While the open aerobic reactors and EFBs are found in almost all Living Machines, the other components are not always utilized in the treatment process. The specific components used are selected by the designers depending upon the characteristics of the wastewater to be treated and the treatment objectives. Sometimes additional process components may be added if considered necessary by the designers [36].

Anaerobic Reactor (*Step 1*)

In case it is incorporated into the treatment process, the anaerobic reactor serves as the initial step of the process. The reactor, which is similar in appearance and operation to a septic tank, reduces the concentrations of BOD5 and solids in the wastewater prior to treatment by the other components of the process. Raw influent enters the reactor, which acts as a primary sedimentation basin. Some of the anaerobic reactors used have an initial sludge blanket zone, followed by a second zone for clarification. Additionally, strips of plastic mesh netting are

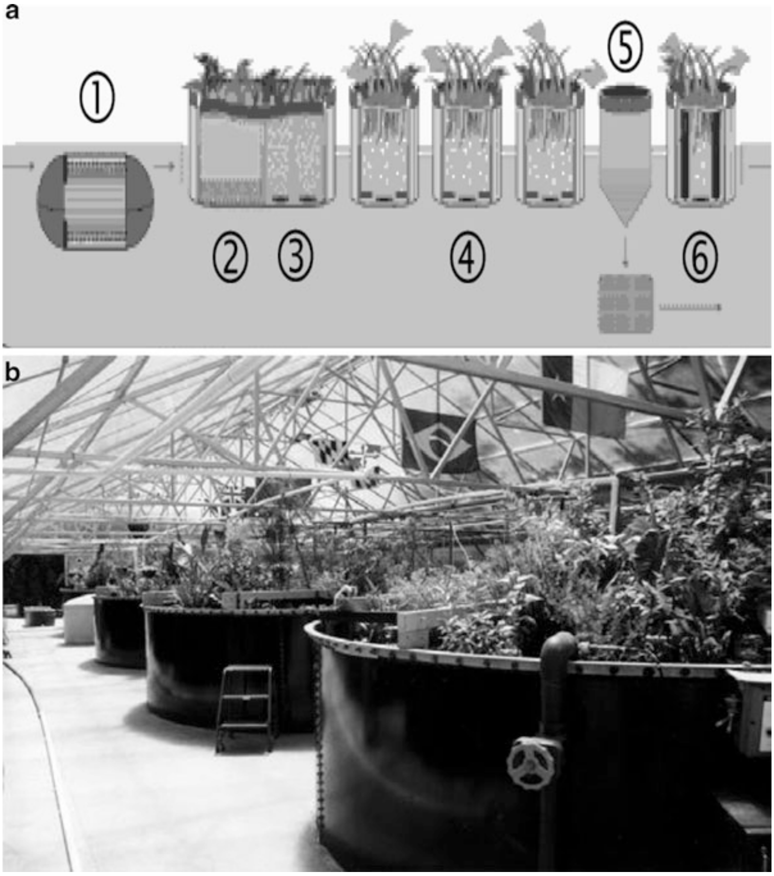

Fig. 14.1. (**a**) This illustrates the operational setup and components of the Living Machine®: (1) anaerobic reactor, (2) anoxic reactor, (3) closed aerobic reactor, (4) open aerobic reactors, (5) clarifier, and (6) "ecological fluid bed". (**b**) This illustrates the operational setup of the open aerobic tanks of the Living Machine in South Burlington, VT. A series of tanks in a greenhouse are shown (Adapted from US Environment Protection Agency Fact Sheet, 2002).

sometimes used in the clarification zone to assist with the trapping and settling of solids, and to provide surface area for the colonization of anaerobic bacteria, which help to digest the solids. Sludge is typically removed periodically via perforated pipes on the bottom of the reactor and wasted to a reedbed or other biosolids treatment processes. Gases produced are passed through an activated carbon filter or biofilter for odor control [36].

Anoxic Reactor (*Step 2*)

The primary purpose of the anoxic reactor is to promote growth of floc-forming microorganisms, which will remove a significant portion of the incoming BOD_5. The anoxic reactor is mixed and has controlled aeration to prevent anaerobic conditions and to encourage floc-forming and denitrifying microorganisms. Mixing is accomplished through aeration by a coarse bubble diffuser. These diffusers are typically operated so that dissolved oxygen is maintained below 0.4 mg/L. The space over the reactor is vented through an odor control device, which is usually a planted biofilter. In addition, an attached growth medium may be placed in the compartment to facilitate growth of bacteria and other microorganisms. Settled biosolids from the clarifier (Step 5) and nitrified process water from the final open aerobic reactor (Step 4) are recycled back into this reactor. The purpose of these recycles is to provide sufficient carbon sources to the anoxic reactor to support denitrification without using supplemental chemicals, such as methanol [36].

Closed Aerobic Reactor (*Step 3*)

The purpose of the closed aerobic reactor is to reduce the dissolved wastewater BOD_5 to low levels, to remove further odorous gases, and to stimulate nitrification. Aeration and mixing in this reactor are provided by fine-bubble diffusers. Odor control is again achieved by using a planted biofilter. This biofilter typically sits directly over the reactor and is planted with vegetation intended to control moisture levels in the filter material.

Open Aerobic Reactors (*Step 4*)

Next in the process train are the open aerobic reactors or aerated tanks. They are similar to the closed aerobic reactor in design and mechanics (i.e., aeration is provided by fine-bubble diffusers); however, instead of being covered with a biofilter, the surfaces of these reactors are covered with vegetation supported by racks. These plants serve to provide surface area for microbial growth, perform nutrient uptake, and can serve as a habitat for beneficial insects and microorganisms. With the variety of vegetation present in these reactors, these units (along with the ecological fluidized beds—Step 6) set the Living Machine apart from other treatment systems in terms of their unique appearance and aesthetic appeal (Fig. 14.1b). The aerobic reactors are designed to reduce BOD_5 to better than secondary levels and to complete the process of nitrification. The size and number of these reactors used in a Living Machine design are determined by influent characteristics, effluent requirements, flow conditions, and the design water and air temperatures [36].

Clarifier (*Step 5*)

The clarifier is basically a settling tank that allows remaining solids to separate from the treated wastewater. The settled solids are pumped back to the closed aerobic reactor (Step 3), or they are transferred to a holding tank and then removed for disposal. The surface of the clarifier is often covered with duckweed, which prevents algae from growing in the reactor.

Ecological Fluidized Beds (*Step 6*)

The final step in the typical Living Machine process is the "ecological fluidized beds" (EFBs). These are polishing filters that perform final treatment of the wastewater, and one to three are used in series to reduce BOD_5, TSS, and nutrients to meet final effluent requirements. An EFB consists of both an inner and outer tank. The inner tank contains an attached growth medium, such as crushed rock, lava rock, or shaped plastic pieces. The wastewater flows into the EFB in the annular space between the inner and outer tanks and is raised by air lift pipes to the top of the inner ring that contains the media. The bottom of the inner tank is not sealed, so the wastewater percolates through the gravel media and returns to the outer annular space, from where it is again moved back to the top of the gravel bed. The air lifts also serve to aerate the water and maintain aerobic conditions. The unit serves as a fixed bed, downflow, granular media filter and separates particulate matter from the water. Additionally, the microorganisms that occupy the granular media surfaces provide any final nitrification reactions. As sludge collects on the EFB, it reduces its ability to filter. This would eventually clog the bed completely. Therefore, additional aeration diffusers beneath the gravel bed are periodically turned on to create an upflow airlift, reversing the flow direction. This aeration is intended to "fluidize" the bed and release the trapped sludge (hence the name of this unit). This sludge is washed over and accumulated at the bottom of the outer annular space where it can be collected manually and wasted along with the biosolids from the anaerobic reactor. Consequently, the name "ecological fluidized bed" is somewhat misleading for this unit since, in its treatment mode, it acts like a typical, conventional, downflow coarse media contact filter unit. Only during backwash cleaning does the bed become partially fluidized. After this last step, the wastewater should be suitable for discharge to surface waters or a subsurface disposal system or reused for landscape irrigation, toilet flushing, vehicle washing, etc. [36].

7. CASE STUDIES OF CONSTRUCTED LIVING MACHINE SYSTEMS FOR BIOREMEDIATION, WASTEWATER TREATMENT, AND WATER REUSE

7.1. *Sewage Treatment in Cold Climates: South Burlington, Vermont AEES, USA*

Ocean Arks International, which is a not-for-profit organization dedicated to the development of ecological design and its implementation into society, in 1995 constructed a tank-based "advanced ecologically engineered system" (AEES) or Living Machine in South Burlington, Vermont, to determine if the technology is capable of treating sewage to high standards in a northern New England climate, particularly during the cold and short day-length seasons [17]. The AEES facility, housed within a 725 m^2 (7,800 ft^2) greenhouse, contained two parallel treatment systems designed to treat 300 m^3 per day (80,000 gal per day) of sewage from the city of South Burlington to advanced tertiary wastewater standards for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitrate (NO^-_3), and total nitrogen (TN). The performance target for removal of fecal coliforms in the system was 2,000 cfu/100 mL without disinfection. The Vermont Living Machine was biologically diverse. Over 200 species of vascular and woody plants were evaluated for their effectiveness and suitability for waste treatment between 1995 and 2000. Plants were evaluated for (a) their ability to tolerate sewage, (b) the extent of the root zones, (c) disease and pest resistance, (d) ease of management, and (e) secondary economic value. The plants were physically supported on the surface of the water by rigid plant racks designed to provide gentle flow over the roots in a highly aerated and turbulent surrounding environment. The system was designed to utilize microbial communities attached to plant roots, as well as flocculating bacteria in the open water to affect treatment. Invertebrates including microcrustaceans and freshwater clams provided biological filtration, while snails and fish were incorporated into the design to digest residual biosolids.

The flow was split between two 150 m^3 per day (40,000 gal per day) treatment trains with a hydraulic retention time (HRT) of 2.9 days. The facility was started in December 1995, operated at its design flow capacity by May 1996, and was maintained at this steady state until the end of 1999. Each treatment train comprised nine tanks connected in series and each tank was 4.6 m wide × 4.6 m deep (15 ft × 15 ft). Raw effluent entered and was mixed in an anoxic reactor. To control odors normally associated with raw sewage, an ecological gas scrubber, employing higher plants and a soil/bark/compost media, was mounted over the anoxic reactor tank. The wastewater flowed from the anoxic reactor into four aerobic reactors. Dense plantings were maintained on surface racks. The waste then flowed to a clarifier covered with floating aquatic plants. Biosolids from the clarifier were recycled to the anoxic reactor or wasted [17].

Downstream of the clarifier were three tanks containing ecological fluidized beds (EFBs) in series. The EFB in essence serves as a submerged trickling filter capable of supporting plants mounted over an outer ring of open water. The media that comprises the inner part of the EFB physically supports benthic organisms, including mollusks. Depending upon water quality and their position in the series, the EFBs could be operated anoxically to aid denitrification or aerobically for polishing and final filtration. The facility met and exceeded its design parameters for $CBOD_5$, TSS, TKN, NH_3, NO_3^-, and TN as well as fecal coliform bacteria. A high level of performance was maintained even during the coldest months. In addition, phosphorus design standards were also met, but the AEES technology has yet to demonstrate phosphorus removal beyond what would be expected in a nitrifying activated sludge process.

One of the goals of the project was to grow organisms that not only provided treatment but also had potential economic benefits. Botanicals with economic value included young trees such as *Taxodium distichum* L. (bald cypress), *Zantedeschia aethiopica* L. (calla lily), and plants used for environmental remediation or wetland mitigation. Fish grown and harvested from the system included *Notemigonus crysoleucas* M. (golden shiners) and other bait fish, *Pimephales promelas* R. (fathead minnows), and ornamental fish including *Carassius auratus* L. (goldfish) and Japanese koi. All of the fish species fed upon organic material and plankton produced internally within the facility. One of the most striking aspects of the Vermont facility was its beauty. It remains a frequently visited educational facility and is currently operated as a test facility for the treatment of different types of high-strength organic wastes including brewery wastes. It is also a site where new economic by-products from both liquid and solid waste conversion processes are being developed [17].

7.2. Environmental Restoration: Flax Pond, Harwich, Massachusetts, USA

The Flax Pond, which is a 15 acre (6 ha) pond in Harwich, Massachusetts, has for decades been heavily impacted by leachates from an adjacent landfill and unlined septage holding lagoons. By 1989, the pond was closed to recreation and fishing because of contamination caused by the daily intrusion of 295 m^3 (78,000 gal) of leachate from the landfill [17, 37]. The pond had low oxygen levels, high coliform counts, excessive sediment buildup, and organic pollutants in the water column including volatile organic compounds (VOCs). Macrobenthic organisms were absent from many of the bottom sampling stations. Flax Pond had unusually high sediment concentrations of total phosphorus (300 times greater) and iron (80 times greater) compared with other Cape Cod ponds [17, 38]. Ammonia levels in the sediments were found to be as high as 8000 mg/kg. The pond is delineated into an eastern zone and a western zone, the cloudier eastern zone being the predominant zone of impact from the landfill. The pond also had a maximum depth of 6 m and stratifies in its western end. In the autumn of 1992, construction of the first floating Pond Restorer was completed and anchored at the eastern end. It employed a windmill and solar panels for electrical generation and was capable of circulating through its nine cells up to 380 m^3 per day (100,000 gal per day) of water drawn from the bottom of the pond. The first three cells were filled with semi-buoyant pumice rock that supported diverse benthic life including freshwater clams of the genera *Unio* and *Anodonta*. Since phosphorus was limiting in the pond's water column, a slow release form of a clay-based soft phosphate was added to the EFB cells in the Restorer. Moreover, bacterial augmentation and mineral enrichment in the first three cells was routinely done. The final six cells supported over two-dozen species of terrestrial plants on racks. The Restorer was not operated during the winter months to allow the pond to freeze completely.

The first noticeable effect of the Restorer on the pond was the return of a positive oxygen regime to the bottom. By 1995, the sediment depth throughout the pond had been reduced by an average of 64 cm representing a total of 38,000 m^3 of digested sediments. Between the years 1999 and 2001, dramatic changes in the sediments took place, including large reductions (exceeding 50 %) in total phosphorus, ammonia, and TKN. However, total iron increased in the western end and decreased slightly in the eastern end of the pond. Alkalinity followed a similar pattern. The investigators could not establish which internal mechanisms were involved in the changes in sediment phosphorus, although TKN reduction was with certainty associated with nitrification and denitrification in the sediments (i.e., nitrates were below detectable limits in all sediment samples in both 1999 and 2001). Water clarity and the overall health of the pond have improved over the past decade, and biodiversity has increased [17].

7.3. *Organic Industrial Wastewater Treatment from a Poultry-Processing Waste in Coastal Maryland: Using Floating AEES Restorer*

In the late 1990s, the design of the Pond Restorer used in Flax Pond evolved into a linear AEES Restorer design for use on new and existing wastewater treatment lagoons. This technology combines the benefits of the small footprint AEES tank-based technology (Sect. 6.1) with the simplicity and efficiency of constructed wetlands. The first large-scale wastewater application of the floating AEES Restorer technology was installed in June 2001 on a wastewater treatment lagoon that treats 3,785 m^3 (1 million gallons per day) of high-strength poultry-processing waste in coastal Maryland. The Restorers were installed in a 34,100 m^3 (9 million gallon) storage lagoon downstream of a lagoon that had been run as a sequencing batch reactor (SBR) for over 15 years [17].

Twelve Restorers run 43 m (140 ft) each across the lagoon and are secured from the banks in multiple cells, creating a serpentine flow pattern with floating baffles. Twenty-five species of native plants (25,000 individuals) were installed in plant racks on the outside edges of the Restorers. The plants are a critical element in the technology. Their root system provides surface areas and nutrient support for microbial communities, some nutrient uptake and they shade/inhibit suspended algae in the lagoons. Water is treated in the open areas on each side of the Restorers with fine-bubble linear aerators installed at the bottom of the lagoon. The center zones of the Restorers, with suspended fabric media, provide surface area for attachment and growth of microbial communities and as such are submerged, aerobic, fixed film reactors. The transition between the old SBR system and the new Restorer lagoon took place in October 2001. Although definitive quantitative data is not yet available, qualitative successes of the project in these early stages are worth noting.

Since start-up of the Restorer system, effluent standards have not exceeded state permit levels. The electrical energy use in the lagoons has been reduced by approximately 74 % compared to the former sequencing batch reactor (SBR) system [39, 40]. Energy reduction is the result of higher biological reaction rates in the Restorer lagoon and the efficiency of the new aeration design. Sludge has been trucked for 20 years from the poultry-processing plant for land application at nearby farms. The sludge comes from a variety of locations within the wastewater system, including the lagoons. Since installation of the Restorers the average truckloads of sludge leaving the processing facility have decreased significantly. This overall sludge reduction is the direct result of reduced sludge coming from the Restorer lagoon. Operation of the former SBR system required wasting of sludge for 8 h every day from the lagoons. Following installation of the new Restorer system, sludge is wasted for approximately 1 h every few weeks. In addition, 45 Sludge Judge samples have been taken monthly within the Restorer lagoon. Since August 2001 total sludge levels have decreased by approximately 10 cm (4 in.). This decrease indicates that sludge degradation is faster than sludge accumulation, even as the lagoon treats waste [17, 34].

7.4. Architectural Integration: Oberlin College, Ohio, USA

In recent decades architecture has begun to include ecologically designed systems within structures for air purification, humidity control, water reuse, waste treatment, and food production. The bio-shelters developed by the Todds are being integrated in ecologically designed systems for living and life support [41]. A number of new buildings are employing ecologically engineered technologies for waste treatment, water reuse, and education including the Ontario, Canada, Boyne River School, and the Kitchener/Waterloo YMCA rural campus. The most recent of these is the Lewis Environmental Studies Center at Oberlin College in Ohio. The building includes renewable energy, natural daylighting, and nontoxic and recyclable materials. Within the structure is an AEES system or Living Machine for sewage treatment and biological research. This system, similar to the Vermont AEES, includes tanks connected in series and a constructed wetland within the building. The tanks support a diverse community of tropical and temperate plants. The purified wastewater is sterilized with UV before reuse in the toilets in the building. There is a growing interest in redefining the functioning of buildings in ecological terms. This is driving some architects towards conceptualizing buildings as “organisms.” New light-transmitting designs and self-regulating technologies optimize internal climates and support a diversity of ecological elements within the buildings. Nature is increasingly being brought indoors for practical and aesthetic reasons [17].

7.5. Tyson Foods at Berlin, Maryland, USA

The poultry-processing facility acquired by Tyson Foods at Berlin, Maryland, came with a wastewater treatment system that was known to be the worst in the state. The major problem with this system was that it discharged its contents to Chincoteague Bay, which is a protected bay used for fishing and harvesting crabs and scallops. Owing to its inability to comply with the State of Maryland discharge standards, the downstream aquatic ecosystems could not be protected. This one million gallon per day poultry-processing waste treatment system required a wastewater treatment upgrade to meet effluent treatment standards and to reduce energy costs and the use of chemical treatment [34]. Ocean Arks International (OAI) installed such Restorers. Adding Restorers to existing waste treatment lagoons provided a robust and flexible treatment option. In the modified treatment system, an existing aerated lagoon is maintained with subsurface aeration only. At the beginning of this lagoon is an anoxic denitrifying cell. Wastewater is polished in a 9 million gallon lagoon using 12 linear Restorers. The nitrified effluent can be recycled back to the anoxic zone. This treatment method has reduced energy input by 70–80 %. Twelve floating Restorers (2,100 ft^2 each) were installed in the lagoon and secured from the banks in four separate cells, created with suspended fabric baffles. Water flows through the Restorer lagoon in a serpentine path to maximize treatment, gently aerated and circulated by subsurface, fine-bubble aeration. The wastewater is treated both beneath the Restorers and in the open channels between them. The plant roots and the curtains of suspended fabric media act as submerged, aerobic, fixed film reactors.

The biological design of the Restorers and their placement within the lagoon provides diverse habitat (in the water column, sediments, and the Restorers) for a variety of microbial communities, each of which performs an important function in the treatment process. Approximately 25,000 plants of 25 species were planted on the Restorers, only a handful of the 500 species that Ocean Arks has researched for use in wastewater treatment. Aquatic and water-loving species native to the region were chosen for their treatment properties, their ease of maintenance, and root mass area. The operation and maintenance of the Restorers is simple and low in cost. Walkways provide access to the plants. In addition to the newly planted diversity, several local plants as well as turtles have migrated into the system, creating a unique self-organizing ecosystem.

7.6. Old Trail School, Bath, Ohio, USA

Old Trail School is an independent, coeducational day school for students aged toddler through grade eight. The Living Machine system at the school is an advanced on-site wetland system, composed of 3 different wetland processes which treat 5,000 gpd of wastewater. The alternating anaerobic and aerobic cycles are effective to treat the school's high-strength sewage in a safe, attractive, and cost-effective manner [42, 43].

7.7. US-Mexico Border, San Diego, California, USA

The alternating anaerobic and aerobic Living Machine system treats 1,500 gpd of wastewater at the busiest commercial Otay Mesa Land Port of Entry. The system provides not only on-site wastewater treatment but also water reuse for the major facility [44].

7.8. US Marine Corps Recruit Depot, San Diego, California, USA

The US Marine Corps Recruit Depot (MCRD) in San Diego provides basic training for over 21,000 recruits per year and has been recognized as one of the leading Department of Defense facilities for implementing clean green technology. The on-site Living Machine system recycles 10,000 gpd of wastewater for subsurface irrigation, minimizing its water usage in drought-prone San Diego area [45].

7.9. San Francisco Public Utilities Commission Administration Building, California, USA

A 13-story, 277,500 ft^2 building generates its own energy through integrated solar panels and wind turbines, treats 5,000 gpd wastewater using a Living Machine system, and recycles all treated water for reuse. It can be seen that even in a dense urban area, it is possible to create buildings, communities, and regions that are resilient, sustainable, and able to produce and reuse valuable water resources on-site. The footprint of the San Francisco Living Machine system is about 1,000 ft^2 [46].

7.10. Esalen Institute, Big Sur, California, USA

Many educational institutions around the world are trying to conserve the water and protect the environment [47-50]. For instance, the Esalen Institute, Big Sur, California, applies the Tidal Flow Wetland Living Machine technology to treat its laundry and lodging facility wastewaters and reuses the treated effluent for subsurface irrigation. Alternatively, the treated effluent is discharged to its existing leach fields for recharging the groundwater [49].

7.11. Guilford County School District, California, USA

The Guilford County School District uses plant-based strategies to cleanse 30,600 gpd of wastewater and produces enough clean water to irrigate 3 athletic fields. This environmentally sound, on-site Living Machine system costs less than other pretreatment strategies and helps to reduce the amount of nitrogen entering the watershed [50].

7.12. Las Vegas Regional Animal Campus, Nevada, USA

The Las Vegas Regional Animal Campus (RAC) serves the animal sheltering and adoption needs in the region. The 5,000–10,000 gpd of wastewater is treated by a Tidal Flow Wetland Living Machine system and reused for kennel washdown and other appropriate water uses [51].

7.13. Port of Portland, Oregon, USA

The new headquarters office facility for the Port of Portland has adopted the Living Machine system as its showcase feature. The system includes a tiered series of wetland cells supporting the growth of indoor landscaping and ornamental flowers. It is designed to treat all of the facility wastewater to a quality for reuse, including toilet flushing and makeup water for cooling towers [52, 53].

7.14. El Monte Sagrado Resort, Taos, New Mexico, USA

El Monte Sagrado Resort's Living Machine system is designed to treat 4,000 gpd of wastewater for producing a comprehensive design solution for a high desert resort. Wastewater from kitchens and bathrooms is treated by the Living Machine system, is filtered further by a set of constructed wetlands, and finally flows into the pond and waterfall. In addition, storm water on the site is collected through an extensive system of roof gutters and underground drainage pipes. Collected water is utilized to offset evaporative losses in a series of four cascading trout ponds and small waterfalls that utilize physical and biological filtration to promote flourishing and productive pond ecosystems. Rainwater is circulated in the irrigation channels to support agricultural practices downstream [54].

8. FUTURE PROSPECTS OF LIVING MACHINES

8.1. Integration of Industrial and Agricultural Sectors: Proposed Eco-Park in Burlington, Vermont, USA

Ecological design concepts are starting to be applied to the development of integrated economic systems in an industrial context. A good example of one such system is the development or construction of eco-industrial parks. An eco-industrial park has been defined as "a community of businesses that cooperate with each other, and with the local community, to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat) leading to economic gains, improved environmental quality, and equitable enhancement of human resources for business and local community" [55]. This idea is clearly illustrated by the work pioneered by the city of Burlington and the Intervale Foundation established the Intervale Community Enterprise Center (ICEC). The ICEC undertook to develop a year-round, agriculturally based eco-park in a 280 ha flood plain within Burlington's city limits. The eco-park would derive most of its energy from the utilization of waste heat from the 53 MW McNeil power station. The project has brought together a number of allied businesses including a brewery, several food processors, a restaurant, and a host of Intervale growers and suppliers to the eco-park. The University of Vermont's ecological design studio would also be housed in the complex [17]. The structure that will support the project combines greenhouses with a conventional light-manufacturing facility in a 3,800 m^2 (40,900 ft^2) structure. The food culture team at Ocean Arks International (OAI) has been developing some of the agricultural components for the eco-park. Their approach has been to start with readily available organic wastes and through ecological processes convert the wastes to high-value products. The main goal is ecological and economic amplification of organic materials in an integrated manner similar to that developed by Yan and Ma [56]. On a pilot scale the materials being used include spent grain from a local brewery, straw, and bedding from an organic poultry operation. There are several stages in the conversion of materials.

Stage 1: The organic materials are blended, pasteurized, and inoculated with oyster mushroom spawn (*Pleurotus ostreatus* (Jacq: Fr.)). The substrate is placed in plastic bags punched with holes and placed in a mushroom incubator room. When the bags are fully colonized by the mushroom mycelium, they are transferred to a grow room for fruiting and harvest. Biological efficiency of conversion, the ratio of wet weight of harvested mushrooms to the dry weight of the substrate, has exceeded 60 %. After harvest the remaining substrate has the potential to be used as a high-quality animal feed for livestock. In the process of mushroom production, the vegetative forms of fungi colonize the straw and spent grains and produce essential amino acids such as lysine. Tests with cattle and the fish tilapia have demonstrated a ready acceptance of the material.

Stage 2: The spent mushroom substrate is placed in earthworm or vermiculture chambers. The earthworms rapidly convert the materials to enriched compost. The earthworms, a product of the process, are then blended with aquatic plants, *Azolla* sp. (water fern) and *Lemna* spp. (duckweeds), to produce protein-rich fish feeds.

Stage 3: The mushroom/earthworm-based compost is then utilized in the growing of tropical plants in pots and the culture of salad greens. No additional fertilization to the compost is required for the production of greens. After several harvests of salad greens, the medium is then utilized as a soil amendment or as a potting soil.

8.2. *Aquaculture*

Another key component in the design of integrated food systems for urban settings is aquaculture. The food team at OAI has designed recirculating systems based upon four tank modules for the culture of aquatic animals. To date, OAI has successfully cultured *Oreochromis* sp. (tilapia) and *Perca flavescens* M. (yellow perch) in these systems. The system is designed to produce feeds for the fish internally, including attached algae turfs and their associated communities, floating aquatic plants including Lemna and *Azolla*, zooplankton, and snails. External feeds to the system include earthworms and commercial feeds. These ecosystem-based fish culture systems have proven to be efficient. The multiplicity of pathways for nutrients and materials to flow in the production of a diversity of crops is an integral part of ecological design. If such an approach proves to be economically viable in an urban setting, the larger issue of food security can be addressed through the application of applied ecological concepts [17, 39, 40].

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