STATE-OF-THE-ART UTILIZATION OF AQUATIC PLANTS IN WATER POLLUTION CONTROL

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ABSTRACT

Research, pilot-scale and operational studies conducted within the past 15 years have shown that aquatic macrophyte-based treatment systems offer a promising, low-cost method for removing contaminants from wastewaters and polluted natural waters. The vascular plants cultured in such treatment systems perform several functions, including assimilating and storing contaminants, transporting O₂ to the root zone, and providing a substrate for microbial activity. Among the various types of aquatic treatment systems, pond systems containing floating macrophytes such as the water hyacinth are most commonly utilized for wastewater treatment in tropical and sub-tropical regions, whereas in temperate regions, emergent plants cultured in artificial wetlands (e.g., root zone method, nutrient film techniques) appear to be more appropriate. However, due to concerns about system management and reliability, aquatic plant treatment systems are currently used only on a limited basis throughout the world.

This review discusses the general performance, contaminant removal processes and criteria for plant selection in aquatic macrophyte wastewater treatment systems. Case studies on the use of floating plants for domestic wastewater treatment and the renovation of eutrophic lake water are presented, and future research needs for aquatic macrophyte-based wastewater treatment systems are discussed.

INTRODUCTION

Aquatic plants occur in water bodies enriched both by natural processes and by nutrient-loading from urban and agricultural activities. A few examples of aquatic plants commonly found in eutrophic water bodies include Eichhornia crassipes (water hyacinth), Pistia stratiotes (water lettuce), Alternanthera philoxeroides (alligator weed), Salvinia rotundifolia (salvinia), Lemna minor (duckweed), Elodea canadensis (elodea), Egeria densa (egeria or Brazilian elodea), Hydrilla verticillata (hydrilla), Typha latifolia (cattail), and Phragmites communis (reed).

Much of the attention focused on vascular aquatic plants has been directed toward their elimination from water bodies, since dense stands of aquatic vegetation can impede navigation and threaten the balance of biota in aquatic systems. For these reasons, a vast amount of literature is available on methods to control the growth of aquatic plants. For example, about 90% of
the 1500 literature citations available on water hyacinth are related to control (Gopal and Sharma, 1981).

In spite of their nuisance characteristics, the high productivity and nutrient removal capability of many aquatic plants has created substantial interest in their photosynthetic and physiological characteristics and in their potential use for beneficial purposes. For the past few years, research has been directed toward the use of aquatic plants for wastewater treatment. However, the successful exploitation of aquatic plants to remove nutrients and renovate wastes has been constrained by the lack of "exported uses" of the plants after their harvest from the system. Recently, the possible use of harvested plant biomass as an energy feedstock has spurred considerable interest in wastewater aquaculture.

The economic success of energy production and water treatment using an aquatic plant-based water treatment/biomass production system depends to a large extent on the photosynthetic activity and growth rates of the plants. Several aquatic plants have been found to be more efficient in utilizing solar energy than many terrestrial plants. Among the aquatics, the floating water hyacinth has the highest growth rate, with a yield potential of about 200 dry metric tons ha⁻¹ year⁻¹ (Reddy and DeBusk, 1984). Certain emergent (e.g., cattail) and submerged plants (e.g., elodea) are also quite productive, and can be utilized in an artificial wetland system for treating wastewaters. Artificial wetlands have made use of various woody, shrub, and herbaceous species for renovating wastewater while accumulating nutrients in the growing biomass (Gersberg et al. 1984a,b; 1986). Other species (e.g., paragrass, napiergrass) have shown promise in nutrient film techniques (Handley et al., 1986).

Engineering analyses have shown that in some locations the cost of secondary and advanced domestic wastewater treatment can be reduced by utilizing aquatic macrophyte-based systems (AMATS) rather than conventional treatment methods (Duffer, 1982). Floating macrophytes (e.g., water hyacinth) are the plants most commonly used for wastewater treatment in tropical and subtropical climates, whereas in temperate climates, emergent species (e.g. Phragmites sp., Typha spp.) are most often utilized.

The objectives of this paper are 1) to summarize existing information on the concept of using aquatic plants in pollution control; 2) to critically examine the role of aquatic plants in water treatment; 3) to describe two case studies utilizing aquatic plants for water treatment and resource recovery; and 4) to identify future research needs in each of these areas.

CONCEPT

Aquatic macrophyte-based treatment systems typically consist of a monoculture or polyculture of vascular plants cultured in shallow ponds or raceways which receive wastewater at a long residence time relative to that of conventional wastewater treatment systems. The long wastewater residence time of AMATS facilitates contaminant removal by a number of mechanisms (Figure 1).

Aquatic plants are stocked in these systems and, in many instances, are periodically harvested in order to maintain a young, viable crop. Unfortunately, the apparent simplicity of design and operation of AMATS has obviated for many wastewater engineers the need for research on system optimization. This problem is exacerbated by the fact that even a poorly designed AMATS system can satisfactorily remove many wastewater contaminants. However, the mechanisms for contaminant removal in these systems may be complex, involving physiological characteristics of the plants and biological and physico-chemical reactions in the pond environment (Reddy, 1983,1984a). Consequently, even though AMATS have been utilized for wastewater treatment for at least two decades, techniques for optimizing contaminant removal are poorly understood.

The optimum design or configuration of AMATS is dictated by such factors as climate, wastewater characteristics, and effluent quality requirements.
AQUATIC MACROPHYTE-BASED WASTEWATER TREATMENT

CONCEPT

LONG WASTEWATER RETENTION TIME ENHANCES
• SOLIDS SETTLING
• PLANT UPTAKE OF CONTAMINANTS
• BIOCHEMICAL AND PHYSICO-CHEMICAL TRANSFORMATIONS

Fig. 1. Aquatic macrophyte-based wastewater treatment

System designs currently being studied include: floating aquatic macrophyte systems (FAMS); the nutrient (thin) film technique (NFT); gravel bed treatment (GBT); and artificial wetland treatment (AWT).

The significance of macrophytes in contaminant removal varies according to the treatment system design, which in turn, depends on the desired contaminant removal goals. Certain types of AMATS incorporate plants primarily as living substrates for microbial activity. There is evidence that this design strategy is effective for reduction of such parameters as suspended solids, BOD, and nitrogen (N) (Boyd, 1969). For other treatment purposes, such as removal of phosphorus (P), metals and some organics, the preferred system designs are those which optimize conditions for plant uptake (Stowell et al., 1981; Reddy and Sutton, 1984; Tchobanoglous, 1987). The basic function of plants in the latter is that of assimilating, concentrating and storing contaminants on a short-term basis. Subsequent harvest of plant biomass results in permanent removal of stored contaminants from the treatment system.

Regardless of the design of AMATS, the actual role and potential significance of plant uptake and storage of contaminants are poorly understood. This is, in large part, due to the "black box" approach frequently employed in studies of these systems, for which inflows and outflows are monitored with little regard for internal nutrient fluxes and transformations. Evaluation of internal system processes, including plant uptake and storage, permits more efficient development and optimization of design parameters, and can greatly reduce the use of trial-and-error methods.
PLANT SELECTION

The following criteria should be used in selecting a plant for inclusion in water treatment systems. These include:

- Adaptability to local climate
- High photosynthetic rates
- High oxygen transport capability
- Tolerance to adverse concentration of pollutants
- Pollutant assimilative capacity
- Tolerance to adverse climatic conditions
- Resistance to pests and diseases
- Ease of management

The most common plants used in FAMS include water hyacinth, water lettuce, and pennywort. These plants are productive with mean annual growth rates of 10 g m\(^{-2}\) d\(^{-1}\) under central Florida conditions (Reddy and DeBusk, 1984; Reddy, 1984b, 1987). Potential growth rates of selected aquatic plants cultured in nutrient-enriched water are shown in Table 1. Nutrient assimilation capacity of aquatic macrophytes is directly related to growth rate, standing crop, and tissue composition.

Water hyacinth and water lettuce are sensitive to temperature. Freezing temperature for a sustained period of more than 24 hours can result in death of the plants. To overcome this problem, cold tolerant plants such as pennywort can be used in polycultures along with water hyacinth. This type of polyculture was successfully used to improve wastewater treatment efficiency at the WDW site described later in this paper (Clough et al., 1987).

<table>
<thead>
<tr>
<th>TABLE 1 Growth and Nutrient (N and P) Contents of Selected Macrophytes (Reddy and DeBusk, 1987)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>FLOATING MACROPHYTES:</td>
</tr>
<tr>
<td>Eichhornia crassipes (water hyacinth)</td>
</tr>
<tr>
<td>Pistia stratiotes (water lettuce)</td>
</tr>
<tr>
<td>Hydrocotyle sp. (pennywort)</td>
</tr>
<tr>
<td>Alternanthera sp. (alligator weed)</td>
</tr>
<tr>
<td>Lemna spp. (duckweed)</td>
</tr>
<tr>
<td>Salvinia spp.</td>
</tr>
<tr>
<td>EMERGENT MACROPHYTES:</td>
</tr>
<tr>
<td>Typha (cattail)</td>
</tr>
<tr>
<td>Juncus (rush)</td>
</tr>
<tr>
<td>Scirpus (bulrush)</td>
</tr>
<tr>
<td>Phragmites (reed)</td>
</tr>
<tr>
<td>Eleocharis (spike rush)</td>
</tr>
<tr>
<td>Saururus cernuus (lizard's tail)</td>
</tr>
</tbody>
</table>
Emergent macrophytes can be used for water treatment by using 1) natural stands in wetlands for disposal of treated wastewater, and 2) artificial wetlands with intensive culture of emergent macrophytes. The former are usually unmanaged and are used as a site for discharging previously treated wastewater (Dolan et al., 1981). The artificial wetlands may be either managed by plant harvesting or left unmanaged (Seidel, 1976; Wolverton, 1982; Gersberg et al., 1984a, b). The growth rate and nutrient assimilative capacity of emergent macrophytes is controlled by the culture system, wastewater loading, plant density, climate, and management factors imposed on the system.

### POLLUTANT REMOVAL PROCESSES

#### Storage in the Plant Biomass

The potential rate of pollutant storage by an aquatic plant is limited by the growth rate and standing crop of biomass per unit area. Some examples of nutrient storage of floating and emergent aquatic macrophytes are shown in Table 2.

Nitrogen and P storage in floating macrophytes are related to the standing crop of biomass. Plants with a large biomass per unit area have the potential to store a large amount of nutrients (Table 2). For example, the standing crop of water hyacinth can reach 30 t (dw) ha⁻¹, thus resulting in a maximum storage of 900 kg N ha⁻¹ and 180 kg P ha⁻¹. Plants with a low standing crop of biomass per unit area typically have low nutrient storage capabilities. Storage of nutrients in floating aquatic plants is short-term because of rapid turnover. If plants are not harvested, the dead tissue will decompose rapidly and release nutrients into the water. Frequent harvesting of the biomass is necessary to avoid losses of nutrients.

Although storage of nutrients is short-term, many aquatic plants have high nutrient uptake rates. Maximum N removal was found to be 5850 kg N ha⁻¹ yr⁻¹ for water hyacinths, as compared to 1200 kg N ha⁻¹ yr⁻¹ for duckweed (Table 2).

#### Table 2. Standing Crop (Storage) of Nitrogen and Phosphorus and Rate of Plant Uptake for Selected Aquatic Macrophytes (Reddy and DeBusk, 1987)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Nitrogen Storage</th>
<th>Nitrogen Uptake</th>
<th>Phosphorus Storage</th>
<th>Phosphorus Uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating Macrophytes:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eichhornia crassipes</td>
<td>300-900</td>
<td>1950-5850</td>
<td>60-180</td>
<td>350-1125</td>
</tr>
<tr>
<td>Pistia stratiotes</td>
<td>90-250</td>
<td>1350-5110</td>
<td>20-57</td>
<td>300-1100</td>
</tr>
<tr>
<td>Hydrocotyle umbellata</td>
<td>90-300</td>
<td>540-3200</td>
<td>23-75</td>
<td>130-770</td>
</tr>
<tr>
<td>Alternanthera philoxeroides</td>
<td>240-425</td>
<td>1400-4500</td>
<td>30-53</td>
<td>175-570</td>
</tr>
<tr>
<td>Lemna minor</td>
<td>4-50</td>
<td>350-1200</td>
<td>1-16</td>
<td>116-400</td>
</tr>
<tr>
<td>Salvinia rotundifolia</td>
<td>15-90</td>
<td>350-1700</td>
<td>4-24</td>
<td>92-450</td>
</tr>
<tr>
<td>Emergent Macrophytes:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typha spp. (cattail)</td>
<td>250-1560</td>
<td>600-2630</td>
<td>45-375</td>
<td>75-403</td>
</tr>
<tr>
<td>Juncus (rush)</td>
<td>200-300</td>
<td>800</td>
<td>40</td>
<td>110</td>
</tr>
<tr>
<td>Scirpus (bulrush)</td>
<td>175-530</td>
<td>125</td>
<td>40-110</td>
<td>18</td>
</tr>
<tr>
<td>Phragmites (reed)</td>
<td>140-430</td>
<td>225</td>
<td>14-53</td>
<td>35</td>
</tr>
</tbody>
</table>

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High nutrient removal rates by plant uptake can only be achieved by frequent harvesting of plants. Floating aquatic plants also have the capability to assimilate large quantities of trace elements, some of which are essential for plant growth. The demand for these elements can be increased when plants are cultured in wastewaters containing high levels of macronutrients. For example, water hyacinths cultured in NO₃-rich water exhibited chlorosis, even though N was present at adequate levels. Upon addition of Fe-EDTA, the chlorosis symptoms disappeared (Reddy, 1983). Water hyacinths and other aquatic plants can readily absorb heavy metals such as Cu, Zn, Pb, Cd, Hg, Ni (Wolverton and McDonald, 1975a,b; Tatsuyama et al., 1977; Cooley et al., 1979; Muramoto and Oki, 1983). However, most of these studies were conducted on a short-term basis, so maximum storage capabilities of heavy metals cannot be evaluated using these data.

Emergent macrophytes have the capability to grow in a wide range of substrates and in a variety of wastewaters. The influence of substrate and wastewater type can result in a wide range of nutrient composition in the plant tissue. For example, Boyd and Hess (1970) attributed variations in nutrient levels of Typha latifolia to differences in plant available nutrients at various sites. In many soils, major plant nutrients (N and P) may limit plant growth. Upon additions of these nutrients, either through wastewater or fertilizer, growth rate and tissue nutrient content increases (Cary and Weerts, 1984; Ulrich and Burton, 1985; Reddy and Portier, 1987). In wetland systems used for wastewater treatment, nutrients are supplied from 1) internal sources such as the decomposition of soil organic matter, biological N₂ fixation, and decomposition of detritus tissue; and 2) external sources such as wastewater and rainfall. Concentrations of nutrients in plants growing in natural stands can provide baseline estimates of nutrient assimilation, but these concentrations can vary greatly with the age of the plant and the time of sampling. Data summarized in Table 1 demonstrate the wide range of N and P concentration in emergent macrophyte plant tissue. Low tissue N levels are found in plants analyzed at maturity or cultured in nutrient-limited systems, while high tissue N concentrations reflect plants cultured in nutrient-enriched systems or plants analyzed at early stages of growth.

Limited information is available on the critical nutrient levels for maximum growth and nutrient uptake of emergent macrophytes. For perennial plants, critical nutrient levels can be affected by age of the plant, soil fertility, and environmental conditions. Nutrient availability can also affect the plant morphology. Root growth of Typha sp. was shown to be inversely related to the plant available N (Bonnewell and Pratt, 1978). Similarly, Ulrich and Burton (1985) observed that N fertilization increased aboveground growth of Phragmites australis and decreased root/shoot ratios from 2:1 to 0:75. Although P fertilization increased shoot growth, it had very little or no effect on root/shoot ratio (Ulrich and Burton, 1985).

Maximum storage of nutrients by emergent macrophytes is in the range of 200 to 1560 kg N ha⁻¹ and 40 to 375 kg P ha⁻¹ (Table 2). More than 50% of nutrients were found to be stored in below ground portions of the plants, tissues which may be difficult to harvest to achieve effective nutrient removal. Because emergent macrophytes have more supportive tissue than floating macrophytes, they may have greater potential for storing the nutrients over a longer period. Frequent harvesting may not be necessary to achieve maximum nutrient removal, although harvesting aboveground biomass once a year may improve the overall nutrient removal efficiency.

Biochemical/Physico-Chemical Processes

In addition to plant assimilation, nutrient removal in AMATS is affected by a number of biological, physical, and chemical processes functioning in the water, sediment, and root zone. These processes were discussed in detail by Reddy (1984) and Good and Patrick (1987).

Carbon. Organic carbon in wastewaters, which is typically measured as 5-day biochemical oxygen demand (BOD₅), is utilized by bacteria as an energy source and for cell synthesis. These bacteria inhabit microenvironments in the
Utilization of aquatic plants

sediment, the plant root zone, and may also be dispersed throughout the water column. Aerobic bacteria utilize oxygen as an electron acceptor in the breakdown of substrate carbon, whereas facultative anaerobic bacteria utilize oxidized inorganic compounds such as NO₃ and SO₄ as electron acceptors. Our recent studies show that BOD₅ removal from primary domestic effluent is accelerated by the addition of O₂ or NO₃ (Reddy and DeBusk, unpublished), which suggests that electron acceptor availability is the factor limiting organic carbon removal in aquatic plant-based wastewater treatment systems.

Aquatic plants have a unique feature of transporting O₂ through the leaves, stems, and roots. Oxygen thus transported, if not consumed during root respiration, can enter the water column and be utilized by aerobic bacteria for the oxidation of organic carbon. Little is known of this O₂ "pumping" process by plants, although recent experiments in our laboratory have shown that aquatic macrophytes differ in their ability to oxidize their rhizosphere. Pennywort, for example, transports O₂ 2.5 times as rapidly (per unit weight of root tissue) as water hyacinth, which in turn transports O₂ four times more rapidly than water lettuce (Table 3).

Oxygen concentration of sewage effluent placed in 500 ml flasks increased by 10-fold in treatments with pennywort plants as compared to those without plants (Table 4). Oxygen transfer by plants into the root zone plays a significant role in supporting aerobic bacteria in the root zone and subsequent degradation of wastewater carbon. For example, O₂ transport through either pennywort or water hyacinth plants was found to be responsible for 90% of BOD removal, while the remaining 10% of BOD removal was due to O₂ transport directly from air (Reddy, 1987, unpublished results) (Table 5).

### TABLE 3 Oxygen Transport Through Selected Aquatic Macrophytes

<table>
<thead>
<tr>
<th>Plant</th>
<th>Root mass/plant</th>
<th>O₂ transport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>------- g-------</td>
<td>mg O₂ g⁻¹ hr⁻¹</td>
</tr>
<tr>
<td>Hydrocotyle umbellata</td>
<td>0.02 - 0.05</td>
<td>3.95 ± 1.86</td>
</tr>
<tr>
<td></td>
<td>0.06 - 0.12</td>
<td>2.49 ± 1.05</td>
</tr>
<tr>
<td>Pistia stratiotes</td>
<td>0.05 - 0.25</td>
<td>0.30 ± 0.13</td>
</tr>
<tr>
<td>Eichhornia crassipes</td>
<td>0.03 - 0.10</td>
<td>1.29 ± 1.18</td>
</tr>
<tr>
<td></td>
<td>0.11 - 0.25</td>
<td>1.27 ± 0.61</td>
</tr>
<tr>
<td></td>
<td>0.26 - 0.50</td>
<td>0.31 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>0.51 - 0.99</td>
<td>0.12 ± 0.14</td>
</tr>
<tr>
<td>Sagittaria latifolia</td>
<td>0.03 - 0.06</td>
<td>1.72 ± 0.87</td>
</tr>
<tr>
<td></td>
<td>0.07 - 0.14</td>
<td>0.61 ± 0.22</td>
</tr>
<tr>
<td>Typha spp.</td>
<td>0.02 - 0.10</td>
<td>1.39 ± 1.49</td>
</tr>
<tr>
<td></td>
<td>0.11 - 0.53</td>
<td>0.19 ± 0.15</td>
</tr>
</tbody>
</table>

### TABLE 4 Effect of Pennywort Plants on Oxygen Concentration of the Sewage Effluent Placed in 500 ml Flasks. Oxygen Concentration of the Effluent at the Start of the Experiment was <0.1 mg l⁻¹. The Values Shown Below are the O₂ Concentration of the Effluent After 7 Days.

<table>
<thead>
<tr>
<th>Sewage effluent BOD₅</th>
<th>PB</th>
<th>PNB</th>
<th>NPNB</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>---mg l⁻¹---</td>
<td>------</td>
<td>-----</td>
<td>------</td>
<td>---</td>
</tr>
<tr>
<td>180</td>
<td>4.47</td>
<td>4.87</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>135</td>
<td>4.48</td>
<td>5.21</td>
<td>0.34</td>
<td>0.36</td>
</tr>
<tr>
<td>90</td>
<td>5.64</td>
<td>5.34</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>45</td>
<td>4.55</td>
<td>5.65</td>
<td>0.86</td>
<td>0.59</td>
</tr>
</tbody>
</table>

PB = plant with barrier; PNB = plant with no barrier, NPNB = no plant, no barrier; B = no plant - barrier.
The role of O\textsubscript{2} transport by emergent macrophytes in carbon removal has not been examined. However, the principal concept of designing artificial wetlands is with the assumption that O\textsubscript{2} transported by emergent aquatic macrophytes supports nitrification in the root zone (Brix, 1986).

**Nitrogen.** Although large quantities of N can be removed by plant uptake and harvest, nitrification-denitrification reactions are more often the dominant N sink in AMATS (Stowell et al., 1981; Reddy, 1984; Good and Patrick, 1987). Nitrification of wastewater ammonium can occur in the oxidized root zone of macrophyte systems. This nitrification process may be enhanced beneath stands of plants which transport large quantities of O\textsubscript{2}, such as pennywort. Nitrate-N thus formed diffuses into reduced microenvironments in the pond system, where it is utilized as an electron acceptor by facultative anaerobic bacteria and lost from the system as N gas. Both native wastewater carbon and plant detritus can be utilized by these bacteria as a carbon source. Denitrification rates in excess of 1 g m\textsuperscript{-2} d\textsuperscript{-1} have been reported in AMATS (Stowell et al., 1981; Moorhead et al., 1987).

In studies on the fate of N added to floodwater in reservoirs containing aquatic plants, mass balances indicated that plant uptake accounted for 13 to 67\% of total N removal, while the unaccounted for N was assumed to be lost through nitrification and denitrification or NH\textsubscript{3} volatilization (Reddy, 1983; Reddy and DeBusk, 1985). In field studies, mass balance of N for a water hyacinth-based water treatment system has indicated that 50\% of the total N was lost through means other than plant uptake, presumably via biochemical processes and seepage (Reddy et al., 1982). For a water hyacinth system receiving secondary sewage effluent, 40 to 92\% of the input N was estimated to be lost through denitrification (DeBusk et al., 1983; Moorhead et al., 1987). Results of these studies indicate that denitrification plays a significant role in N removal when water hyacinth plants are cultured in NO\textsubscript{3} rich waters. Similar results have been observed in emergent macrophyte systems. In a freshwater marsh containing Typha latifolia, about 25\% of added N was lost from the system, while 54\% of the added N was recovered in the plant (Dean and Biesboer, 1986).

**Phosphorus.** In AMATS, P can be removed from the wastewater by plant uptake, microbial assimilation, precipitation with cations such as calcium, magnesium, iron, manganese and adsorption onto clay and organic matter. However, many studies have shown plant uptake and harvest as the most effective means of removing P from AMATS.

**CASE STUDIES**

Aquatic Macrophyte-Based Treatment Systems at WALT DISNEY WORLD Resort Complex, Florida, USA

Since 1978, research on the use of aquatic macrophytes to treat domestic wastewaters has been conducted at the community waste research facility (CWRF) located in the WALT DISNEY WORLD Resort Complex, Lake Buena Vista, Florida. The research/demonstration project at this site focuses the efforts of a multi-disciplinary, multi-institutional team on solving pressing community waste disposal problems. Of primary importance to this program is the

<table>
<thead>
<tr>
<th>Initial Sewage effluent</th>
<th>PB</th>
<th>FNB</th>
<th>NPNB</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg l\textsuperscript{-1}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>12.3</td>
<td>6.6</td>
<td>58.1</td>
<td>133.7</td>
</tr>
<tr>
<td>43</td>
<td>11.5</td>
<td>5.0</td>
<td>9.4</td>
<td>30.6</td>
</tr>
</tbody>
</table>
implementation of non-energy intensive waste treatment technology and the net conversion of waste resources to methane. Many communities, for example, are involved in the application of AMATS for low-cost treatment and renovation of wastewaters. Under certain management regimes, these AMATS generate large amounts of high moisture biomass that represent a potential renewable energy resource. Over the past five years, research at the CWRF has centered on an integrated water hyacinth/anaerobic digestion system in which pollutant removal, biomass production, and methane generation can be maximized while controlling sludge output and disposal costs to acceptable levels.

Studies on the use of aquatic macrophytes for wastewater treatment are conducted in small tanks and raceways, and in five 0.1 ha test channels. Some of the recent findings on the use of FAMS for treating wastewaters at this site are as follows.

Annual BOD₅ removal from primary sewage effluent has been found to average 210 kg ha⁻¹ d⁻¹ in water hyacinth systems. Based on this average removal rate, the area of water hyacinth pond required to treat 3800 m³ d⁻¹ (1 million gallons d⁻¹) of domestic wastewater to secondary standards (from 200 mg BOD₁⁻¹ to 30 mg BOD₁⁻¹) is approximately 3 ha. Wastewater suspended solids concentrations in such systems are reduced from 75 to 16 mg l⁻¹, total N concentration from 20 to 23 mg l⁻¹, and total P from 10 to 8 mg l⁻¹.

A number of studies have been conducted at this site to determine the effect of organic matter loading on contaminant removal. Four channels containing water hyacinth were fed primary sewage for one year at loadings of 55, 110, 220, and 440 kg BOD₅ ha⁻¹ d⁻¹, corresponding to channel hydraulic retention times (HRT) of 24, 12, 6 and 3 days, respectively. A summary of contaminant removal in these channels is provided in Table 6. Results of these studies are also discussed by Hayes et al. (1987) and Reddy et al. (1985).

A two-stage (two channel) 0.2 ha water hyacinth system was also operated for a 12 month period in order to evaluate contaminant removal at different locations through a "plug-flow" system. These channels were operated at a loading rate of 250-440 kg BOD₅ ha⁻¹ d⁻¹, at 3.2 (stage I) and 6.4 day (stage I + II) HRT. Data on seasonal changes in BOD₅ and SS removal are presented in Tables 6 and 7. BOD₅ removal rates at stage I (3.2 day HRT) were in the range of 28-83%, while at stage II (6.4 d HRT), removal was in the range of 68-95%.

A one year study conducted in batch-fed, microcosm tanks demonstrated that pennywort (Hydrocotyle umbellata) monocultures and pennywort-water hyacinth polycultures can remove BOD₅ from primary domestic effluent at a rate 11% 


<table>
<thead>
<tr>
<th>Month 1986</th>
<th>Effluent</th>
<th>Stage I 3 days HRT</th>
<th>Stage II 6 days HRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>127</td>
<td>102 (19.7)</td>
<td>49 (61.4)</td>
</tr>
<tr>
<td>February</td>
<td>226</td>
<td>83 (63.7)</td>
<td>62 (72.6)</td>
</tr>
<tr>
<td>March</td>
<td>246</td>
<td>123 (50.0)</td>
<td>69 (72.0)</td>
</tr>
<tr>
<td>April</td>
<td>231</td>
<td>91 (60.6)</td>
<td>41 (82.3)</td>
</tr>
<tr>
<td>May</td>
<td>231</td>
<td>49 (78.8)</td>
<td>24 (89.6)</td>
</tr>
<tr>
<td>June</td>
<td>298</td>
<td>67 (77.5)</td>
<td>23 (92.3)</td>
</tr>
<tr>
<td>July</td>
<td>147</td>
<td>70 (52.4)</td>
<td>29 (80.3)</td>
</tr>
<tr>
<td>August</td>
<td>195</td>
<td>88 (54.9)</td>
<td>26 (86.7)</td>
</tr>
<tr>
<td>September</td>
<td>159</td>
<td>78 (50.9)</td>
<td>32 (79.9)</td>
</tr>
<tr>
<td>October</td>
<td>206</td>
<td>119 (42.2)</td>
<td>63 (69.4)</td>
</tr>
<tr>
<td>November</td>
<td>185</td>
<td>121 (34.6)</td>
<td>54 (70.8)</td>
</tr>
<tr>
<td>December</td>
<td>181</td>
<td>100 (44.8)</td>
<td>51 (71.8)</td>
</tr>
</tbody>
</table>
TABLE 7  Contaminant Removal Rates (Percent) in the Walt Disney World Channels (1984) as a Function of Hydraulic Retention Time

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hydraulic Retention Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Days</td>
</tr>
<tr>
<td>BOD₅</td>
<td>81</td>
</tr>
<tr>
<td>SS</td>
<td>80</td>
</tr>
<tr>
<td>TKN</td>
<td>14</td>
</tr>
<tr>
<td>NH₃</td>
<td>8</td>
</tr>
<tr>
<td>T-PO₄</td>
<td>16</td>
</tr>
<tr>
<td>O-PO₄</td>
<td>10</td>
</tr>
</tbody>
</table>

higher than that of water hyacinth monocultures (Clough et al., 1987). Treatment systems containing pennywort also produce more plant biomass and remove nitrogen and phosphorus from wastewater at a higher rate than water hyacinth monocultures during the winter months in central Florida.

Measurements of sediment accrual in a water hyacinth channel which received primary domestic effluent for 39 months revealed a sedimentation rate of 5.4 metric tons ha⁻¹ yr⁻¹, or 0.6 cm yr⁻¹, assuming a bulk density of 0.1 g cm⁻³ for the sediment. Based on literature values for detritus production and decomposition of water hyacinth in eutrophic waters, it was estimated that 70% of this sediment was autochthonous in origin (plant-derived) with the remainder contributed by solids which entered the pond via the influent waste stream.

Water Hyacinths for Improving Water Quality of a Eutrophic Lake in Florida, USA

Lake Apopka, a 12,500 ha lake located in central Florida, is currently considered highly eutrophic due to point and non-point nutrient loading from surrounding vegetable farms, citrus groves, and domestic wastewater discharges. A 19-month study was conducted on the northern shore of Lake Apopka to determine the effects of water hyacinth growth on eutrophic lake water quality.

This experiment was performed from June 1984 to December 1985 at the Zellwood field station of the University of Florida's Central Florida Research and Education Center. Three concrete block channels were constructed approximately 400 m from the northern shore of Lake Apopka. Channels 1 and 2 were stocked with water hyacinths at a density of 15 kg (fresh wt) m⁻². Channel 1 was periodically harvested to maintain density in the range of 15-25 kg m⁻², while Channel 2 was maintained with no harvest. Channel 3 functioned as control with no plants. Channel dimensions were 61 m long x 6.1 m wide x 0.6 m deep. This resulted in a length to width ratio of 10, which was adequate to prevent short-circuiting. Each channel was supplied with lake water, gravity-fed from Lake Apopka, at an approximate flow rate of 95 l min⁻¹, resulting in a hydraulic loading rate of 45 m³ d⁻¹. Hydraulic retention time was 1.5 days. Influent and effluent water samples were analyzed for several water quality parameters using standard methods.

Table 8 presents the average analysis of influent water from Lake Apopka used in the experimental channels. Note that plant-available forms of N and P were quite low, with nitrate and ammonium averaging 55 and 122 µg N l⁻¹, respectively. Soluble reactive P (roughly equivalent to ortho-P) averaged approximately 20 µg l⁻¹. Most of the N and P in Lake Apopka water is tied up in algal biomass; hence, it is unavailable for immediate plant uptake. Total Kjeldahl N and total P concentrations were quite high, averaging 4.33 and 0.29 mg l⁻¹, respectively. These conditions reflect the high algal biomass and are indicative of a highly eutrophic lake. Average influent pH was 8.39, sometimes ranging over 9.0. High pH levels were primarily due to algal photosynthetic activity. Chlorophyll-a averaged 60 mg m⁻³, but under bloom conditions, values as high as 150 mg m⁻³ were observed.
It was determined in a previous study (DeBusk et al., 1986) that under nutrient-limited conditions maximum growth is obtained by water hyacinths maintained within a density range of 15-25 kg (fw) m⁻². The plants in the harvested channel were therefore maintained in this density range.

Plant uptake of N and P was influenced by plant growth rate and harvest regime. Average N and P removal efficiencies in the harvested channel were 54 and 63%, respectively, compared with 45 and 57%, respectively, in the unharvested channel during the 19-month study period. Actual removal rates showed a great deal of monthly variation, undoubtedly due to seasonal variances in plant uptake and fluctuating biological activity in the lake. Nitrogen and P removal rates for the channel without plants were 36 and 42%, respectively.

The channels stocked with water hyacinths consistently provided higher nutrient removal than the channel without water hyacinths. The difference between the two channels with different plant management strategies was less dramatic. The plants in channel 4 (the unharvested channel) were usually stressed due to overcrowding and insect damage, but although overall growth in this channel was slow, removal rates nearly equaled those of the intensively-managed channel. This was due to the ability of the water hyacinth, regardless of physiological condition, to shade out algal cells. This seemed to be the primary nutrient-removal mechanism in this system. It has been reported that an 80% coverage of the water surface with water hyacinth is sufficient to shade out suspended algae.

The overall N budgets for the three channels showed that sedimentation of N was the dominant removal mechanism. Thirty-three and 37% of the incoming N in the channels with harvesting and without harvesting, respectively, ended up in the sediment. Only 16 and 10% of the influent N removal in the channels with harvesting and without harvesting, respectively, was due to plant uptake.

Thirty percent of the P loading into the harvested channel was recovered in the sediment, whereas 32% of the influent P turned up in the sediment for the channel with no harvesting. Twenty-five percent of the P removal in the harvested channel was accounted for by plant uptake, whereas 13% of the incoming P removal in the unharvested channel was due to plant uptake. Plant uptake of N and P in the channel without harvesting was considerably lower due to greatly reduced growth rates.

The water hyacinths in both harvested and unharvested channels were dependent on the mineralization of N and P from the sediment to satisfy their requirements for growth. For P, such release can be as high as 5.25 to 9.18 mg P m⁻² d⁻¹ (Pollman and Bresnik, 1979). Thus, a secondary function of aquatic plants in a lake water treatment system is removal of mineralized N and P released from the sediment.

During the next three years, Lake Apopka will be the subject of a larger study on the use of aquatic plants for improving lake water quality. This $2 million study recently funded by the Florida Legislature is designed to evaluate the effect of water hyacinths on water quality and sediment decomposition in a 10 ha portion of the lake.
Long-term operational data for a case study in the U.S. is not available for artificial wetlands. In this section we present a brief review of the research currently being conducted on artificial wetlands. A variety of artificial wetland systems has emerged in recent years. Unlike FAMS, artificial wetlands have applicability over a wider geographical range, because the macrophytes used are much more cold tolerant than floating macrophytes. Some of the earlier work was conducted by Seidel (1976), Kikuth and Kaitzis (1975). These systems were called 'root zone method' (RZM). A recent review by Cooper and Boon (1987) describes the applicability of these systems for wastewater treatment in European communities. More recently, Wolverton et al. (1983) and Gersberg et al. (1984a, b) have conducted research on artificial wetland systems applicable to municipalities in the U.S. These systems use gravel as substrate to grow emergent aquatic macrophytes. A review by Wolverton (1987) discusses the efficiency of some of these systems currently in operation. Another version of artificial wetlands is nutrient film technique (Jewell et al., 1981; Dierberg et al. 1987). In this system, aquatic plants are grown in a shallow raceway and receive a thin layer of wastewater, which stimulates the development of a dense root mat. This root mat effectively filters BOD, and suspended solids. Although such systems show promise for treating wastewaters in cold climates, their long-term effectiveness is still unknown.

ECONOMICS

Aquatic plant-based water treatment systems appear to be attractive when costs are compared with conventional activated sludge systems (Crites and Mingee, 1987). However, at this time, data on operational and maintenance costs of artificial wetlands or water hyacinth systems are not available. The costs presented in Table 9 represent only capital costs needed for each system. On this basis, aquatic plant-based systems were found to be 2-8 times cheaper than conventional activated sludge systems. These costs will obviously differ among locations.

FUTURE RESEARCH NEEDS

A summary of results from various studies reveal that floating macrophyte systems or artificial wetlands can be used for improving the quality of polluted waters. Similar conclusions can also be drawn from the papers presented at the seminar on the use of macrophytes in water pollution control in Pirracicaba, Brazil. The papers presented at a similar conference conducted in Orlando, Florida, U.S.A. (July 20-24, 1986), on aquatic plants for water treatment and resource recovery also support the concept of using aquatic plants cultured in ponds or artificial wetlands for water treatment (for details see Reddy and Smith, 1987). These two conferences in this topical area show a worldwide interest in the use of aquatic plants for pollution control. Although a number of studies have been published in recent years, a few of these have utilized a systematic approach, in which processes functioning within the system are described. Poor design information generated from many of the studies, when applied to large-scale systems, often resulted in failure of the systems to treat wastewater effectively.

Future research should be directed to areas such as system design, plant selection, and plant biology, processes functioning at the root-water-sediment interface, plant biomass utilization, and ecological and environmental considerations. This systematic approach should result in an optimized system for water pollution control using aquatic plants both in managed artificial systems or natural systems. For wastewater treatment AMATS can be integrated into conventional treatment systems to reduce overall costs (Figure 2).

System Design

Some design information is already available on floating macrophyte-based systems (Duffer, 1983; Reddy and Sutton, 1984) or artificial wetlands
TABLE 9 Comparative Costs of Analysis of Aquatic Plant-based Water Treatment System as Compared to Conventional Treatment Systems in the United States (Crites and Mingee, 1987)

<table>
<thead>
<tr>
<th>Location</th>
<th>System type*</th>
<th>Design flow m³ d⁻¹</th>
<th>Area ha</th>
<th>Construction cost $ million</th>
<th>Unit cost $ m⁻³ d⁻¹</th>
<th>Ratio AMATS/CTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannon Beach, Oregon, USA</td>
<td>Existing wetland</td>
<td>3,440</td>
<td>6.5</td>
<td>0.58</td>
<td>170</td>
<td>0.19</td>
</tr>
<tr>
<td>Gustine, California, USA</td>
<td>Created marsh</td>
<td>3,785</td>
<td>10</td>
<td>0.88</td>
<td>230</td>
<td>0.26</td>
</tr>
<tr>
<td>Incline Village, Nevada, USA</td>
<td>Created &amp; existing wetland</td>
<td>8,100</td>
<td>49</td>
<td>3.3</td>
<td>410</td>
<td>0.46</td>
</tr>
<tr>
<td>Iron Bridge Plant, Orlando, Florida, USA</td>
<td>Hyacinth system</td>
<td>30,280</td>
<td>12</td>
<td>3.3</td>
<td>110</td>
<td>0.12</td>
</tr>
<tr>
<td>Anywhere in USA</td>
<td>Activated sludge</td>
<td>3,785</td>
<td>--</td>
<td>3-3.8</td>
<td>800-1,000</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*All systems provide secondary domestic treatment, except Iron Bridge, which provides advanced wastewater treatment.

†AMATS = aquatic macrophyte-based treatment systems.

CTS = convention treatment system.

AQUATIC MACROPHYTE-BASED DOMESTIC WASTEWATER TREATMENT

MULTI-STAGE SYSTEM

Fig. 2. Integration of AMATS and conventional systems for domestic wastewater treatment
(Wolverton, 1987; Cooper and Boon, 1987). However, the following information is still needed for system optimization.

- hydrology/hydraulic loading effects
- pond size, shape, length to width ratio
- water depth (floating macrophyte system)
- sediment characteristics
- hydraulic properties of the soil or gravel used in artificial wetlands (root zone method)
- wastewater characteristics and effects of varying loadings of BOD, nutrients, metals, and toxic organics on the system performance
- management strategies - frequency of harvesting
- optimization techniques for improving system efficiency and for year-round performance
- integration of aquatic-plant-based systems with conventional wastewater treatment systems

**Plant Selection**

Plants play a significant role in water treatment either by directly assimilating pollutants or creating a suitable environment in the root zone for microorganisms to transform pollutants. For many systems, an aquatic plant is arbitrarily selected for inclusion in water treatment systems, an approach which may not work under all conditions. Future research should be conducted to develop a database on plant biology in the following areas:

- adaptability of plants for varying climatic conditions - i.e., cold tolerant species
- tolerance to a wide range of pollutant concentrations
- oxygen transport capability of plants
- growth characteristics/biomass production
- nutrient storage capabilities
- resistance to pests/diseases
- ease of management/harvesting

**Biochemical/Physico-Chemical Processes**

Research in this area is largely ignored because many systems are operated as "black boxes" by monitoring only the inflow/outflow chemistry (Reddy, 1984; Good and Patrick, 1987; Reed et al., 1987). Future research should be conducted to develop a fundamental understanding of the processes functioning in the system and to utilize these processes to maximize treatment efficiency. The following processes should be studied in the root zone, water column, and in the underlying sediments:

- oxygen consumption in the root zone
- carbon removal processes (aerobic, facultative anaerobic and anaerobic respiration of bacteria)
- nitrogen removal processes (nitrification/denitrification, NH, volatilization, detritus breakdown, nitrogen fixation, adsorption, and diffusion of N species)
- phosphorus removal processes (adsorption and precipitation, mineralization/ microbial assimilation)
- metal removal processes (adsorption, precipitation and complexation)
- toxic organic compounds - processes include decomposition, identification of intermediate compounds, adsorption to roots, detritus components and soil particles

**Biomass Disposal/Utilization**

Aquatic plant biomass is often considered a waste material which must be disposed of. However, under certain conditions, this biomass can be a resource which can be used in some beneficial way to offset the costs of overall treatment. Economics of utilization dictate whether such biomass is
to be considered a waste product or resource. A detailed discussion of the biomass utilization options is presented by Chynoweth (1987) and Lakshman (1987). Research in the following areas is needed for biomass utilization or disposal:

- system management for low/high rates of biomass production
- biomass utilization options
  - methane/alcohol production
  - cattle feed
  - industrial products
  - soil amendment
  - compost/organic fertilizer
- Effective methods for disposal of biomass not suitable for utilization

**Ecological and Environmental Considerations**

This issue becomes very important when natural ecosystems are used in pollution control. For example, natural wetlands are used in many areas of the United States for disposal of treated sewage effluent. Continuous disposal of waste effluent has a significant impact on natural environments. Recently, aquatic plants have also been considered as a means of improving water quality of lakes and streams. Under these conditions, the impact of managed aquatic vegetation on fish and invertebrates needs to be studied. Mosquito problems in aquatic plant-based sewage treatment systems need further evaluation and suitable biological control methods should be integrated into overall management of the system. As suggested by Reed (1987), fewer experiments should be conducted in the future, with greater attention given to conducting more measurements (biological, chemical, and physical) within the experiments conducted.

**Data Management/Transfer of Technology**

Data generated from various studies in different regions of the world should be pooled through organized workshops and conferences, so that the feasibility of using systems for water treatment can be evaluated. For example, a specialist technical group within the International Association on Water Pollution Research and Control (IAWPRC) can be established. This group can develop a standard protocol which can be circulated to the researchers in this topical area. This group can exchange technical information through newsletters and reprints. The protocol developed by this group can be used by the researchers to collect the data on all necessary input/outputs for designing and optimizing aquatic plant-based water treatment systems.

**SUMMARY AND CONCLUSIONS**

The review presented in this paper reveals that aquatic plant-based treatment systems (AMATS) using ponds or artificial wetlands are effective in water pollution control. Aquatic plants show promise for treating domestic wastewater, industrial effluents, and agricultural drainage water. Aquatic plants are also being considered for improving water quality of lakes and streams.

For wastewater treatment, two types of systems are typically utilized, 1) floating aquatic macrophytes cultured in ponds or channels, and 2) emergent macrophytes cultured in artificial wetlands using gravel or soil substrate. For floating macrophyte systems using water hyacinths and the system receiving primary sewage effluent, a 6-day hydraulic retention time (HRT), water depth of 60 cm and a hydraulic loading of 1860 m³ ha d⁻¹ are adequate for meeting secondary treatment standards. In such a system, BOD₅ and suspended solids have been reduced by 80-90%. Similarly, systems receiving conventional secondary sewage effluent, HRT of 6 days, and hydraulic loading of 800 m³ ha d⁻¹ were found to be adequate for achieving advanced secondary treatment. Similar results have also been observed for artificial wetlands using emergent macrophytes.
Aquatic plants remove pollutants by 1) directly assimilating them into their tissue, and 2) providing a suitable environment for microorganisms to transform pollutants and reduce their concentrations. Such biochemical/physico-chemical processes functioning in these systems include nitrification/denitrification and ammonia volatilization. Oxygen transfer by aquatic plants into the root zone is also requisite for certain microbial pollutant removing processes to function effectively.

Plant harvest is needed to enhance P removal, and it may also influence oxygen transfer into the root zone, thus enhancing N and BOD removal. Removal of heavy metals from wastewaters can also be accomplished when plants are harvested.

Biomass produced can be utilized as a source of feedstock for producing methane, cattle feed, or composted and used as organic manures. Economics of utilization will depend on the costs of conventional materials used for the same purpose. Operating costs for crop management and harvesting may be offset by biomass product resources.

Future research needs were identified in several areas (engineering design, plant biology, biochemistry of root-water-soil interface, and ecological and environmental implications). Successful application of this technology will be dependent on the systematic data base developed in the key research areas.

**ACKNOWLEDGMENT**

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**REFERENCES**


