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 O_2 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

WASTEWATER

(CONTAINING
ORGANIC
AND/OR
INORGANIC
CONTAMINANTS

PURIFIED
EFFLUENT

LONG WASTEWATER RETENTION TIME ENHANCES

- SOLIDS SETTLING
- PLANT UPTAKE OF CONTAMINANTS
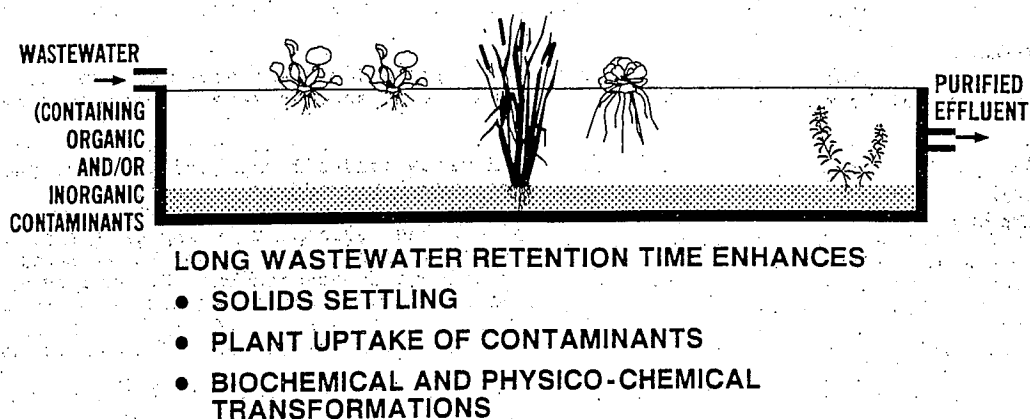- BIOCHEMICAL AND PHYSICO-CHEMICAL TRANSFORMATIONS

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:

- o Adaptability to local climate
- o High photosynthetic rates
- o High oxygen transport capability
- o Tolerance to adverse concentration of pollutants
- o Pollutant assimilative capacity
- o Tolerance to adverse climatic conditions
- o Resistance to pests and diseases
- o 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 1 Growth and Nutrient (N and P) Contents of Selected Macrophytes
(Reddy and DeBusk, 1987)

| Plant | Biomass | | Tissue composition | |
	Standing crop	Growth rates	N	P
	t (dw) ha^{-1}	t ha^{-1} yr^{-1}	--------g kg^{-1}-------	
FLOATING MACROPHYTES:				
Eichhornia crassipes (water hyacinth)	20.0 - 24.0	60 - 110	10 - 40	1.4 - 12.0
Pistia stratiotes (water lettuce)	6.0 - 10.5	50 - 80	12 - 40	1.5 - 11.5
Hydrocotyle sp. (pennywort)	7.0 - 11.0	30 - 60	15 - 45	2.0 - 12.5
Alternanthera sp. (alligator weed)	18.0	78	15 - 35	2.0 - 9.0
Lemna spp. (duckweed)	1.3	6 - 26	25 - 50	4.0 - 15.0
Salvinia spp.	2.4 - 3.2	9 - 45	20 - 48	1.8 - 9.0
EMERGENT MACROPHYTES:				
Typha (cattail)	4.3 - 22.5	8 - 61	5 - 24	0.5 - 4.0
Juncus (rush)	22.0	53	15	2.0
Scirpus (bulrush)			8 - 27	1.0 - 3.0
Phragmites (reed)	6.0 - 35.0	10 - 60	18 - 21	2.0 - 3.0
Eleocharis (spike rush)	8.8	26	9 - 18	1.0 - 3.0
Saururus cernuus (lizard's tail)	4.5 - 22.5	--	15 - 25	1.0 - 5.0

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)

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

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 NO_3^--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 N_2 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 2:2 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 (BOD$_5$), is utilized by bacteria as an energy source and for cell synthesis. These bacteria inhabit microenvironments in the

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 NO_3 and SO_4 as electron acceptors. Our recent studies show that BOD_5 removal from primary domestic effluent is accelerated by the addition of O_2 or NO_3 (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 O_2 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 O_2 "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 O_2 2.5 times as rapidly (per unit weight of root tissue) as water hyacinth, which in turn transports O_2 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, O_2 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 O_2 transport directly from air (Reddy, 1987, unpublished results) (Table 5).

TABLE 3 Oxygen Transport Through Selected Aquatic Macrophytes
(Moorhead and Reddy, 1987)

Plant	Root mass/plant	O_2 transport	n
	--------g-------	mg O_2 g^{-1} hr^{-1}	
Hydrocotyle umbellata	0.02 - 0.05	3.95 ± 1.86	18
	0.06 - 0.12	2.49 ± 1.05	8
Pistia stratiotes	0.05 - 0.25	0.30 ± 0.13	10
Eichhornia crassipes	0.03 - 0.10	1.29 ± 1.18	10
	0.11 - 0.25	1.27 ± 0.61	10
	0.26 - 0.50	0.31 ± 0.11	8
	0.51 - 0.99	0.12 ± 0.14	4
Sagittaria latifolia	0.03 - 0.06	1.72 ± 0.87	15
	0.07 - 0.14	0.61 ± 0.22	3
Typha spp.	0.02 - 0.10	1.39 ± 1.49	4
	0.11 - 0.53	0.19 ± 0.15	14

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 O_2 Concentration of the Effluent After 7 Days.

Sewage effluent BOD_5	PB	PNB	NPNB	B
----mg l^{-1}----	-----------------dissolved O_2, mg l^{-1}-----------------			
180	4.47	4.87	0.35	0.33
135	4.48	5.21	0.34	0.36
90	5.64	5.34	0.36	0.36
45	4.55	5.65	0.86	0.59

PB = plant with barrier; PNB = plant with no barrier, NPNB = no plant, no barrier; B = no plant - barrier.

The role of O_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_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_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 $1\ g\ m^{-2}\ d^{-1}$ 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_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_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 5   Effect of Pennywort Plants on BOD_5 Concentration of the Sewage Effluent. The Values Shown Below are the BOD_5 Levels Measured After 7 Days

Initial Sewage effluent	PB	PNB	NPNB	B
		BOD_5 mg l^{-1}		
180	12.3	6.6	58.1	133.7
43	11.5	5.0	9.4	30.6

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 BOD_5 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 m^3 d^{-1} (1 million gallons d^{-1}) of domestic wastewater to secondary standards (from 200 mg BOD l^{-1} to 30 mg BOD l^{-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 BOD_5 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 BOD_5 ha^{-1} d^{-1}, at 3.2 (stage I) and 6.4 day (stage I + II) HRT. Data on seasonal changes in BOD_5 and SS removal are presented in Tables 6 and 7. BOD_5 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 BOD_5 from primary domestic effluent at a rate 11%

TABLE 6   Changes in BOD_5 Concentration of the Influent (Primary Sewage Effluent) Entering Water Hyacinth Channels, and the Effluent After 3.2 and 6.4 Day Hydraulic Retention Time. Experimental Site: Walt Disney World Resort Complex, Florida (T. A. DeBusk and K. R. Reddy, Unpublished Results). Values Shown in the Parenthesis are Percent Reduction in Concentration.

Month 1986	Influent	Effluent Stage I 3 days HRT	Stage II 6 days HRT
January	127	102 (19.7)	49 (61.4)
February	226	83 (63.7)	62 (72.6)
March	246	123 (50.0)	69 (72.0)
April	231	91 (60.6)	41 (82.3)
May	231	49 (78.8)	24 (89.6)
June	298	67 (77.5)	23 (92.3)
July	147	70 (52.4)	29 (80.3)
August	195	88 (54.9)	26 (86.7)
September	159	78 (50.9)	32 (79.9)
October	206	119 (42.2)	63 (69.4)
November	185	121 (34.6)	54 (70.8)
December	181	100 (44.8)	51 (71.8)

TABLE 7   Contaminant Removal Rates (Percent) in the Walt Disney World
            Channels (1984) as a Function of Hydraulic Retention Time

Parameter	Hydraulic Retention Time			
	3 Days	6 Days	12 Days	24 Days
	------------------------% Removal------------------------			
BOD_5	81	84	87	89
SS	80	83	72	71
TKN	14	20	41	45
NH_4	8	10	36	42
$T-PO_4$	16	16	31	29
$O-PO_4$	10	10	23	25

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 m^{-3} 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.

TABLE 8   Lake Apopka water chemistry, 1984-85

Parameter	Units	Mean	Min.	Max	n
Nitrate	μg N l^{-1}	55	0	504	153
Ammonium	μg N l^{-1}	122	11	570	151
TKN	mg N l^{-1}	4.33	1.81	9.43	140
Total P	mg P L^{-1}	0.29	0.032	0.86	150
pH	units	8.39	6.31	9.92	70
EC	$\mu mhos$ cm^{-1}	381	185	650	72
DO	mg L^{-1}	6.04	0.87	14.02	72
Chl-a	mg m^{-3}	60	10.32	197.5	73

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 equalled 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 Brezonik, 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.

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)

| Location	System type†	Design flow	Area	Construction cost	Unit cost	Ratio‡ AMATS CTS
		$m^3 d^{-1}$	ha	$ million	$ $m^3 d^{-1}$	
Cannon Beach, Oregon, USA	Existing wetland	3,440	6.5	0.58	170	0.19
Gustine, California, USA	Created marsh	3,785	10	0.88	230	0.26
Incline Village, Nevada, USA	Created & existing wetland	8,100	49	3.3	410	0.46
Iron Bridge Plant, Orlando, Florida, USA	Hyacinth system	30,280	12	3.3	110	0.12
Anywhere in USA	Activated sludge	3,785	--	3-3.8	800-1,000	1.0

†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
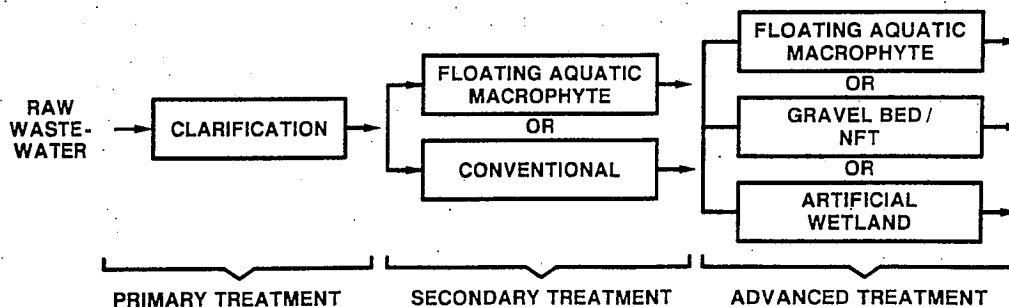
TYPE OF SECONDARY OR ADVANCED TREATMENT
WILL BE DICTATED BY
- WASTEWATER CHARACTERISTICS
- TREATMENT REQUIREMENTS
- CLIMATE
- LAND AVAILABILITY

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.

- o   hydrology/hydraulic loading effects
- o   pond size, shape, length to width ratio
- o   water depth (floating macrophyte system)
- o   sediment characteristics
- o   hydraulic properties of the soil or gravel used in artificial
      wetlands (root zone method)
- o   wastewater characteristics and effects of varying loadings of
      BOD_5, nutrients, metals, and toxic organics on the system
      performance
- o   management strategies - frequency of harvesting
- o   optimization techniques for improving system efficiency and for
      year-round performance
- o   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:

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

- o   oxygen consumption in the root zone
- o   carbon removal processes (aerobic, facultative anaerobic and
      anaerobic respiration of bacteria)
- o   nitrogen removal processes (nitrification/denitrification, NH_3
      volatilization, detritus breakdown, nitrogen fixation,
      adsorption, and diffusion of N species)
- o   phosphorus removal processes (adsorption and precipitation,
      mineralization/ microbial assimilation)
- o   metal removal processes (adsorption, precipitation and
      complexation)
- o   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:

- o   system management for low/high rates of biomass production
- o   biomass utilization options
    - methane/alcohol production
    - cattle feed
    - industrial products
    - soil amendment
    - compost/organic fertilizer
- o   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 m^3 ha d^{-1} are adequate for meeting
secondary treatment standards. In such a system, BOD_5 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 m^3 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.

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