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WASTEWATER TREATMENT WITH AQUATIC PLANTS

S.A. Abbasi

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Minsitrry of Water Resources, Govt. of India)

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
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Prof. S.A. Abbasi
Director
Centre for Pollution Control & Biowaste Energy
Pondicherry University
Pondicherry

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Dr. K.K.S. Bhatia
Member Secretary, INCOH &
Scientist F
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PREAMBLE

It has been estimated that the total world population will increase from 4.5 billion in 1980 to about 6.5 billion by the year 2000, with the most rapid growth in the developing countries. By that time, the countries within the humid tropics and the other warm humid regions will represent almost one-third of the total world population. This proportion will continue to rise in the twenty-first century. The developing and under-developed countries thus quite clearly are the regions facing potentially serious water problems. Hence, it is urgent to question as to whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources. Hence it becomes very important and expeditious to review and update the state-of-art in different facets of hydrology and component processes. This calls for compiling and reporting present day technology in assessment of water resources and determining the quality of these water resources.

Vascular aquatic plants like water hyacinth and salvinia, which are otherwise known as weeds, have been proved effective as bioagents for treating municipal and some types of industrial wastewaters. The technology is essentially labour intensive and energy-saving with lower overall costs than conventional treatment systems. In these respects this technology is appropriate for the third world but whereas the initiative for aquatic plant based waste treatment system has historically come from orient, the lead in this area has at present been taken by USA and Europe. The present report which describes the Asian initiative for aquatic-plant based wastewater treatment systems in the background of global state-of-art comes at a time when there is a lull in the Indian efforts in the field.

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The committee is also effectively participating in the activities of Unesco and is the National Committee for International Hydrological Programme (IHP) of Unesco. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites experts in the country to prepare these reports on important areas of hydrology.

The Indian National Committee on Hydrology with the assistance of its Panel on Water Quality Erosion & Sedimentation has identified this important topic for preparation of this state-of-art report and the report has been prepared by Prof. S.A. Abbasi, Director, C.P.C.B. and Professor at Pondicherry University, who is one of the handful of Third World scientists who have contributed to this field. The guidance, assistance and review etc. provided by the Panel are worth mentioning. The report has been compiled and finalised by Dr. K.K.S. Bhatia, Member Secretary of the Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

(S.M. Seth)
Executive Member, INCOH
& Director, NIH

Roorkee

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WASTEWATER TREATMENT WITH AQUATIC MACROPHYTES - A GLOBAL OVERVIEW

The realisation that aquatic plants can improve water quality must have come about several centuries ago with the observations that wastewaters flowing out of channels infested with vascular plants like water hyacinth seemed to be clearer than the wastewaters entering such channels. However systematic efforts to employ aquatic plants as biogents in water purification began only during the 1960s. There were occasional publications on the subject but the studies that caught the imagination of environmental engineers all over the world and gave a major spurt to R&D on macrophyte-based water treatment systems came from B.C Wolverton, a scientist with NASA, USA. Through a series of publications appearing in rapid succession Wolverton, mainly with R.C. Mc Donald as co-author, brought forth the amazing capability of water hyacinth in treating sewage and trade effluents (Wolverton 1979, Wolverton & McDonald 1977, 1979, 1979a, 1980a, 1980b, 1980c, Wolverton et al 1976).

Since then, research and development efforts, including pilot-scale and operational studies have demonstrated that aquatic macrophyte-based water treatment systems offer a low-energy consuming, low-cost method for removing contaminants from polluted waters. It has been shown that secondary as well as tertiary treatment is possible with the same aquatic plant, sometimes even in a single unit process.

Vascular plants when cultured over wastewaters can perform several functions, including assimilating and storing contaminants, transporting oxygen from the atmosphere to the root zone, thus facilitating aeration of wastewater, and providing a substrate for microbial activity which helps in the stabilisation of the wastes. Among the various types of aquatic treatment systems, pond systems containing floating macrophytes such as water hyacinth are the most commonly utilized for wastewater treatment in tropical and sub-tropical regions. In temperate regions, emergent plants such as cattails cultured in artificial wetlands have found large applicability. Due to still-to-be-perfected knowledge about system management and reliability, aquatic plant treatment systems are currently used on a limited basis throughout the world, but their potential for widespread use is enormous.

INTRODUCTION

Aquatic plants occur in water bodies enriched either by natural processes or by nutrient-loading from urban and agricultural activities, or by both. Aquatic plants commonly found in eutrophic water bodies include Eichornia crassipes (water hyacinth), Pistia stratiotes (water lettuce), Alternanthera philoxerides (alligator weed), Salvinia molesta (Salvinia), Lemna minor (duckweed), Eodea canadensis (elodea), Egeria densa (egeria or brazilian elodea), Hydrilla verticillata (hydrilla), Typha latifolia (cattail), and Phragmites communis (reed).

Wastewater Treatment with Aquatic Plants

Baring efforts of the type described in this report, the attention on vascular aquatic plants has mainly been directed towards their elimination from water bodies, since dense stands of the plants harm water resources in terms of quality as well as quantity (Abbasi & Nipaney 1986, 1988, 1991a). They adversely effect the fisheries, impede navigation, hasten water loss, support insect pests, and stress the fragile oxygen balance through death and decay. For these reasons, a vast amount of literature is available on methods to control the growth of aquatic plants (Abbasi 1986, Abbasi & Nipaney, 1986, 1992). 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. Encouraging results have specially been forthcoming vis a vis the use of aquatic plants as biogents for wastewater treatment. Till recently the successful exploitation of aquatic plants in this respect has been constrained by the lack of availability of economically viable methods of post-harvest utilisation of the 'spent' plants but now the feasibility of using such plants as an energy feedstock has been demonstrated (Abbasi & Nipaney 1984a, 1984b, 1989, 1991b, 1991d, 1992) spurring considerable interest in macrophyte-based wastewater treatment systems.

The economic success of energy production and water treatment using an aquatic plant-based system for water treatment/biomass production 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 utilising solar energy than many terrestrial plants. Among the aquatics, the floating weeds water hyacinth (Eichhornia crassipes) and salvinia (Salvinia Molesta) have the hightest growth rate, with a yield potential of about 200 dry metric ton ha^{-1} $year^{-1}$ (Reddy and DeBusk, 1984, Abbasi & Nipaney, 1991c, 1992). Certain emergent and submerged plants such as cattail and elodea, respectively) 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 (Hanadley 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 (AMS) rather than conventional treatment methods (Duffer, 1982).

The objectives of this report are 1) to provide a broad overview of the concept and existing engineering know-how of using aquatic plants in pollution control (Part I); ii. to summarise Asian experience in the field with special reference to India (Part II).

CONCEPT OF AMS

Aquatic macrophyte-based treatment systems (AMS) typically consist of a monoculture or polyculture of vascular plants grown in shallow ponds or raceways which receive wastewater at a longer residence time relative to that of conventional wastewater treatment systems. The long wastewater residence time of AMS 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, due to the apparent simplicity of design and operation of AMS, many wastewater engineers do not feel the need for research on system optimization. This problem is aggravated by the fact that even a poorly designed AMS system can satisfactorily remove many wastewater contaminants. Thus, a "black box" approach is frequently employed in studies of these systems, for which inflows and outflows are monitored with little regard for internal nutrient fluxes and transformations. 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 AMS have been utilized for wastewater treatment for at least two decades, techniques for optimizing contaminant removal are poorly understood. AMS can be used to much greater advantage than being done now if the systems are optimised on the basis of the hydrological, biological, and chemical considerations.

AMS SYSTEM DESIGN

Plant Selection

The following criteria have been identified over the years for selecting a plant as the main bioagent in water treatment systms:

- Adaptability to local climate
- High photosynthetic rates; in other words high growth rate
- High oxygen transport capability
- Tolerance to adverse concentration of pollutants
- High Pollutant uptake efficiency
- Tolerance to adverse climatic conditions
- Resistance to pests and diseases
- Ease of management

The plants commenly used so far in AMS include water hyacinth, salvinia, cattail, bulrush and pennywort (Figure 1). These plants are productive with mean annual, mean growth rates ranging from 15 to 80 dry tonnes ha $^{-1}$ yr^{-1} (Abbasi & Nipaney 1992). Potential growth rates of selected aquatic plants cultured in nutrient-

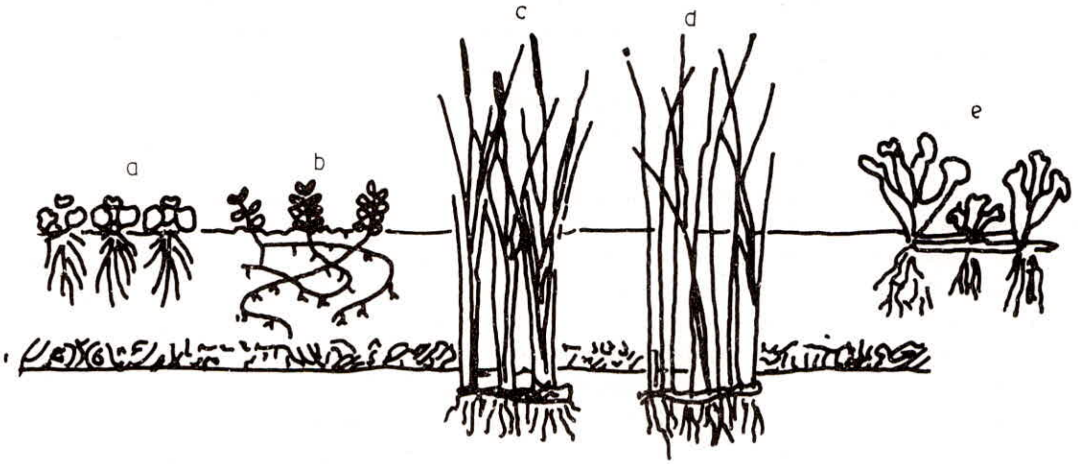

Figure 1 : Typical aquatic macrophytes; a: salvinia; b: water primrose; c: cattail; d: bulrush; e: water hyacinth. Water quality improvement takes place through sedimentation facilitated by plants, plant-uptake, oxygen, `pumping' and other biophysical-biochemical processes.

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 temperatures for a sustained period of more than 24 hours can result in the death of the plants. To overcome this problem, cold tolerant plants such as pennywort have been used in polycultures along with water hyacinth. This type of polyculture has been successfully used to improve wastewater treatment efficiency in Japan and USA (Anonymous 1986, Kira 1986, Clough et al. 1987). Emergent macrophytes can be used for water treatment by using 1) natural stands in wetlands for the 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 systems, wastewater loading, plant density, climate, and management factors imposed on the system.

The functions of the plant parts below water and those above water are summarised in Table 2. The mechanisms by which different types of aquatic plants help in wastewater treatment, together with the role played by associated fauna, are summarised in Table 3.

Table 1: Productivity and N/P contents of selected macrophytes

Plant	Biomass		Tissue composition	
	standing crop t (dw) ha^{-1}	Growth rates t ha^{-1} yr^{-1}	N	P
			gkg^{-1}	
Flaoting Macrophytes:				
Eichhornia crassipes	20.0-24.0	60-110	10-40	1.4-12.0
Pistia Stratiotes	6.0-10.5	50-80	12-40	1.5-11.5
Hydrocotyl sp.	7.0-11.0	30-60	15-45	2.0-12.5
Alternanthera sp.	18	78	15-35	2.0-9.0
Lemna spp. (duckweed)	1.3	6-26	25-50	4.0-15.0
Salvinia molesta				
Emergent Macrophytes:				
Typha	4.3-22.5	8-61	5-24	0.5-4.0
Juncus	22	53	15	2.0
Scirpus			8-27	1.0-3.0
Phragmites	6.0-35.0	10-60	18-21	2.0-3.0
Eleocharis	8.8	26	9-18	1.0-3.0
Saururus Cernuus	4.5-22.5	–	15-25	1.0-5.0

Typical Reactor Configurations and AMS Flowshets

Reactor Configurations : Typical reactor configurtions housing free-floating macrophytes like water hyacinth and salvinia are shown in Figure 2. Of these, the most commonly used reactors are 2a, 2b, 2c and 2d. The step-feed system with recycle (2d) is used at a treatment system in San Diago, USA. Configurations 2g to 2i are suitable for reducing the organic loading to the front end of the treatment process. Variants of configuration 2h have been mainly used in Germany.

The design details of the reactors depicted in Figure 2 are summarised in Table 4. The best working depths are in the range 0.5 - 0.7 metres though depths upto 2.4 metres have been employed. Depending on the strength of the wastewater and hydraulic retention time, the bottom of the reactor may be sloped towards the effluent end.

Typical AMS Flowsheets

Typical AMS flowsheets are presented in Figures 3 and 4

Table 2 : Functions of aquatic plants in aquatic treatment systems

Plant Parts	Function
Roots and/or stems in water column	1. Surfaces on which bacteria grow. 2. Media for filtration and adsorption of solids.
Stems and/or leaves at or above water surface	1. Attenuate sunlight and thus growth of suspended algae. 2. Reduce effects of wind on water (such as rooling of settled matter) 3. Reduce transfer of gases and heat between atmosphere and water

Table 3 : Mechanisms of action of aquatic plants and associated fauna in AMS

Organism	Mechanism
Flaoting aquatic plants	
water hyacinth (Eichornia spp.)	Its extensive root system (Figure 1) has excellent filtration bacterial suppot potentials, but extends less than 8 in (200 mm) below the water surface in most wastewater treatment applications. Hyacinths will not winter-over in cooler climates.
water primrose (Ludwigia spp.)	The filtration and bacterial support potentials of the primrose's submerged stems and roots (Figure 1) are less than those for the hyacinth. Primrose roots may extend to over 2ft (600 mm) below the wastewater surface. This plant survies in colder climates but is winter dormant even in mild climates.
Emergent aquatic plants	
Cattails (Typha spp.) Bulrush (Scirpus spp.)	The submerged portion of the stems of these plants (Figure 1) has been filtration and bacterial support potential than the roots of floating plants, but has the advantage of extending through the entire water column. These plants survive in colder climates. Though they tend to be winter dormant, their physical structure remains intact during dormancy.
Submerged aquatic plants	
Algae	Algae release oxygen to water at the expense of creating SS and BOD. Algae respire at night. Algae can be grown to raise the pH to volatilize ammonia and then be removed in subsequent APU's. Successions in algal population, particularly in fall, cause odors.

pondweeds (Potamogeton spp.)	The filtration and bacterial support potentials of this category of plant are unknown. Other effects of submerged macrophytes are similar to those described for algae, except that SS problems are not created.
Aquatic animals	
Zooplankton	These organisms feed on algae and other suspended particulates. Their presence and effect are difficult to mange.
Fish	
Blackfish Carp Catfish Mosquitofish	Fish serve in a role similar to that described for zooplankton. Fish can also be used to reduce the vegetative standing crop and control mosquitoes. Fish populations are manageable.

REMOVAL PROCESSES OCCURRING IN AMS

Solids Removal

AMS have long hydraulic retention times, generally of the order of a few days. This facilitates removal of the bulk of settleable and floatable solids from the wastewater. Normal mechanisms of sedimentation are operative. In addition the roots of aquatic plants serve as nucleii for the growth of elusters which them settle down. There is also secration of biopolymers from the plants roots which assist in flocculation. Nonsettling and colloidal particles are also removed, at least partially, by bacterial growth - which result in the settling of some colloidal solids and the microfial decay of others.

Storage in the Plant Biomass and Frequency of Harvesting

The rate of pollutant storage by an aquatic plant is a function of the growth rate and standing crop of the biomass per unit area. Some examples of storage of nutrients by floating and emergent aquatic macrophytes are shown in Table 5.

Nitrogen and phosphorous floating macrophytes are related mainly 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 5). Plants with a low standing crop of biomass per unit area typically have low nutrient storage capabilities. The looking of nutrients in floating aquatic plants is short-term because of rapid turnover. If plants are not harvested, the dead tissues decompose rapidly and release nutrients back into the water. Frequent harvesting of the biomass is necessary to avoid this phenomena of releaseback of nutrients.

With some aquatic plants event hough the storage of nutrients is short-term, the nutrient uptake rates are high. High nutrient removal rates through plant uptake can also be exploited by frequent harvesting of plants.

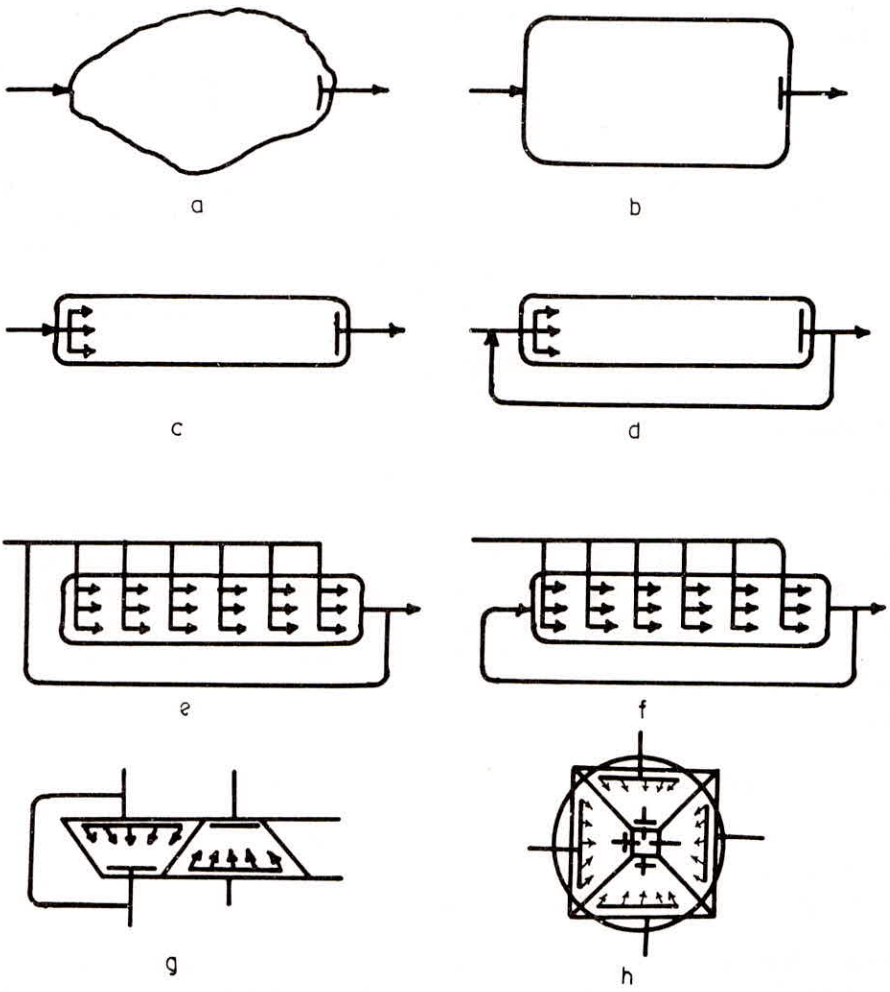

Figure 2 : Typical flow-patterns employed in AMS;
a : arbitrry flow;
b : semi-plug flow;
c : plug-flow;
d : plug flow with recycle;
e&f : semi plug-flow with step-fed and recycle;
g&h : variable geometry
semi-plug flow

with/without recycle.

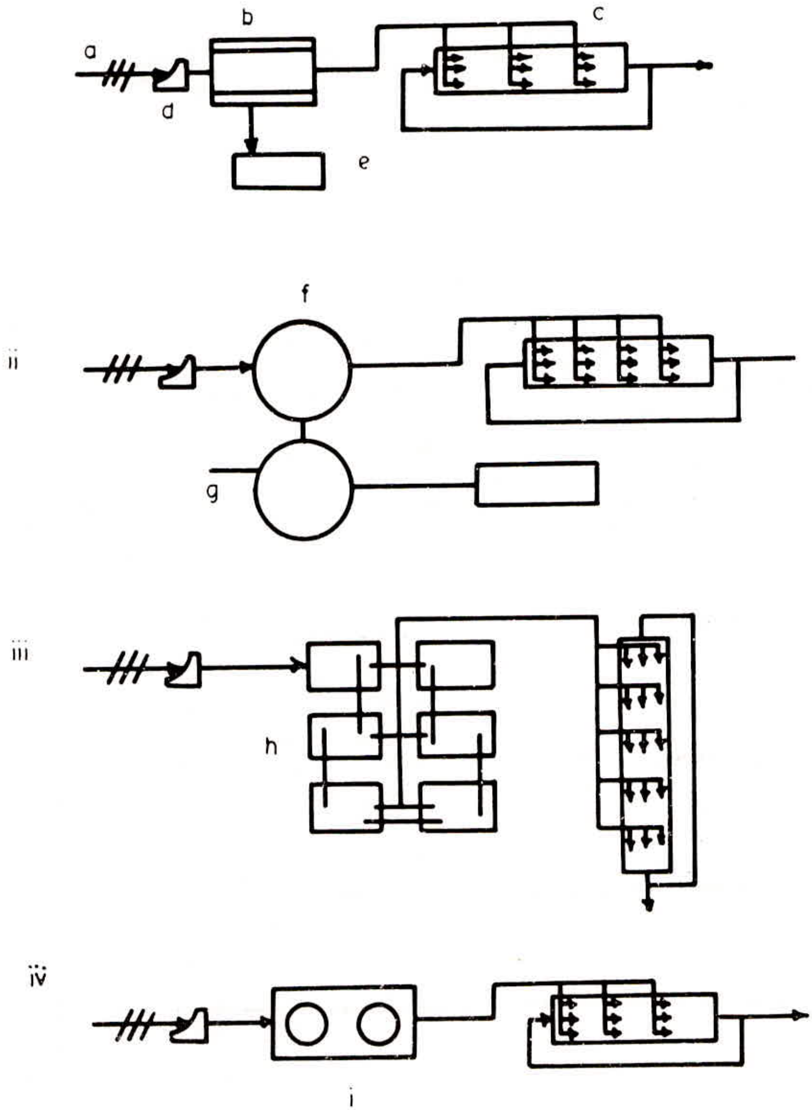

Figure 3 : Typical wastewater treatment flowsheets making use of aquatic macrophytes; a: bar racks; b: imhoff tank; c:ponds containing aquatic macrophytes; d:fixed screens; e: sludge drying beds; f: primary seidmentation; g:anaerobic digestion; h:stabilisation ponds; i: aerobic stabilisation pond.

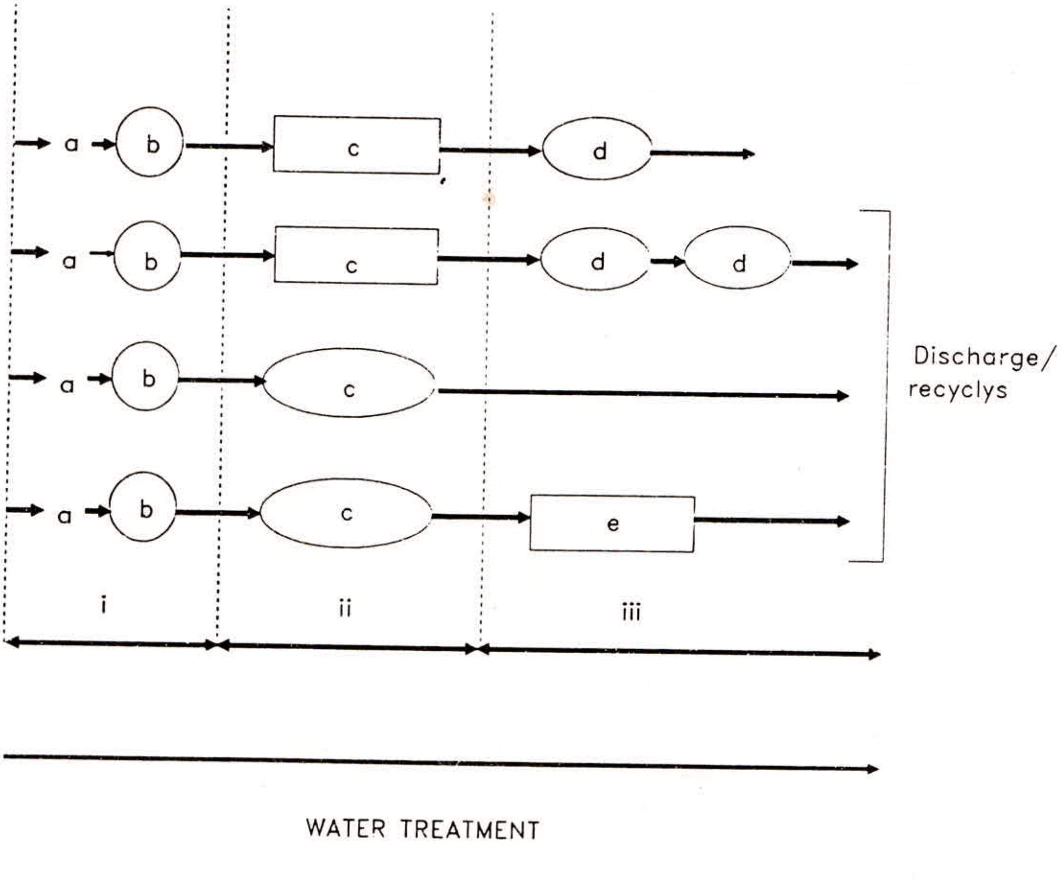

Figure 4 : Typical flow-sheets for primary (i), secondary (ii), and tertiary (iii) treatmebnt of municipal wastewaters with AMS; a: communication/screening; b: clarification; c:convetiuonal; e:advanced (through conventional) treatment processes.

Table 4 : Typical physical dimensions for aquatic treatment systems

Treatment system	Corresponding figure	Range	Typical value
Floating Aquatic plants			
Depth of water, mm	2a	600-2400	900
	2b	600-1000	900
	2c-2i	350-1000	500-700
Aspect ratio			
(length:width)	2a	1-2	-
	2b	1-3	-
	2c-2f	4-15	8
	2g-2i	1-1.5	1.25
Emergent Aquatic plants			
Depth of water, mm	2a-2i	250-750	300-600
Aspect ratio	2a-2b	1-3	
	2c-2f	4-10	
	2g-2i	1.5-2	
Packed-bed			
Depth of bed, mm	3a-3e	600-1000	900
Depth of water, mm	3a-3e	450-900	850
Aspect ratio	3a-3b	4-10	6
	3c	1-1.5	1.25
	3d	1-1.5	1.25
Gravel Type	3a-3e		
Gravel layer			
Depth, mm		700-800	
size, mm		12.5-12.5	
Cover layer			
Depth, mm		100-200	
Size, mm		2.5-12.5	
Rock Type	3a-3e		
Rock layer			
Depth, mm		700-800	
Size, mm		25-75	
Cover layer			
Depth, mm		100-200	
Size, mm		2.5-12.5	

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 nitrate-rich water exhibited chlorosis, even though N was present at adequate levels. Upon addition of Fe-EDTA, the chlorosis syptoms disappeared (Reddy, 1983). Water hyacinths salvinia 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; Muramato and Oki, 1983 Abbasi & Nipaney 1986, 1992).

Table 5 : Standing crop (storage) of N and P, and rate of plant uptake for selected aquatic macrophytes

Plant	Nitrogen		Phosphorus	
	Storage kg ha^{-1}	Uptake kg ha^{-1} yr^{-1}	Storage kg ha^{-1}	Uptake kg ha^{-1} yr^{-1}
Floating Macrophytes:				
Eichhornia **crassipes**	300-900	1950-5850	60-180	350-1125
Pistia stratiotes	90-25	1350-5110	20-57	300-1100
Hdrocotyle **Umbellata**	90-300	540-3200	23-75	130-770
Alternanthers Philoxeroides	240-425	1400-4500	30-53	175-570
Lemna minor	4-50	350-1200	1-16	116-400
Salvinia Molesta	300-950	1900-6000	60-170	380-1200
Emergent Macrophytes:				
Typha spp.	250-1560	600-2630	45-375	75-403
Juncus	200-300	800	40	110
Scirpus	175-530	125	40-110	18
Phragmites	140-430	225	14-53	35

Emergent macrophytes such as typha, bulrush, and phragmitis have the capability to grow in a wide range of substrates and in a variety of wastewater types which 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, biologial nitrogen 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 aer found in plants analyzed at maturity or cultured in nutrient-limited systms, 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 above ground growth of Pharagmites australis and decresed root/shoot ratios from 2:2 to 0:75. Although fertilizsation 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 250 to 1560 kg. nitrogen ha^{-1} and 45 to 375 kg. phosphorous ha^{-1} (Table 5). 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 above ground biomass once a year may improve the overall nutrient removal efficiency.

Biochemical/Physico-chemical Processes

In addition to plant assimilation, nutrient removal in AMS 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).

BOD/Carbon : Organic carbon in wastewaters, which is typically measured as 5-day biochemical oxygen demand (BOD_5) is removed as a result of metabolic activity by micro-organisms that are: a) suspended in water column; b) attached to the sediments; and c) attached to the roots and stems of the aquatic plants. Thus BOD removal mechanism in AMS is akin to the one that occurs in slow-rate, horizontal flow trickling fitters with built-in secondary clarification; plants replacing grvel as bacterial support structure.

In AMS, BOD is utilised by bacteria as an energy source and for cell synthesis. These bacteria inhabit micro-environments 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 nitrate and sulphate as electron acceptors. Recent studies show that BOD_5 removal from primary domestic effluent is accelerated by the addition of nitrate, which suggets that electron acceptor availability is the factor limiting organic C removal in macrophyte-based wastewater treatment systems.

Oxygen pumping : Aquatic plants have a unique feature of transporting oxygen 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 oxygen "pumping" process by plants, although recent experients have shown that aquatic macrophytes differ in their ability to oxidize their rhizosphere. Pennywort, for example, transports oxygen 2.5 times as rapidly (per unit weight of root tissue) as water hyacinth, which in turn transports oxygen four times more rapidly than water lettuce (Table 6).

Oxygen concentration of sewage effluent increases by 10-fold in treatments with pennywort plants as compared to those without plants (Reddy and DeBusk, 1984; Table 7). 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, oxygen transport through either pannywort or water haycinth plants was found to be responsible for 90% of BOD removal, while the remaining 10% of BOD removal was due to oxygen transport directly from air (Reddy, 1987, unpublished results) (Table 8).

The role of oxygen transport by emergent macrophytes in carbon removal has not been examined. However, the principal concept of designing artificial wetlands is with the assumption that oxygen transported by emergent aquatic macrophytes supports nitrification in the root zone (Brix. 1986).

Nitrogen : Nitrogen is removed from AMS by a number of mechanisms: a) uptake by and subsequent harvesting of plants; b) volatilization of ammonia; and c) bacterial nitrification/denitrification. Of these bacterial nitrification - denitrification has the most dominant influence on nitrogen removal.

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 oxygen, such as pennywort. Nitrate-N thus formed diffuses into reduced micro-environments in the pond system, where it is utilized as an electron acceptor by facultative anaerobic bacteria and lost from the system as nitrogen gas. Both native wastewater carbon and plant detritus can be utilized by these bacteria as a carbon source. Denitrification rates in excess of 1 gm^{-2} d^{-1} have been reported in AMS (Stowell et al., 1981; Moorhead et al., 1987).

In studies on the fate of nitrogen added to floodwater in reservoirs containing aquatic plants, mass balance studies have indicated that plant uptake accounted for 13 to 67% of total nitrogen removal, while the unaccounted nitrogen was assumed to be lost through nitrification and denitrification or ammonia volatilization (Reddy, 1983; Reddy and DeBusk, 1985). In field studies, mass balance of nitrogen for a water hyacinth-based water treatment system has indicated that 50% of the total nitrogen 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 nitrogen removal when water hyacinth plants are cultured in nitrate rich waters. Similar results have been observed in emergent macrophyte systems. In a freshwater marsh containing Typha Latifolia, about 25% of added nitrogen was lost from the system, while 54% of the added nitrogen was recovered in the plant (Dean and Biesboer, 1986).

Table 6 : Oxygen transport through selected aquatic macrophytes

Plant	Root mass/plant	Oxygen transport mg oxygen/g/hr	n
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 7 : Effect of pennywort plants on oxygen concentration of the sewage effluent. Oxygen concentration of the effluent at the start of the experiment was < 0.1 mg L. The values shown below are the oxygen concentration of the effluent after seven days

Sewage effluent BOD_5 mg/litre	PB	PNB dissolved oxygen,	NPNB mg/litre	B
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.

Table 8 : Effect of pennywort plants on BOD concentration of the sewage effluent. The values shown below are the BOD_5 levels measured after seven 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

Phosphorous. In AMS, phosphorous can be removed from the wastewater by plant uptake, microbial assimilation, precipitation with cations such as Ca, Mg, Fe, Mn and adsorption onto clay and organic matter. However, many studies have shown plant uptake and harvest as the most effective means of removing phosphorous from AMSs.

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 are 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 seminars on the use of macrophytes in water pollution control in Pirracicabe, Brazil (1987). The papers presented at a similar conference conducted in Orlando, USA, in 1986, on aquatic plants for water treatment and resource recovery, and at Chattanooga, USA, in 1989 on constructed wetlands also support the concept of using aquatic plants cultured in ponds or artificial wetlands for water treatment. These 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, only 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 under-performance, even failure, of the systems.

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

Future research should be directed mainly in the areas of system design, plant selection, plant biology, proceses 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 polution control using aquatic plants both in managed artificial systems or natural systems. For wastewater treatment AMS can also be integrated into conventional treatment systems to reduce overall costs (Figures 3&4).

Table 9 : Comparative costs-benefit analysis of aquatic macrophyte-based water treatment system (AMS) as compared to conventional treatment systems (CTS) (Crites and Mingee, 1987)

	System Type	Design flow $m^{33}d^{-1}$	Area ha	Concentration cost $ million	Unit cost $ m^3d^{-1}	Ratio $\frac{AMS}{CTS}$
Canon 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, Floridaa, USA	Hyacinth system	30,280	12	3.3	110	0.12
Anywhere in the USA	Activated sludge	3,785	--	3-3.8	800-1,000	1.0

System Design

Some design information, already available on floating macrophyte-based systems (Duffer, 1983; Reddy and Sutton, 1984) or artificial wetlands (Wolverton, 1987; Cooper and Boon, 1987), has been summarised earlier in this report. However, the following inforamtion is still needed for system optimization.

- Hydrology/hydraulic loading effects
- Reactor (Pond) size, shape, dimensions

- Water depth (specially in floating macrophyte system)
- Sediment characteristics
- Hydraulic properties of the soil or gravel used in artificial wetlands
- Wastewater characteristics and effects of varying loadings of BOD_5, nutrients, metals and toxic organics on the system performance
- Management strategies - frequency of harvesting
- Optimization techniques for improving system efficiency for year-round performance
- Integration of aquatic-plant-based systems with conventional wastewater treatment systems

Plant Selection

The macrophyte species plays a significant role in water treatment either by directly asimilating pollutants or creating a suitable environment in the root zone for microorganisms to transform pollutants. For many systems, an aquatic plant is arbitarily 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
- Tolerance to a wide range of pollutant concentrations
- Oxygen transport capability
- Growth characteristics/biomass productivity
- Nutrient storage capabilities
- Resistance to pests/diseases
- Ease of management/harvesting

Biochemical/Physio-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, 1987). Future research should be conducted to develop a fundamental understanding of the processes to maximize treatment efficiency. The following processes should be studied in the root zone, water column, and 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, ammonia volatilization, detritus breakdown, nitrogen fixation, adsorption, and diffusion of nitrogen species)'

- Phosphorus removal processes
  adsorption and precipitation, mineralization/microbial assimilation
- Metal removal processes
  adsorption, precipitation and complexation
- Toxic organic compounds
  decomposition, identification of intermediate compunds, adsorption to roots, detritus components and soil particles.

Biomass Disposal/Utilization

Aquatic plant biomass has been traditionally considered a waste material which must be disposed of. However, under certain conditions, this biomass can be a resource which can be used in beneficial ways to offset the costs of overall treatment. The 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 Abbasi (1987); Abbasi & Nipaney (1986, 1991, 1992), Chynoweth (1987), and Lakshman (1987). Research in the following areas is needed for biomass utilization or disposal :

- Systems 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

These considerations become very important when natural ecosystems are used in pollution control. For example, natural wetlands are used in many areas 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 organised workshops and conferences, so that the feasibility of using systems for water treatment can be evaluated. For example, a specialist technical groups within Ministry of Environment & Forests or Central Pollution Control Board can be established. These groups can develop a standard protocol which can be circulated to the researchers. These groups can exchange technical information through newsletters and reprints. The protocol developed by these groups 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.

WASTEWATER TREATMENT WITH AQUATIC PLANTS - THE ASIAN INITIATIVE

Purification of biodegradabale wastewaters through lagooning or 'ponding' has been common in Asia, especially in India, China and the South-east Asia. Culture of fish and aquatic plants has been traditionally used with lagoonning to improve water quality and facilitate recovery of nutrients from wastes. While the traditional systems have been operated by farmers more or less intuitively, the interest in developing the science and technology of aquatic plant-based water treatment systems has gathered momentum from 1970s onwards. Efforts have been made to study at the laboratory scale the feasibility of treating a variety of domestic and industrial effluents with aquatic macrophytes. A few pilot plants for demonstration-cum-research as well as a few full-scale plants have been set up.

The present chapter attempts to bring together published as well as previously unpublished information on aquatic plant-based water treatment systems in Asia. The review includes: i) an assessment of research on the use of aquatic plants especially macrophytes for water treatment; ii) typical case-studies of laboratory scale, pilot and full-scale systems with information on design, operation and maintenance; iii) biomass utilistaion efforts for cost recovery; iv) economics of these system compared to conventional systems; and v) long-term implications of the past and present R&D efforts.

INTRODUCTION

Water treatment through lagooning or 'ponding' has been common in Asia, especially Indo-china and the Southeast Asian countries. The relative inexpensiveness, extreme simplicity in operation and maintenance, and appropriateness in treating low volumes of wastes have all contributed to the popularity of lagooning. It has also been known for centuries that fish and vegetation if grown in ponds receiving human or agricultural wastes not only speed up the treatment of wastes but 'recover' the nutrients in the form of live biomass. Farmers in China, and South-east Asia, have developed the recycling of nutrient rich organic wastes into an art. It has been common to situate household latrines over the family fish ponds. In rural areas barns are built so that the manure from dairy animals falls directly into ponds to fertilize crops of aquatic plants. Harvested regularly, the plants provide feed for the animals (Le Mare 1952). The Bayan Lepas Form near Penang (Malaysia) was organised in the 1950s to combine pig-rearing with fish-farming and vegetable growing. The centerpiece of this intensive system is a lagoon stocked with herbivorous fish and planted with water spinach (Ipomoea aquatica or L. reptans). Wastes from pig sties are flushed into the lagoon to fertilise and maintain the water spinach crop. A portion of the crop is eaten by the fish and the rest is harvested for pig food. Yeoh (1983) reports that water hyacinth (Eichhornia crassipes Mart Solms) has long been grown in Malaysia by small-scale pig farmers in ponds receiving piggery washings. The hyacinths harvested from such ponds are used as animal feed supplement. Simple systems like these that harness aquatic plants to recycle nutrients are reportedly common in Asia (Hara 1951, NAS 1976) but unfortunately little, if any, scientific information is available on the design basis and performance of such systems. Systems like these, though useful in recovering nutrients, are never free from the hazards of introducing pathogens into the human food chain. A large number of parasitic deceases prevalent in the East could have their origin in the practices of recycling human excreta and other animal-based biowastes as fertilisers (Pacey 1978).

ALGAE BASED WATER TREATMENT SYSTEMS

Algae are known to influence the biological, chemical and visual features of facultative waste-stabilisation ponds. The symbiotic relationship between the decomposer bacteria and algae - the former producing carbon-dioxide, ammonia and other nutrients while the latter utilising these nutrients and generating oxygen through photosynthesis for maintaining the aerobic zone in the pond is essential for the functioning of faculative ponds. However such ponds are not traditionally referred as 'algae-based' systems; rather the production of algae in such systems, though essential, is to be firmly kept under control. Excessive algal production can destabilise the desired functions of a faculative pond, and the problems associated with this phenomena are believed to be the biggest drawbacks of facultative pond systems. On the other hand the 'high-rate pond' concept, initiated in the 1950s in the United States (Gotaas et al 1985) and followed up in the Philippines, Israel, India, Singapore and other countries, places emphasis on the maximization of algal production. Such ponds are kept shallow (0.2 to 0.4 m) to aid in the penetration of light and increase the efficiency of solar conversion. The pond contents need to be mixed at low speed to keep the algae in suspension and in good contact with the wastewater nutrients. It is also essential to prevent algae from getting into the final effluent.

In Asia high-rate ponds have been built below ground level as well as above ground level (Lee et al 1980; Majid and Akhtar 1980). Some ponds have been built into the roof of animal housing units (Stanton W.R. 1976). The ponds are stirred with pumps or paddle-wheel mixers. Innovative approaches include use of low-cost asbestos sheets for building ponds in Singapore and small windmills for stirring the ponds in India (NAS 1981).

The Prime objective of the high-rate ponds being algal production, the conventional systems in Asia have slanted towards maximising biomass production rather than wastewater treatment. Attempts to develop optimal algae based water treatment with biomass production systems have been made mostly in Israel by Oron and coworkers (1982, 1977, 1980).

Shelef et al (1977) operated two 0.1 ha, 0.4 m deep high-rate ponds with domestic wastewater. Mixing was provided by a paddle wheel. Detention times where 2 days during summer and 10 days during winter. Micractinium, Scendesmus, Oocystis and Euglena were dominant algae genera at various times. The biomaass was harvested by alum flocculation followed by dissolved air flotation. Subsequent to the harvest 93% of the BOD and phosphorus and 50% of the nitrogen had been removed from the wastewaters. Extrapolation of the results of pilot scale studies indicated that the wastewaters produced by a community of 6000-8000 people received in a 1 ha high-rate stabilisation pond system would yield about 100 ton dry biomass per year. About 60% of the biomass would be a algal origin while the remainder would be mostly bacteria. Dried biomass can be used as an alternative protein source for chicken, fish and pig feed.

Shelelf et al (1978a, 1978b) operated a pond receiving domestic waste-waters at depths of 35-0.5 m. A horizontal caged rotor produced flow rates of 3-5 cm s^{-1} during the day and 7-12 cm^{s-1} during the night. The rotor also accomplished mixing of pond contents. Mean oorganic loading on the pond was 46.5 gm $^{2-d}$-1 and detention times varied from 1.8 days in summer to 7 days in the winter. Total biomass production was calculated to be 40.7 g m^{2-d-1} with algal substance being produced at a rate of 35.1 g m^{2-1}.

The biggest drawback of the algae-based wastewater systems is the high cost of algae harvesting and drying. Shelef et al; (1978) estimated that the aeration-mixing required for a high-rate stabilisation pond is only one-third that of an activated sludge plant. However the total energy required exceeded that needed for separation and disposal of activated sludge due to the energy used for the concentration and drying of the biomass. Total construction and operating costs of a high-rate algae pond would approach that of an activated sludge treatment facility. The availability of sunlight is a critical factor controlling the algal growth; artificial light is not economically viable because at the very best an efficiency of only 20% may be obtained from the energy supplied. High-rate algae ponds have a light conversion efficiency of a about 3 % (Shelef et al; 1977); thus sunshine is the only practical light source for algae production. However, illumination from the sun may often exceed light requirements for maximum algal photosynthesis and may damage exposed algal cells. Other recognized but yet to be overcome limitations of the algae-based systems include difficulties in maintaining desirable algal species in the ponds; sudden shifts in algal species composition occur as a result of weather or operational changes. Such shifts have an impact on the cost of harvesting. Genera such as Micractinium and Scenedesmus which are colonial, and Spirulina are readily harvested while a genus such as Chlorella, small coccoid, single-celled alga is difficult to harvest. Grazers also pose problems. In Singapore the cladoceran Moina is an intermittent grazer; else where Daphnia and rotifers are common algal grazers. Such filter feeders rapidly decimate the algal population and adversely effect the effluent quality by adding soluble BOD.

While researchers in Israel are focussing current research on duckweed culture in preference to algae (Oron et al; 1984; 1986) in view of the abovementioned problems, especially the high costs involved in algae harvesting and drying, researchers elsewhere in Asia are trying to develop more economical harvesting and post-harvest processing techniques. In Singapore research on a pilot-scale project with 2.9 ha high-rate ponds involves continuous filtration using commercially viable fineweave filter fabrics (National Academy of Sciences ;1981). Attempts are also being made to develop a process in which the alum used in flocculation of the algae is recovered by acidification of the algal slurry and recycled. Success in these attempts will lead to reduction of residual alum in the algae and lower costs. Another alternative being explored is to pump the algal-bacterial slurry grown over a high-rate pond supplied with swine-wase directly into the feeding trough of the swine. Swine accept liquid food and de-watering of algal biomass maybe avoided if the slurry can turn out tobe as desirable a feed as dewatered algae. Alternatively, harvested algal slurry can be cooked, preferably by steam, and fed in wet forms to pigs. Cooking requires less energy than drying, but the product must be used immediately as it has poor stability. Feeding trials have shown that steam cooked alga can replace half of the 15 percent soybean meal in the ration of pigs. When algae totally replaced the soybean meal, the growth performance of the pigs was only slightly depressed (Majumdar et al; 1983).

Researchers in the Philippines are evaluating a natural process of autofloculation of algae as a means of pre-concentrating the algae suspension and have achieved better than 90 percent algae recovery. Harvesting, therefore, may no longer be a major constraint to the broad application of high-rate pone technology. The potential impact of algal protein production (56-82 tons ha^{-1} year $^{-1}$) on livestock and poultry feed supply and the environmental benefit of wastewater treatment, just if continued efforts to develop algae-harvesting technology.

In a rare attempt of using algae in treating industrial wastewater, (John; 1983) allowed algea to grow in pre-treated black rubber effluent in a shallow (0.25 m) tank using retention times ranging from 2-10 days. No marked improvement in BOD and total solids removal was observed in the algal system, but COD and suspended solids increased. This adverse effect was greater with high retention times; at a 10-day retention COD increased from 200 mg 1^{-1} to 440 mg 1^{-1} and suspended solids increased from 80 mg 1^{-1} to 330 mg 1^{-1}.

MACROPHYTE BASED WATER TREATMENT SYSTEMS

Given the traditional expertise of the Asian farmers in recycling human and animal wastes through aquaculture and the practices intutively developed by them of recovering nutrients from wastes by aquatic macrophytes propogated over waste-fed ponds (Hara; 1951, Yeoh; 1983), Asian researchers could have taken a lead in developing macrophyte based water treatment systems along scientific lines. This, however, has not happened and the lead in taking up systematic research on the treatment of domestic wastewaters using aquatic macrophytes has come from the west - mainly West Germany, USA and the Netherlands. Yet, one the first research reports on the treatment of domestic wastewaters using aquatic macrophytes his come from the West - mainly West Germany, USA and the Netherlands. Yet, one of the first research reports on the treatment of industrial wastewater with aquatic macrophyte did appear from Asia. This publication (Sinha S.N. & Sinha L.P. (1969), which preceeded reports on this subject from other parts of the world by some years, describes experiments for evaluating the capacity of water hyacinth to purify digested sugar factory wastes. Treatment of septic tank effluents is also described. The anaerobically digested sugar factory waste with BOD 258 mg 1^{-1}, turbidity 150 mg 1^{-1}, odour 24 mg 1^{-1}, pH 7.05 and redox potential - 129 mv was retained in containers with or without water hyacinth cover. At all retention times studied, varying from 1-7 days, water hyacinth facilitated waste treatment achieving reductions in BOD; 94%, turbidity 97% and odour 96%. The redox potential changed to + 984 mv and pH to 7.50. In containers without water hyacinth the corresponding change were BOD: 54% turbidity 40%, odour 92%, redox potential + 431 mV and pH 7.35. Similar results were achieved with septic tank effluent. The authors also investigated the mechanism of the purifying action of water hyacinth and demonstrated the presence of the enzyme dehydrogenase in the hyacinth roots to which they attributed the capability of the macrophyte to 'oxidise' the organic wastes. It was suggested that during absorption of water, the colloidal particles of the waste strike the surface of the hyacinth roots and get agglomerated after loosing their electrical charges. While settling, the agglomerated particles carried with them more suspended solids. It was also suggested that suspended solids removal was possibly being facilitated by the absorption of natural peptising agents from the wastewater hyacinth covered wastewater from - 129 mV to + 784 mV. the authors suggested that facultative anaerobes and aerobes were operative. The study was fairly detailed and promising and it is unfortunate that the authors did not follow it up with larger-scale trials.

In the late 1970s there was a world-wide increase, in interest, in developing aquatic plant based wastewater treatment systems, and several studies were undertaken in Asia too, particularly in the 1980s, on this aspect. Most of the work has centered round water hyacinth, with some reports on duckweed, Salvinia and water cress-water hyacinth combination.

TREATMENT OF INDUSTRIAL WASTE WATERS

Using water hyacinth

Water hyacinth has been explored for treating wastewaters from dairies, piggeries, tanneries, distillaries, suger factories pulp & paper industries, taxtile industries, palm oil mills, natural rubber factories, electroplating units and metal work industries. Efforts have also been made to assess the capability of water hyacinth

Table 10 : Treatment of Industrial Wastewaters and Some Specific Pollutants Using Water Hyacinth

Wastewater	Type and capacity/ dimensions of holding tanks/ containers	Retention time, days (RT. a)	Influent characteristics in Mgl^{-1} , maximum removal achieved in parenthesis	Remarks	References
(1)	(2)	(3)	(4)	(5)	(6)
Sugar refinery (predigested)	Beakers 2 1	0-7	BOD 256 (74%), Turbidity 150 (97%), odour 24 (96%).		Sinha S.N. & Sinha L.P. (1969)
Sugar refinery	Fibreglass tanks 3mX2mX1m: 4000 1: operated at depth of	7	BOD 993 (43%), COD 1915 (36%), 55 32 (21%), 75 3163 (85%)	Plants tended to decay after 6 weeks	Goel P.K., et. al., (1985)
Dairy	Plastic containers 0.6 m dia, 0.12m deep: glassd containers	1-14	BOD 1442 (84%), COD 1690 (88%), 55 1107 (40%), TS 3693 (50%), fats &	Decayed plants were removed from time to time	Aowal A.F.S.A.& Singh J. (1982)
Dairy	Plastic tubs 0.33 m dia, 12 1	7.14	BOD 61 (87%), COD 120 (63%), total N 35 (60%) inorg P 0.4 (50%), total P 3.5 (79%)	Maximum BGD, COd and total P removal was achieved at rT 7d. for other pollutants RT 7d. for d was required. Plants tended to accumulate as leach out Ca, Mg and N.	Goel P.K., et. al., (1985) and (1983)
Distilary (diluted 24 times with water)	Cement tanks 1m X 1m X 0.8 m	16.31 49	Ca 40 (6%) Mg 32 (11.6%) available P 0.31 (19.4%), total dissolved P 0.75 (96%), total dissolved N 0.44 (87.4%)	Available P was removed by 19.4% in 31 days but increased thereafter; total dissolved N removed by 75.5% in 16 days.	Trivedi R.K. & Khomane B.V. (1985)

Contd....

Table 10 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)
Piggery (Sun-dried pig waste mixed with water	Fibreglass tanks 200 1	16.3	BOD 70 (74%), 146 (61%), 196 (68%), 320 (67%): COD 245 (42%), 463 (32%), 675 (30%), 920 (21%)	In general water hyacinth was 20-30 more efficient than algae, waste with BOD 320 and COD 920 caused to to decay after 5 days	Yeoh B.G. (1963)
Palm Oil (pretreated by anaerobic digestion followed by extended aeration	Fibreglass tanks 3mX2mX1m: 4000 1: operate at depth of 0.66 m	5	BOD 82 (40%) COD 388 (35%) SS 116 (85%), NH_3-N 1.23 (54%) total N 32 (69%)	Field trials under actual mill operation condictions indicated that hyacinth plants tended to wither after a few days because of high NH_3 in the wastewater; further trials are underway.	Yeoh B.G. (1983) & (1986)
Palm Oil (Partially digested)	Concrete tanks 120 1, depth 0.3 m/p.6 m/1.2 m	10,20,25	BOD, 4980 (96%), COD 8850 (87%), SS 3560 (96), TS 8210 (45%), total N 285 (77%), NHPVAPV-N 120 (83%), oil & grease 660 (97%)	Attempts to extend this system to ponds treating palm oil mill effluents were not successful as the plants tended to die soon after introduction.	John C.K. (1983) & (1984) & (1986)
Natural rubber (raw effluent)	Concrete tanks 120 1, depth 0.3 m/0.6 m/1.2 m	5,10,15	BOD 1430 (94%), COD 248 (89%), TS 1420 (57%), SS 810 (89%). NH_4 100 (70%), Total N 150 (67%)	At RT 10d, 85%, BOD, 80% COD, 88%, SS, 50% NH_4-N and 53% NH_4-N were removed. Optimum operating depth was 0.3 m, Plants grew best at pH 5.0-7.5	John C.K. (1984)
Natural rubber (effluent from anaerobic lagoon)	Lagoons in remilling factories, generating 1 million 1 effluent per day	12-15	BOD 160 (89%), COD 380 (66%), TS 700 (72%), SS 255 (88%), NH_4-N 20 (70%), Total N 30 (50%)	The plants were harvested periodically; average yield was 500 kg dry matter/ha/d.	John C.K. (1984)
Tannery (diluted times with water)	Plastic tubs 33 cm 33 cm dia. 12 1	7.14	BOD 380 (35%), COD 800 (70%), Total N 108 (72%) Inorg P 1.4 (86%), Total P 4 (64%)	Addition of sewage hastended BOD & COD removal but slowed down the removal of N & P	John C.K. (1984)

Contd....

Table 10 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)
Tannery (Mixed with Sewage)	Cement tanks 600 1	Upto 24	BOD 700 (80%) Chromiium 80 (100%)	With tannery waste -1 (BOD) (BOD 2000-2500 mg 1 and Cr 150-200 mg 1 mixed with sewage in 1:4 ratio. BOD was reduced by 80% and chromium by nearly 100% in 16 days. Plants tended to decay after 4 weeks.	Prasad B.G.S., et. al., (1983)
Tannery	Earthwenweare Vessels 2 65	2	TS 12300 (absorption of metals and reduction of BOD & COD was observed; values not reported)	The plants wilted in two days	Haider S.Z., et. al., (1963a) & (1938b)
Pulp & Paper	Pots 8 1	1,3,5	Na 104,8 Si) O 33.3, Cl 66.7 S 6.8: optimum absorption was RT Na 7850	Optimum absorption occurred at RT 3d; dilutiuon of the wastewater did not improve treatment; harvested plants could be used for paper pulp.	Widyanto L.S. et. al., (1979)
Pulp & Paper (paper machine/ combined)	Pots 30 f for survivability and surface coverage studies; tanks 200 1 for other studies Batch as well continuous process were studied	1-15	Combine effluent COD 485 655 and SS 174-300 were reduced by 70% and 80% respectively at RT 15 d in a continuous process. For paper machine effluent 90% COD was removed in 6 days	The plants exhibited excellent growth and survivability at pH 4-10	Behera N.C., et. al. (1982)
Pulp & Paper	Vessels 1.5 1 and 65 1	Upto 10	TS 5100	Wilting of the plants started after 3 days. Of the various parameters studied, significant reductions were observed in COD (44%) and BOD 53%)	Haider S.Z., et. al., (1983a) and (1983b)

Contd....

Table 10 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)
Textile	Plastic pails 4.51	Upto 10	TS 347, SO_4 146, NO_3, 0.34 NH_4 2.03, PO_4 0.17	There was a stimulation in the growth of water hyacinth on effluents diluted 50% with water	Widyanto L.S. (1975)
Textile (diluted 3 times with water)	Cement tanks 1m X 1m X 0.8m	16,31,49	Ca 45 (32%), Mg 12 (31%), available P 0.19 (42%), total dissolved P 0.4 (72%), total dissolved N 0.7 (31%), particulate N 0.7 (31%), 0.5 (75%)	Significant reduction of Mg and particular N occurred at RT 16 d	Trivedi R.K. & Khomane B.V. (1985)
Textile (raw/ settled/diluted with water)		1-4	Influent; characteristics not available. Raw effluent mixed with water in ratios 1:0, 1:1 and 1:3 was studied. Significant reductions in BOD, TS, TDS, TSS, N,P,K were observed.	There was accumulation of Na, K and N in the plant shoots while there was reduction of Mg and N in the roots	Trivedi R.K. ((1966)
Electroplating (Chemically treatment and diluted 2, 5 times)	Cement tanks 700 1	1-5	TDS 3180 (72%), Cr 0.2 (100%), Cu 5 (60%), Ni 2.3 (22%)		Shrof K.C. (1983)
Electroplating (with pH adjusted from 1.35 to 5.50)	Cement tanks	1-3	Cu 5 (10%), Fe 62 (22%), Ni 70 (10%), Zn 13 (18%)	Plants began to wither after 24 hours.	Yeoh B.G. (1983)
Metal work	Cement tanks 1m X 1m X 0.8 m	16.31 49	Ca 55 (52%), Mg 13 16%, available p 0.25 (40%) total dissolved n 0.4 (32%), total dissolved p 0.5 (56%), particulate nitrogen 0.8 (79%)		Trivedi R.K & Khomane B.v. (1985)

Contd....

Table 10 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)
Engineering industry		1-3	Industrial waste was mixed with semage in rations of 3:7, 1:1, 7:3 (volume/volume)	In general better removal of pollutions occurred in mixture containing industrial waste and sewage in 7:3 ratio.	Trivedi R.K. (1986)
Mercury				Absorption of mercury from mercury solutions and mercury solutions bearing effluents was influenced by initial concentration of the metal and growth rate of the plants	Das H. (1984)
Pesticide	Plastic buckets 10 1	1-4	Sodium pentachiorophenate 53 (64%), 30 (64%), 29 (76%)	Comparable treatment was seen in controls where algae developed; the hyacinth plants tended to wilt	Gucekar V.R., et. at., (1984)
Formic acid (explosive manufacturing)				Formic acid concentration appropriate for treatment with water hyacinth plants tended to wilt.	Vithal Rajan, et.al., (1983)
Phenol	Circular vessels, depth 0.24m, dia 0.6, 62 1	1.5-2	At flow rate 42 1/d; phenol 25 (96%), 75 (89%), 100 (82%), 125 (76%). At flow rate 62 1/d:phenol 25 (93%), 75 (87%)), 100 (78%), 125 (70%)	Nutrients were added to facilitate plant growth. A method was worked out for designing large scale systems.	Vaidyanathan S., et. al., (983)
Nitrogen (NO 3, NH_4)	Plastic pots 7 1	35	Individually;	Absorption of NO_3 in the series of solutions was 93.7%, 85.4%, 67.7% absorption of NH_4-N was 100%, 99-03% and 98.9%.	Widyanto L.S. & Sushilo H. (1978)

Contd....

Table 10 (contd.)

(1)	(2)	(3)	(4)	(5)	(6)
Flouride	Tanks 50 1	30	Flouride 6-26	Authors concluded that efficiency of uptake was too low to be of practical importance	Rao K.V., et. al.,(1983)
Pathogenic bacteria and virus (in diluted Sewage)	Tanks 50 1	Upto 3	E.coli K 13, vibre chloerae 04	Concentration of bacteria was significantly reduced but there was no increase in the virus die-off	Gilman R.H., et. al., (1983)
Heavy metals		Upto 3	Individually; Au 50 Cd/Ni 100 Pb 78-100 pH 6.9/4.6	Uptake was dramatic upto 24 hours; thereafter plants begans to wither and - te uptake dropped. Pb showed least phytotoxicity.	Yeoh B.G. (1983)
Heavy metals	Plastic pots 4 1		Individually and in mixtures; Cd 3, Hg 3, Ni 3 in 12.5 Hoagland solution	Uptake of metals by hyacinth is rapid and is proportional to the concentration present in water. Maximum absorption took place at RT 3d.	Widyanto L.S. & Susilo H. (1978)
Heavy metals	Containers 0.73m X 0.43m X 0.23m		Individual; Pb 1/10 Cd 10 Cu 10 Pb+Cu, Pb+Cd Cu+Cd, Pb+Cu+Cd	Pb was taken up in the highest amounts, followed by Cu and Cd. Uptake decreased with increase in the temperature of the medium	Tatsuyama K. et.al., (1977)
Heavy metals	Containers 2 1	Upto 7	Pb/Cd/Cu 1-160	Pb was absorbed upto 70 mg/g dry root. Stirring of medium increased metal uptake.	Tatsuyama K. et. al., (1979)
Heavy metals	Plastic pots 2 1	Upto 16 at 25	Cd/Pb 1-6, Hg 0.5-2, individually and in mixtures	All metals were well absorbed by roots; the absorption increased exponentially with time	Muramoto S. & Oki Y. (1983)

Contd....

(1)	(2)	(3)	(4)	(5)	(6)
Heavy metals (in presence of aonic surfactants)	Plastic post 2 1	12	Cd/Ni 1-8, Cd 1 plus Ni with or without sodium dodecyl sulphate 25	In general the metal uptake was lesser in presence of the surfactant	Muramoto S. & Oki Y. (1984)
Heavy metals (radionuclides)	Glass beakers 1 1	2	137 Cs; specific activity 10 -1 -10 -3 Ci/ml 90 Sr; specific activity. 1 X 10 -3 Ci/ml	Both radionuclides were significantly absorbed; the bulk in the roots.	Jayaraman A.P. & Prabhakar S. (1982)

@ Duckweed was also explored but was found to have no significant impact to remove phenol, pesticides, bacteria, virues, fluoride and heavy metals (including radio nuclides) from water. The studies conducted in Asia are summarised in Table 10. Most of the studies have been done at the laboratory scale and eventhough in a large number of cases the authors have found that the presence of water hyacinth significantly improved the treatment of wastewaters in tanks/ponds, very few attempts have been made to scale-up the laboratory studies.

Table 11 : Final treatment of natural rubber effluent with water hyacinth.

Property		Raw effluent	Final Discharge		Regularity standards for discharge
			value	% reduction	
pH	mg L-1	6.1	7.2	--	6-9
BOD	"	160	17	89.4	50
COD	"	380	130	65.8	400
Total solids	"	700	195	72.1	--
Suspended solids	"	255	30	88.2	100
Ammoniacal N	"	20	6	70.0	40
Total N	"	30	15	50.0	60

John (1984) conducted laboratory scale and pilot plant trials on the treatment of effluents from palm oil mills (POM). Water hyacinth was propogated on POM effluent and a retention time of 25 days BOD was reduced from 4980 mg $1^{1}/2^{-1}$ to 180 mg 1^{-1}(96.4% reduction) while COD was reduced from 8850 mg 1^{-1} to 1120 mg 1^{-1} (87.3% reduction). Other pollutants were also significantly removed. However the system was not successful when extended to ponds treating liquid wastes in the POM, as the plants were inhibited in their growth and tended to decay (John C.K. 1986). The experience of Yeoh (1983) has been similar: good results were obtained (Table 11) when POM effluent precreated through anaerobic digestion and extended aeration was subjected to advanced treatment in 4000 1 tanks with water hyacinth. When extended to ponds in a POM, the system did not function satisfactorily as the water hyacinth plants tended to wither and die. This was traced to higher (40 times) concentration of ammoniacal nitrogen in the mill effluent compared to the effluent used in pilot treatment plant. The mill was advised to reduce the ammoniacal nitrogen in the effluent by aeration prior to water hyacinth treatment. According to Yeoh (1986), currently several rubber processing factories and POMs in Malaysia are experimenting with the water hyacinth systems for polishing their effluents.

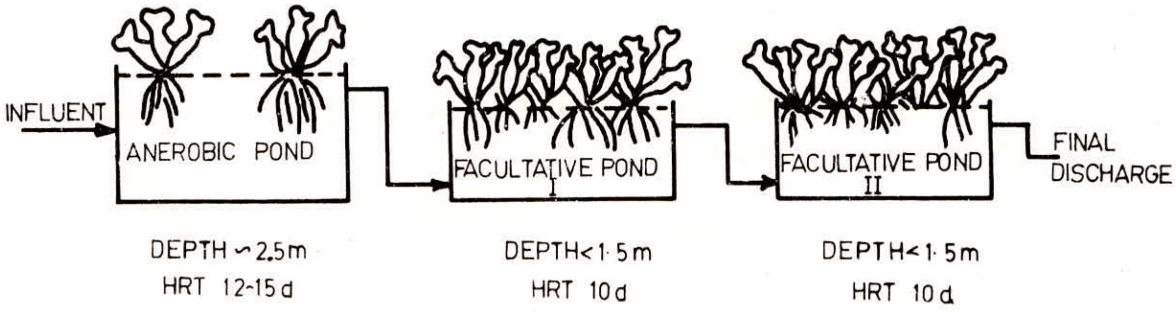

Figure 5 : Treatment of natural rubber factory effluents

John (1986) provided information on the successful extension of his laboratory and pilot plant studies (1984) on the treatment of natural rubber factory effluents. At present some ten factories are using the developed technology. The recommended ponding system consists of one anaerobic pond with a 12-15 day hydraulic retention time (HRT) followed by two facultative ponds, each with HRT 10 days (Figure 5). The water hyacinth grows best in the second pond (i.e first facultative ponds). If the influent BOD is less than 1000 mg 1^{-1} there is good growth of the plant even in the first (anaerobic) pond. However, if the BOD goes above this limit, the growth of the plant in the first pond is inhibited; the rate of inhibition being dependent on the BOD/COD levels of the influent. If the BOD of the influent is above 1500 1^{-1}, there is a near total inhibition in the first pond; however, the plants grow profusely in the second and third (first and second facultative) ponds. The ponds are not basically designed for the popagation of water hyacinth: they are typical lagoons with earthen base and sides. The anaerobic ponds are deeper (2.5 m) than the faculatative ponds, the depth of which is limited to about 1.5 m. Cultivation of water hyacinth is only a secondary feature, which helps in upgrading the stabilisation ponds and enables the effluents to meet the discharge standards. In the ponds water hyacinth doubles its weight every two weeks, and it is recommended to harvest at least 1/3 of the pond every two weeks, followed by 2nd and 3rd portions, taking care to spread out the plants over cacant spaces after each harvest. The yield approximates to 500 kg. (dry matter) $ha^{-1}d^{-1}$. Harvested plants are used as much under rubber or oil palm. The economics have not been worked out but are likely to be favourable as the running cost is limited to the wages of the persons harvesting the water hyacinth plants.

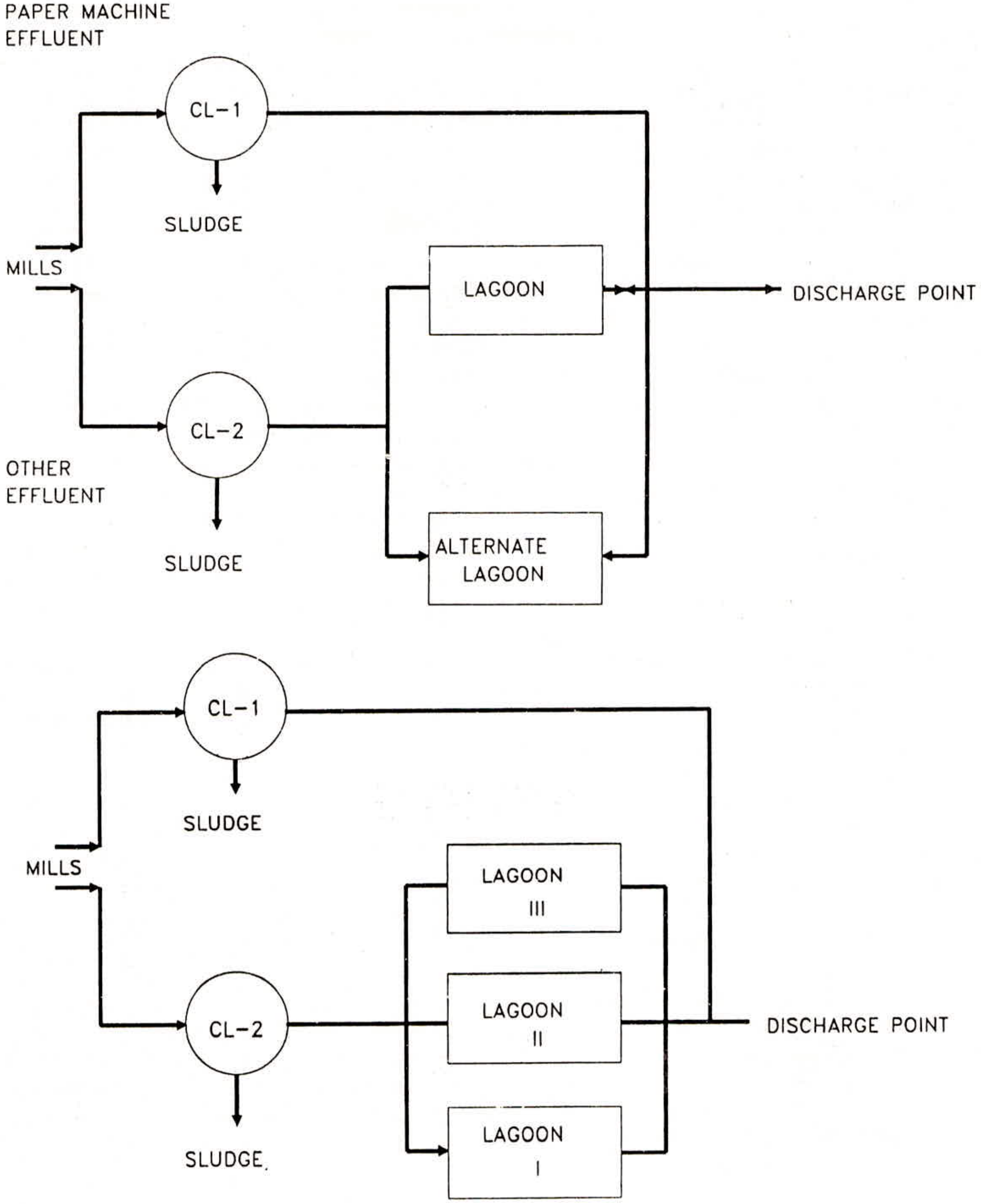

Figure 6a and 6b : Treatment of pulp and paper mill effluents

Behera et al (1982) studied treatment of pulp and paper mill effluents in batch as well as continuous process in experimental lagoons. For combined effluent, at an optimum of 75% water hyacinth coverage and a 15 day retention, the COD (485-655 mg 1^{-1}) was reduced by 80%. For paper machine effluent 90% reduction in COD was achieved in a 6 day retention. Water hyacinth had good growth and survivability in the effluents in the pH range 4-10, and tended to bring the effluent pH to neutral irrespective of the starting pH. The authors proposed two alternatives-continuous process and batch process-for large-scale treatment of the effluents (Figure 6). They estimated that for a wastewater flow of 1 million gallons/day the continous process (Figure 6a) will requre a 5.7 ha lagoon, 1 m deep, with retention time of 15 days. They also proposed an alternate lagoon for use when the first lagoon is to be cleared. For the batch process three lagoons, each 2.3 ha and 1 m deep, were proposed (Figure 6B). The effluent could be filled in the first lagoon over a period of 6 days and subsequently retained for 9 days. The effluent from the seventh to twelveth day could be fed to the second lagoon and retained for 9 days. Similarly effluent from the thirteenth to eighteenth day could be fed to the third lagoon. Thus each lagoon would complete a 15 day cycle. During the remaining 3 days, the effluent in the first lagoon could be discharged and the lagoon cleaned. The same may be repeated for other lagoons in sequence. The paper machine effluent which constitutes roughly 25 % of the total effluent was proposed to be segregated and fed to a clarifier; after settlement of sludge the supernatant could be drained or recycled in the mill. The remaining effluent could be fed to another clarifier and then to the lagoons.

The economics were not worked out but were likely to be favourable. Except for the cost of land no major capital or recurring expenses can be foreseen, and there is always the possibility of gains if water hyacinth harvested from the lagoons could be utilised as a source of biogas or animal feed.

The studies appeared to hold promise but were not carried further. According to one of the authors (24) the main constraint has been the difficulty in acquiring land for the lagoons; the present protracted land acquisition policy, amongst other administrative factors, discourage adopting water hyacinth based systems.

Using Other Macrophytes

Amongst aquatic macrophytes, only African payal (Salvinia molesta Mitchell), apart from water hyacinth, apears to have been used in treatment of industrial wastewaters in Asia. Of the several species of the aquatic fern of the genus Salvinia, the species S. molesta is known to be the most competitive and fast growing. It has colonised large tracts of freshwaters in Sri Lanka, Thailand, and South America. The weed has established itself in Kerala (India) by outcompeting water hyacinth. (Abbasi S.A. et al 1984b).

Abbasi & Nipaney (1981a, 1985, 1986b, 1992) have explored the possibilities of using S. molesta in removing heavy metals and treating effluents from dairies, tanneries, and industries producing rubber, pulp and paper, insecticides and fertilisers. They have simultaneously studied utilisation of this plant in biogas production (Abbasi & Nipaney 1981b, 1985, 1992). In general, S. molesta is comparable with water hyacinth as a wastewater purifier. The water loss due to evapotranspiration by Salvinia is lesser than by water hyacinth.

TREATMENT OF DOMESTIC WASTE WATERS

Using Water Hyacinth

After Sinha & Sinha (1969), reported that water hyacinth increases the rate of removal of BOD, turbidity, coliforms and odour from septic tank effluents, sporadic attempts have been made to utilise water hyacinths in improving treatment capacbility of stabilisation ponds. Pachiyapan (1986) provided information on one such system consisting of two oxidation ponds. 140 m x 21 m, at Phulpur (India) in which water hyacinth was introduced in October, 1979. The initial growth was poor but with the warming of weather, there was vigorous growth and 100% coverage was achieved. The plant helped in reducing the odours and the discharge from the ponds became 'quite clear and free from all suspensions and algal growth'. No quantitative information is available on the level of upgrading achieved by water hyacinth or maintenance of the plant cover.

In recent years efforts have been made to set-up medium scale test facilities to evaluate and control the performance of macrophytes and to obtain basic design information for developing optimal wastewater treatment resource recovery systems. At Sangli (India), Jogledar (1985) and co workers have set up a test facility in which 0.5 million litres day $^{-1}$ of domestic wastewater is treatment in a system of 10 oxidation ponds. The details are given elsewhere in this volume (1986). The system is in the stage of trial and improvement and the economics of the system remains to be worked out.

Oki (1983, 1986) used a pilot plant set up in Okayama prefecture (Japan) designed to treat 20 m^3 day^{-1} of domestic wastewater. Monitoring conducted during April-November 1982 reveal raw wastewater characteristics: BOD 1.81-48.04, COD3.75-49.82, DO O.4-8.4, TOC 4.94-61.75, SS 7.2-97.4, Total N 1.01-12.45, Total-P 0.32-2.98 (all in mg 1^{-1}). On an average the influent BOD was reduced by 70.35% COD by 45.57% SS by 80.29%, TOC by 50.55% Total-N by 60.44% and Total -P by 52.61%. The economics of the system were not evaluated (Oki Y. 1986).

Kira (1986) provided information on a pilot plant in Shiga prefecture (Japan) to evaluate the performance of water hyacinth and water cress in treating domestic wastewater originating from a community of 256 persons. The wastewater is diluted with raw water from a spring and is passed through water cress and water hyacinth channels (Figure 7). Water cress channels have been incorporated in the system to facilitate treatment during the winter when water hyacinth growth slackens or stops. Similar pilot plants are being tested in a number of other districts in Japan, mainly to develop criteria for design and operation of larger scale systems.

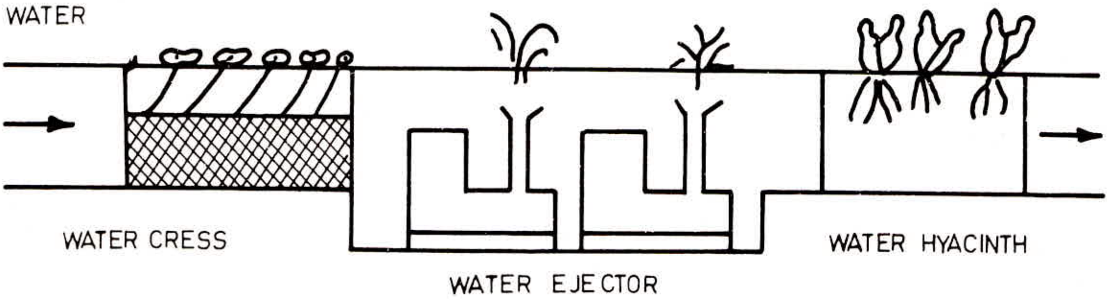

Figure 7 Treatment of Domestic Wastes

An interesting package named 'Bio-Filter System' has recently been offered by Takaneka Komuten Company, Japan (Anonymous, 1986). The system was developed on the basis of a demonstration test plant operated in Doho Pond (3.4 ha) at Tsukuba Science City (Japan). The system consists of four main components, involving culture, recovery processing and reuse of aquatic plants (Figure 8). A section of the Doho Pond is designated as an aquatic plant culture zone. Polluted water is pumped at a flow rate of 300-800 m^3/day through the culture zone via a 'catalytic oxidation pathway'. The matured aquatic plants are vaccum picked into a 'recovery system' in which they are crushed and drained of excess water. The biomass is then dried using a 'solar drying system'. The package includes a 'composting device' and 'pelletisation device'; the solar-dried biomass can be composted and used as manure or 'pelletised and used either as solid fuel or livestock feed. A brochure provided by Degachi (1986) includes conceptuel drawings and some specifications of the various units of the Bio-Filter System package, though no cost estimates are provided. The main distinguishing feature of the system is its reliance on portions of natural ponds or lakes, rather than separate basins, for culturing aquatic plants and purfying wastewater. The system also provides a rather comprehensive package including a cultivation system, a recovery and solar drying system, a composting device and a pelletisation device which should make it relatively easy to adopt.

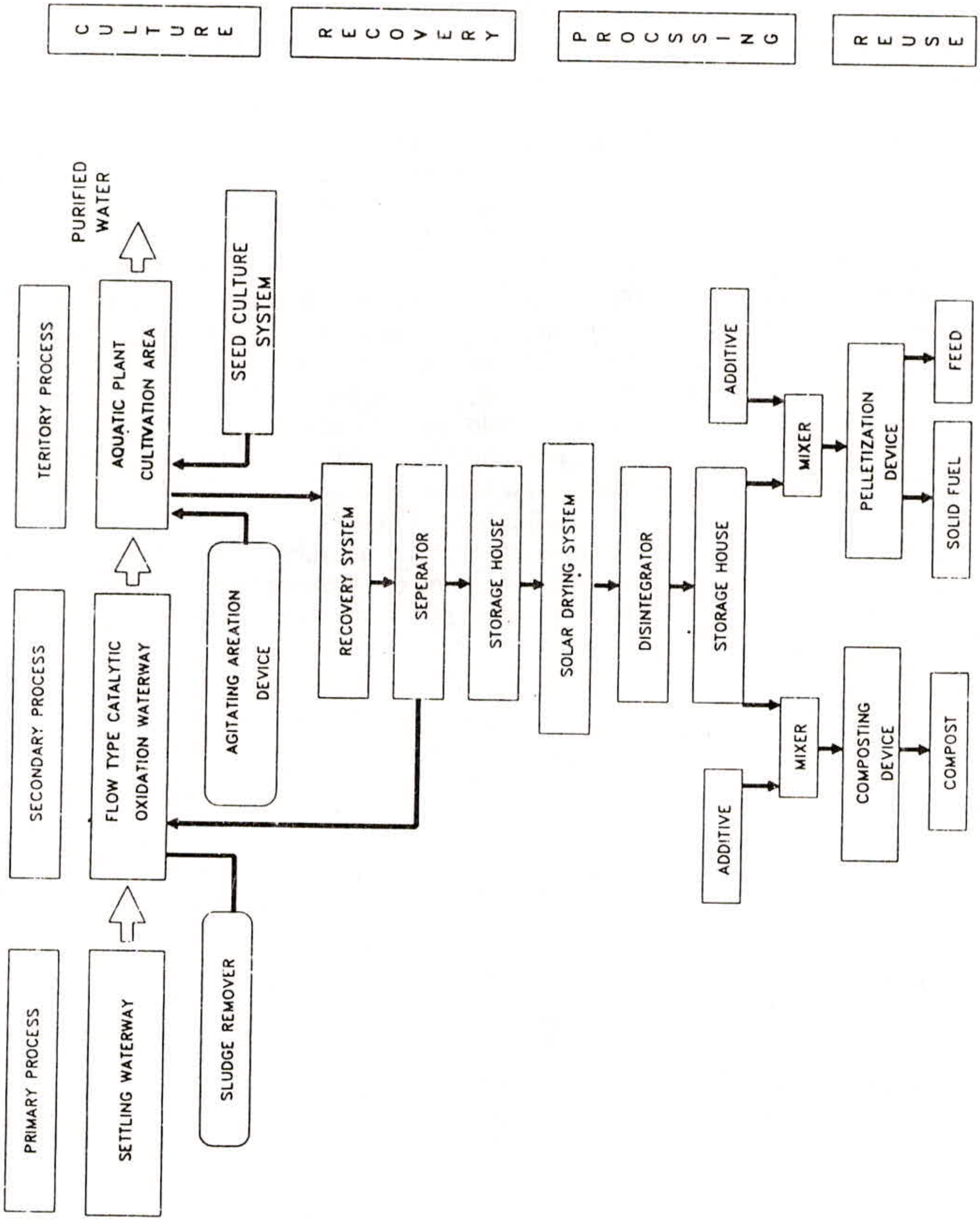

Figure 8 : Bio-filter System

Using other aquatic macrophytes

Duckweed, water cress and African payal (S. molesta) have been explored. Of these, water cress is mainly being evaluated in Japan as a stand by to water hyacinth during winters.

Oron et al (1984, 1986a) screened three duckweed species: Lemna gibba, Wolffia arrhiza and Spirodela polyrrhiza for the treatment of domestic wastewater in miniponds. The main findings include: a) Spirodela and a slightly higher growth rate than Lemna but the latter appeared to be more competitive. Wolffia was unable to maintain itself as pure culture, b) at influent COD levels off 600/300/100 mg 1 ^{1}, nitrogen levels of 600/300/100 mg 1^{-1}, nitrogen levels of 200/50 mg 1^{-1} and detention time of 1/20 days, the removal of COD, uptake of N by the macrophyte, specific growth rate of the macrophyte, and overall N removal were inversely proportional to influent N concentration; c) removal efficiency of major pollutants approached 50-60%; d) duckweed yield was not significanly dependent on COD concentration, and ranged 3-15 g/m^2/day (dry weight) with crude protein content of 30-45%, e) duckweed cover appeared to reduce water losses by 20-30% compared to free-surface waste treatment methods; all in all, the cost of wastewater treatment can be reduced duckweed system by 33-13%. The authors list several advantages of duckweed over water hyacinth, the major ones being higher protein content of the duckweeds and the lesser temperature sensitivity and water loss of the duckweed based system.

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