The Use of Aquatic Macrophytes in Water-Pollution Control

Ecosystems dominated by aquatic macrophytes are among the most productive in the world. Aquatic plants possess an outstanding ability for assimilating nutrients and creating favorable conditions for microbial decomposition of organic matter. This ability can be exploited in the restoration process of natural streams, lakes, and wetlands, and in wastewater-treatment systems. This paper describes different types of macrophyte-based wastewater-treatment facilities, their treatment capacities and their potential applicability under different climatic conditions. Working experiences from Danish facilities are evaluated. The potential for resource recovery by harvesting and utilization of the plant material produced can be regarded as a step in the direction of a holistic solution, where waste products will be regarded and utilized as a resource.

INTRODUCTION

Extensive investments in sewage plants during the last two decades have greatly reduced the organic loading of receiving water bodies in a number of countries. However, an equivalent improvement in water quality has not been achieved since there are many small contributors which still have no cleaning of their wastewater discharge, and since leakage of nitrogen from the agricultural land, as a consequence of the increased use of fertilizers, has greatly increased over the last thirty years (1). Furthermore, only few of the existing wastewater-treatment plants are equipped to remove the nutrients nitrogen and phosphorus. In the early eighties, the local municipalities in Denmark were met with increasing demands for the removal of nitrogen and phosphorus as well as the organic content of the wastewater prior to disposal. The traditional solution for small contributors is to collect the sewage from several small villages in one central-treatment facility. Such a solution is, however, rather expensive, and therefore the municipalities were still searching for more cost-effective solutions.

Shallow, eutrophic, aquatic ecosystems stocked with macrophytes are among the most productive in the world (2). The capacity of such systems to decompose organic matter and assimilate nutrients has long been recognized, and it is well known that streams, lakes, coastal areas, and wetlands contain a considerable "self-purification" capacity (3). During the growing season the plants absorb and incorporate the nutrients into their own structures and function as a substrate for microorganisms.

On an international basis considerable attention is at present being directed to the use of aquatic macrophytes (swamp and water plants) to control pollution, and to treat municipal and industrial wastewater as indicated by the great number of participants at recent international meetings (4–6). This interest is partly coupled to the public demand for increasing stringent water-quality standards, and partly to the need to develop low-cost decentralized constructions capable of serving small to medium-sized communities. Macrophyte-based wastewater-treatment systems have several potential advantages compared to conventional treatment systems (7):

- Lower operating costs
- Lower energy requirements
- They can often be established at sites where the land is marshy
- They are more flexible and less susceptible to shock loading

The potential for resource recovery by harvesting and utilizing the biomass produced as an energy source, as a component or as an animal fodder should also be emphasized (8). The major disadvantages of macrophyte-based systems is the increased land area required, compared to conventional systems, and decreased performance during winter in temperate regions. Macrophyte-based systems are especially suitable for smaller communities with small villages, single farms, pumping sites, summer house areas, and small industries.

WATER-QUALITY IMPROVEMENTS IN NATURAL ECOSYSTEMS

The disposal of large amounts of sewage and the substantial exploitation of agricultural land involving increased amounts of fertilizers, has resulted in pronounced eutrophication of receiving waters. The effects of eutrophication, i.e. water species diversity and decreasing self-purification capacity, have been greatly magnified by destruction of the natural physical-hydrogeology of the ecosystem. Streams have been viewed simply as conduits and have been deepened and straightened, and their vegetation has been removed to augment the drainage of agricultural land. Natural wetlands and marshes have been drained and turned into agricultural land.

Regulations of the main tributary to Lake Balaton (Hungary) has resulted in poor water quality in the lake. The dams enclosing the river have now been removed in an attempt to establish a system of shallow macrophyte-stocked reservoirs as a buffering zone for the river water prior to entering the lake. Photo: P. Brix.
I. Emergent Aquatic Macrophytes

Floating-leaved aquatic macrophytes include both species which are rooted in the substrate, e.g., (d) Ruppia maritima, and species which are free-floating on the water surface, e.g., (g) Eichhornia crassipes and (h) Lemna minor. The floating-leaved species are highly diverse in form and habit, ranging from large plants with rootlets of aerial and or floating leaves and well-developed submerged roots (e.g., Elodea canadensis) to minute surface-floating plants with few or no roots (e.g., Lemna).
The roots and hollow rhizomes of roots (Phragmites australis) penetrate up to 1.5 m into the substrate creating a great volume of active rhizosphere per surface area. Leaching of oxygen from the roots may create oxidized micro-zones in the otherwise reduced substrate, thereby supporting aerobic and anaerobic processes. Photo: H. M. Schierup.

Recently, the value of the biogeochemical diversity and complexity of wetland ecosystems has been recognized, and attempts have been made to restore streams, rivers and wetlands, in order to regain their heterogeneity and thereby their self-purification capacities and buffering effects.

A good example of this recognition is to be found in Hungary. The main tributary to Lake Balaton is the River Zala. In ancient times the water of the river distributed delta-like across 50 km² of wetland before entering the lake. The water velocity was greatly reduced in the wetland, sediments were entrapped by sedimentation, organic matter was decomposed and nutrients taken up by transformed by plants and microorganisms. In general, therefore, the water entering the lake was of good quality. In the recent past, however, the head of the river Zala was regulated and sandwashed by dams in an attempt to drain the wetland for agricultural purposes. The water velocity in the river increased, the physical heterogeneity and biological diversity disappeared, and the self-purification capacity was greatly reduced. The water quality in the river and subsequently in Lake Balaton rapidly deteriorated, and created serious environmental problems in the lake (9). This was particularly noticeable as the lake has a pronounced economic value mainly as a tourist resort and fishing area. Consequently, a system of shallow reservoirs has now been constructed near the mouth of the river Zala in an attempt to regain the buffering zone of macrophyte vegetation as a biological nutrient filter for the river water before it enters Lake Balaton.

WASTEWATER TREATMENT

The capacity of wetlands that are dominated by aquatic macrophytes to assimilate and decompose inputs of nutrients and organic matter has resulted in the extensive use of such systems to treat different types of wastewaters. The pollutants are removed by a complex variety of biological, physical, and chemical processes. The aquatic macrophytes are the most obvious biological component of the systems. However, the uptake of pollutants by the vegetation itself cannot account for the removal efficiency often observed in such systems. Other mechanisms involved are bacterial transformations and physicochemical processes including sedimentation, absorption and precipitation. The macrophytes play an important role by providing surfaces and substrates for bacterial growth, and by altering the physicochemical environment in the water and in the rhizosphere (10).

Aquatic macrophyte-based wastewater treatment systems may be classified into:

1. Floating Macrophyte Treatment Systems.
2. Submerged Macrophyte Treatment Systems.
3. Emergent Macrophyte Treatment Systems - artificial wetlands, natural wetlands.
4. Integrated Macrophyte Treatment Systems (Figure 2).

Treatment of wastewater in ditches planted with rushes (Scirpoidae (eleocharis)) has been practiced for more than two decades in the Netherlands. Photo: H. Brie.
I. Constructed wetland with sub-surface horizontal water flow. Consists typically of a bed planted with Phragmites australis and underlain by an impermeable membrane to prevent seepage. The medium in the bed may be soil or gravel. Treatment processes are a combination of microbial conversion (aerobic and anaerobic) and soil physical-chemical processes. The reed should deliver the majority of the oxygen needed for BOD degradation and nitrification.

II. Constructed wetland with percolation of wastewater. Wastewater is pulse-loaded into the bed and then allowed to percolate to a drainage system in the bottom of the bed. The bed is allowed to dry out in between wastewater applications, so that the pore-space of the medium (soil or sand) is filled with air. Compared to I, flow distance of water is shorter and aeration of substrate better. The bed is sealed from the underground by an impermeable membrane.

III. Wetland with surface-flow of wastewater. May be natural or artificial. Constructed systems consist typically of 3–5 m wide and more than 100 m long surfaces treated with Phragmites australis. The biological wastewater treatment is favored by the presence of submerged portions of plants and litter, which serves as substrate for anaerobic microbial growth. A considerable proportion of wastewater may drain out from the trenches through the bottom.

IV. Free-floating macrophyte treatment system (water hyacinth system). Consists typically of huge low-water lagoons stocked with Eichhornia crassipes. The treatment concept is mainly based on harvesting of produced biomass. Usually the lagoons are not sealed.

V. Submerged macrophyte treatment system. Consists of low-water lagoons planted with submerged macrophytes (e.g. Elodea canadensis). These systems are dependent on light penetration through the water, and therefore mainly used for tertiary wastewater treatment (nutrient removal). Nutrients are removed by harvesting. Usually the lagoons are not sealed.
Floating Macrophyte Treatment Systems

Floating macrophyte systems are a highly variable group of plants, which are not rooted in the substrate. They have aerial and/or floating leaves and may have extensive submerged root systems. The most investigated and promising species of this group are the water hyacinth (Eichhornia crassipes), water lettuce (Pistia stratiotes), and some species of seaweeds (Porphyra spp., Spadella spp.).

The water hyacinth is one of the most prolific and productive plants in the world and in general a severe weed in the tropical and subtropical regions, forming irrigation canals, hindering boat traffic, increasing waterborne diseases, and clogging rivers and canals making drainage impossible (1). The high productivity can, however, be exploited in wastewater treatment facilities. Two different approaches are applied in water hyacinth systems.

(i) Intensive treatment systems (i.e., intensive removal), in which nitrogen and phosphorus are removed by incorporation into water hyacinth biomass. The biomass is harvested frequently to sustain maximum productivity and to remove incorporated nutrients.

(ii) Integrated secondary and tertiary treatment systems (i.e., BOD and nutrient removal), in which decomposition of organic matter and bacterial transformation of nitrogen proceed simultaneously in the water-hyacinth ecosystem (2). Harvesting of water hyacinth is only carried out for maintenance purposes. The performance with respect to phosphorus is poor in these systems.

The harvesting and processing of water hyacinth biomass in tropical areas may be more than 25 g in 2 days of dry matter (14). More than 70% and 0.35 g P m⁻² day⁻¹ can be removed by harvesting (15). Similar amounts of nitrogen must be removed as a consequence of microbial assimilation (nitrification/denitrification) and volatilization of ammonia. Water hyacinth is severely affected by frost, and the growth rate is greatly reduced at temperatures below 10°C. Consequently, in temperate regions, water hyacinth can only be used in greenhouses or outdoors during summer (June to September in the Northern Hemisphere). Pennywort (Hydrocotyle ranunculo-

Artificial wetland planted with reed (Phragmites australis) in Denmark. The working principle is that clarified sewage is led horizontally through the rhizosphere of the reeds, during which the sewage is cleared by microbial degradation and physical/chemical processes in the substrate. Photo: H. Brix.

Floating macrophyte treatment system in Piscatoria (Japan), stocked with water hyacinth (Eichhornia crassipes). The system is part of an experimental integrated treatment system used for purification of polluted study water to produce water of suitable quality. Photo: H. Brix.
Submerged Macrophyte Treatment Systems

Submerged aquatic plants are also able to assimilate nutrients from settling sediments. Submerged plants, however, only grow well in oxygenated water and therefore cannot be used in wastewater with a high concentration of organic and toxic substances in the water. The primary potential use of submerged macrophyte systems is, therefore, for the "polishing" of secondary treated wastewaters. The presence of submerged macrophytes depletes dissolved organic carbon, diverts the water and increases the content of dissolved oxygen during the periods of high photoinhibition. This results in increased pH creating favorable conditions for volatilization of ammonia and chemical precipitation of phosphates. High oxygen concentrations also create favorable conditions for the mineralization of organic carbon in the water. In order to achieve effective nutrient removal, the biomass must be harvested in the amount of nutrients assimilated by the plants, which would otherwise be released to the water supply due to the decay of the dead plant material.

The use of submerged macrophytes for wastewater treatment is still in the experimental stage with species such as Elodea canadensis, Eelgrass (Zostera marina), and a few others. The use of submerged macrophytes is still experimental, and the potential benefits of this treatment system are yet to be fully understood.

Emergent Macrophyte Treatment Systems

Emergent macrophytes have large internal storage spaces for the transport of oxygen to roots and rhizomes. Natural macrophytes may lack from the roots stimulating both decomposition of organic matter and growth of nitrifying bacteria in the rhizosphere (24). Both natural and artificial wetlands have been tested and used as wastewater treatment systems, and it is generally found that both types may act as efficient water purification systems and nutrient sinks (25, 26).

Natural wetlands are characterized by an extremely variable in functional components, making it virtually impossible to predict responses to wastewater application and to translate results from one geographical area to another. Although significant improvement in the quality of the wastewater is generally observed as a result of flow through wetland ecosystems (27), the extent of their treatment capability is largely unknown. The performance may change over time as a consequence of changes in species composition and accumulation of pollutants in the substrate. Therefore, the treatment capacities of natural wetlands are unpredictable, and design criteria for constructed wetlands cannot be extracted directly from results achieved by natural wetlands. Furthermore, the roles of many water pollutants in natural wetlands may not be used deliberately as wastewater treatment systems, but should be preserved for environmental conservation.

Artificial wetlands can be constructed with a much greater degree of control than allowing the establishment of experimental treatment facilities with a well-defined composition of substrate, type of vegetation, flow patterns, etc. The pollutants in such systems are removed through a combination of biological, physical, and chemical processes including assimilation by the plant tissue, microbial transformations, sedimentation, precipitation, and adop-
the hydraulic conductivity of the soil. The quantitative significance of the uptake of nutrients in the plant tissue is negligible as the amount of nutrients taken up during a growing season constitutes only a few percent of the total content introduced with the wastewater. Moreover, the nutrients bound in the plant tissue are recycled in the system upon decay of the plant material.

At present there are approximately 200 macrophyte-based treatment facilities of the Root-Zone Process type in Denmark. Initial experience from the Danish systems shows, that as far as biochemical oxygen demand (BOD) and suspended solids is concerned, the systems are very nearly up to conventional secondary-treatment standards already from the first growing season (Figure 3) (28, 31). Removal efficiencies of nitrogen and phosphorus vary depending on the hydraulic loading rate, but are generally 20-50% (Figure 4). Surface runoff seems to be a general problem in the treatment facilities by preventing the sewage from coming into contact with the rhizosphere. Furthermore, the oxygen transport capacity of the macrophytes seems to be insufficient to ensure aerobic decomposition in the rhizosphere and to deliver the oxygen needed for a quantitatively significant nitrification (32). Nevertheless, the Root-Zone Process and other: artificial wetlands are competitive with the other treatment technologies available for small to medium-sized communities (13). The Root-Zone Process may not, however, necessarily be the best choice for communities under 500 inhabitants. Systems with vertical flow instead of horizontal flow, with several basins laid out in line parallel to each other, containing different species of macrophytes, and with alternating loading, may prove to be more effective in removing nutrients, and will therefore be more flexible from a management point of view. Furthermore, in order to ensure proper reliability and access for maintenance and repair, all systems should be subdivided into several separate parallel cells.

Integrated Macrophyte-Based Treatment Systems

Different types of the above-mentioned macrophyte-based treatment systems may be combined with each other or with conventional treatment technologies. An example could be a multi-stage system consisting of:

(i) A mechanical clarification step for primary treatment.

(ii) A floating or emergent macrophyte-based treatment system for secondary treatment.

(iii) A floating, emergent or submerged macrophyte-based step for tertiary treatment.

The type of secondary- and tertiary-treatment step will, among other factors, be dictated by wastewater quality, the treatment requirements, the climate, and the amount of available land. Such integrated multi-stage systems may prove to be a cost-effective means of treating wastewater. The general opinion of the specialists working in this area is that future construction of macrophyte-based treatment systems should combine the advantages of different process-types. Such integrated systems may include several small units containing different kinds of macrophytes, different substrates, different flow patterns, and with some degree of water recirculation. Further studies to improve the understanding and the capacity of the key cleaning processes are required, however, before the best suit macrophyte-based systems or combination of systems can be selected and applied extensively, at least in temperate regions.

RESEARCH ACTIVITIES

As a consequence of international recognition of the macrophyte-based wastewater-treatment systems, and the need to develop cost-effective, tertiary treatment systems capable of serving smaller contributors, the water authorities and some research institutions in six European countries are conducting an integrative research and development project on Emergent Hydrophyte Treatment Systems (EHTS) (33). The aim of the project is to evaluate the potential for such systems by studying the key cleaning processes under controlled conditions and determining the factors affecting performance, particularly in relation to removal of nitrogen and phosphorus. The research and development work is composed of studies on experimental treatment facilities, studies on full-scale treatment facilities, and laboratory and mesocosm studies. The research will involve studies into the selection of species of macrophyte, type of substrate, flow pattern, geometric design, key cleaning processes, and dimensioning criteria. Some attention will be given to evaluating the functioning and performance under different climatic conditions, in particular the efficiency during cold winters. The project will ultimately lead to the production of a European Design Guide and Operations Manual on the use of Emergent Hydrophyte Treatment Systems.

International exchange of information
and ideas on the use of aquatic macrophytes in water-pollution control is being promoted by a Specialist Study Group on this topic within the International Association on Water Pollution Research and Control (IAPWRC) (33). The main objectives of the study are to encourage co-operation among aquatic biologists working with scientific and technical aspects of using macrophytes for water-pollution control and resource recovery.

The group contributes to the co-ordination of research and development in the field, and it exchanges results of their work in order to prevent unnecessary duplication of efforts and expense.

CONCLUSION AND PERSPECTIVES

On an international basis much effort is currently being put into development of macrophyte-based wastewater-treatment systems. The resource recovery potential in using these systems should further be emphasized. The use of water-hyacinth systems may prove to be a highly cost-effective way of treating wastewater in tropical and subtropical developing countries. In addition, produced water hyacinth biomass may be an important source for energy (e.g. through biogas production), animal feed, and fertilizers used as soil additives. Integrated, macrophyte-based systems may ultimately lead to production of meat by serving herbivorous fish that are grown from the treated wastewater. In temperate regions the use of aquatic macrophytes in water-pollution treatment systems may be of great importance in connection with production of energy crops. The development of macrophyte-based wastewater-treatment systems can ultimately be regarded as a first step in the direction of development of more holistic solutions, where water production will be regarded as a valuable resource which can be utilized for different purposes, instead of being merely products which should be disposed of in the cheapest justifiable way.

Although the philosophy behind the use of aquatic macrophytes in water-pollution control sounds convincing, and although some experience from these constructions is promising, a lot of problems still remain to be solved. The main difference between conventional sewage plants and the "green" solution is the possibility of specific control and regulation of the single biological, and chemical processes in the former. This is only partly possible in the "green" solution where cleaning processes usually are integrated in time and space. Important tasks for the future are:

- To identify the performance in different designs of macrophyte-based systems.
- To select the design best fitted for different cleaning processes (e.g. reduction of BOD, nitrogen, and phosphorus), and to combine these designs in integrated systems.

The use of aquatic macrophyte in water-pollution control is a very promising and intuitively correct approach in the urgent effort towards achieving purification of receiving waters that deserves a period of qualified testing and development.