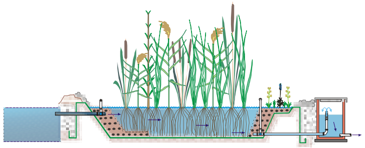

TECHNICAL ARTICLES

PLANTS USED IN CONSTRUCTED WETLANDS AND THEIR FUNCTIONS

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ABSTRACT

Vegetation plays an important role in wastewater treatment wetlands. Plants provide a substrate for microorganisms, which are the most important processors of wastewater contaminants. Plants also provide microorganisms with a source of carbon. Stands of vegetation reduce current velocity, allowing solids to settle out of the water column. Plants assimilate nutrients, but as the plants senesce, some nutrients are released back into the water. A portion of the nutrients is retained in the undecomposed fraction of the plant litter and accumulates in the soils. Plants oxygenate the root zone by release of oxygen from their roots, and provide aerobic microorganisms a habitat within the reduced soil. Plants have additional site-specific values by providing habitat for wildlife and making wastewater treatment systems aesthetically pleasing. Wetland species of all growth forms have been used in treatment wetlands. However, the most commonly used species are robust species of emergent plants, such as the common reed, cattail and bulrush.

KEYWORDS

Aquatic plant; macrophyte; nutrient removal; phytoremediation; propagation; treatment wetland

TRODUINCTION

Wetland ecosystems, including constructed wetlands for wastewater treatment, are vegetated by wetland plants. The ability of wetlands to transform and store organic matter and nutrients has resulted in a widespread use of wetland for wastewater treatment worldwide. Wetland plants are an important component of wetlands, and the plants have several roles in relation to the wastewater treatment processes. The present paper attempts to provide an overview and summarise the role of the wetland plants in constructed wetlands. The paper is largely based on all-ready published papers (Brix, 1993; Tornbjerg et al., 1994; Brix, 1994; Brix, 1997; Vymazal et al., 1998).

PLANTS IN WETLANDS

The larger aquatic plants growing in wetlands are usually called macrophytes. The term includes aquatic vascular plants (angiosperms and ferns), aquatic mosses, and some larger algae that have tissues that are easily visible. Although ferns like *Salvinia* and *Azolla* and large algae like *Cladophora* are widespread in wetlands, it is usually the flowering plants (i.e. angiosperms) that dominate. Macrophytes, like all other photoautotrophic organisms, use the solar energy to assimilate inorganic carbon from the atmosphere to produce organic matter, which subsequently provides the energy source for heterotrophs (animals, bacteria and fungi). As a result of the ample light, water and nutrient supply in wetlands, the primary productivity of ecosystems dominated by wetland plants are among the highest recorded in the world (Westlake, 1963; Brix, 1994; Wetzel, 2001; Cronk and Fennessy, 2001). Associated with this high productivity is usually a high heterotrophic activity, i.e. a high capacity to decompose and transform organic matters and other substances.

The presence or absence of aquatic macrophytes is one of the characteristics used to define wetlands, and as such macrophytes are an indispensable component of these ecosystems. In spite of the fact that the most important removal processes in constructed treatment wetlands are based on physical and microbial processes, the macrophytes possess several functions in relation to the water treatment.

LIFE FORMS OF AQUATIC MACROPHYTES

The macrophytes growing in wetlands may be classified in the following major groups (Fig. 1) according to their life form (Brix and Schierup, 1989; Wetzel, 2001; Cronk and Fennessy, 2001):

(i) *Emergent aquatic macrophytes*: These are the dominating life form in wetlands and marshes, growing within a water table range from 50 cm below the soil surface to a water depth of 150 cm or more. In general they produce aerial stems and leaves and an extensive root and rhizome-system. The plants are morphologically adapted to growing in a water-logged or submersed substrate by virtue of large internal air spaces for transportation of oxygen to roots and rhizomes. This life form comprise species like *Phragmites australis* (Common Reed), *Glyceria* spp. (Mannagrasses), *Eleocharis* spp. (Spikerushes), *Typha* spp. (Cattails), *Scirpus* spp. (Bulrushes), *Iris* spp. (Blue and Yellow Flags) and *Zizania aquatica* (Wild Rice).

(ii) *Floating-leaved aquatic macrophytes*: These includes both species which are rooted in the substrate, e.g. *Nymphaea* spp. and *Nuphar* spp. (Waterlilies), *Potamogeton natans*

(Pondweed), and *Hydrocotyle vulgaris* (Pennyworth), and species which are freely floating on the water surface, e.g. *Eichhornia crassipes* (Water Hyacinth), *Pistia stratiotes* (Water Lettuce) and *Lemna* spp. and *Spirodella* spp. (Duckweed). The freely floating species are highly diverse in form and habit, ranging from large plants with rosettes of aerial and/or floating leaves and well-developed submerged roots (e.g. *Eichhornia*, *Trapa*, *Hydrocharis*), to minute surface-floating plants with few or no roots (e.g. *Lemnaceae*, *Azolla, Salvinia*).

(iii) *Submerged aquatic macrophytes*: These have their photosynthetic tissue entirely submerged but usually the flowers exposed to the atmosphere. Two types of submerged aquatics are usually recognised: the elodeid type (e.g. *Elodea*, *Myriophyllum, Ceratophyllum*), and the isoetid (rosette) type (e.g. *Isoetes*, *Littorella*, *Lobelia*).

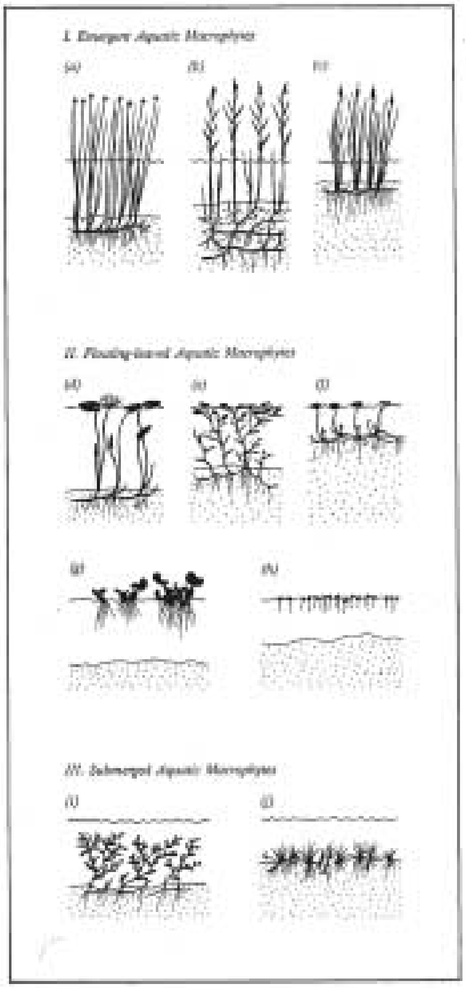

Figure- 1
Sketch showing the dominant life forms of aquatic macrophytes. The species illustrated are (a) *Scirpus lacustris*, (b) *Phragmites australis*, (c) *Typha latifolia*, (d) *Nymphaea alba*, (e) *Potamogeton gramineus*, (f) *Hydrocotyle vulgaris*, (g) *Eichhornia crassipes*, (h) *Lemna minor*, (i) *Potamogeton crispus*, and (j) *Littorella uniflora*. From (Brix and Schierup, 1989)

MACROPHYTES ADAPTATIONS

The primary difference between water-saturated and well-drained soils is the availability of oxygen for root respiration, microbial respiration, and chemical oxidation processes. In well-drained soils, the pore spaces are filled with air with a relatively high content of oxygen, and microorganisms living in the soil and roots of plants growing in the soil therefore are able to obtain oxygen directly from their surroundings. As the soil pore spaces are interconnected to the atmosphere above the soil, the oxygen in the pore spaces is replenished by rapid diffusion and convection from the atmosphere.

In a water-saturated soil, the pore spaces are filled with water. The rate of diffusion of oxygen through a water-saturated soil is some 3×10^6 times slower than through air, principally due to the smaller diffusion coefficient in water but also because of the low solubility of oxygen in water (Drew, 1979). Consequently, water-saturated soils become oxygen-free (anoxic or anaerobic) except for a few millimetres at the surface. Roots and rhizomes of plants growing in water-saturated substrates therefore must obtain oxygen from their aerial organs via transport internally in the plants.

The anaerobic conditions in water-saturated soils also result in release to the soil solution of reduced substances such as Mn^{2+}, Fe^{2+}, H_2S, and organic acids, as a consequence of chemical and biological transformations within the soil (Gambrell et al., 1991). Some of these reduced substances can reach concentrations in the rhizosphere that are toxic to roots. Oxygen leakage from roots of wetland plants is important in relation to detoxification of these reduced substances within the soil solution.

Wetland plants are morphologically adapted to growing in a waterlogged sediment by virtue of large internal air spaces for transportation of oxygen to roots and rhizomes. The extensive internal lacunal system, which normally contains constrictions at intervals to maintain structural integrity and to restrict water invasion into damaged tissues, may occupy up to 60% of the total tissue volume (Studer and Brändle, 1984). The internal oxygen movement down the plant serves not only the respiratory demands of the buried tissues, but it also supplies the rhizosphere with oxygen by leakage from the roots (Armstrong et al., 1991). This oxygen leakage from roots creates oxidised conditions in the otherwise anoxic substrate and stimulates both aerobic decomposition of organic matter and growth of nitrifying bacteria (Fig. 2). The transport of oxygen to the root and rhizomes can be greatly accelerated by internal convective throughflow mechanisms (Armstrong and Armstrong, 1990; Brix et al., 1992; Brix, 1993; Tornbjerg et al., 1994; Allen, 1997).

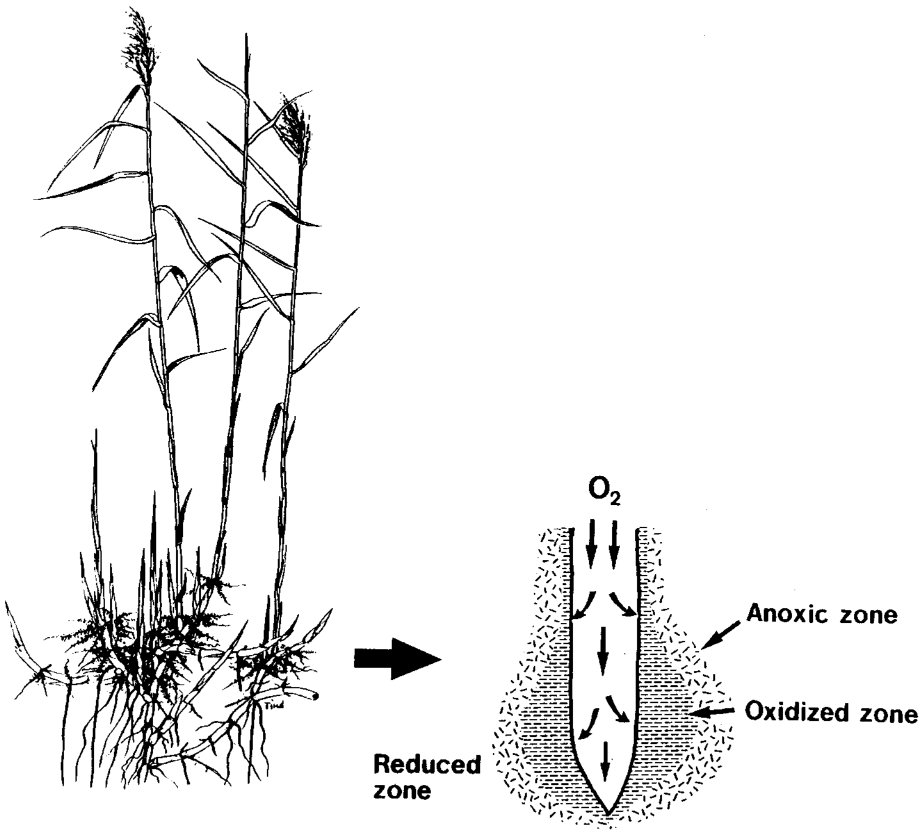

Figure- 2
Sketch of the common reed, *Phragmites australis*. The oxygen leakage from roots creates oxidised conditions in the otherwise anoxic substrate and stimulates both aerobic decomposition of organic matter and growth of nitrifying bacteria.

LE OF ROMACROPHYTES IN TREATMENT WETLANDS

The macrophytes growing in constructed treatment wetlands have several properties in relation to the treatment processes that make them an essential component of the design. The most important effects of the macrophytes in relation to the wastewater treatment processes are the physical effects the plant tissues give rise to (e.g. erosion control, filtration effect, provision of surface area for attached microorganisms). The metabolism of the macrophytes (plant uptake, oxygen release, etc.) affects the treatment processes to different extents depending on design. The macrophytes have other site-specific valuable functions, such as providing a suitable habitat for wildlife, and giving systems an aesthetic appearance. The major roles of macrophytes in constructed treatment wetlands are summarised in Table 1.

Physical effects

The presence of vegetation in wetlands distributes and reduces the current velocities of the water (Pettecrew and Kalff, 1992; Somes et al., 1996). This creates better conditions for sedimentation of suspended solids, reduces the risk of erosion and re-suspension, and increases the contact time between the water and the plant surface areas. The macrophytes are also important for stabilising the soil surface in treatment wetlands, as their dense root systems impede the formation of erosion channels. In vertical flow systems the presence of the macrophytes, together with an intermittent loading regime, helps to prevent clogging of the medium (Bahlo and Wach, 1990). The movements of the plants as a consequence of wind, etc., keep the surface open, and the growth of roots within the filter medium helps to decompose organic matter and prevents clogging (Fig. 3).

Table- 1

Summary of the major roles of macrophytes in constructed treatment wetlands (Brix, 1997)

Macrophyte property	Role in treatment process
Aerial plant tissue	• Light attenuation → reduced growth of phytoplankton • Influence on microclimate → insulation during winter • Reduced wind velocity → reduced risk of resuspension • Aesthetic pleasing appearance of system • Storage of nutrients
Plant tissue in water	• Filtering effect → filter out large debris • Reduce current velocity → increase rate of sedimentation, reduces risk of resuspension • Provide surface area for attached biofilms • Excretion of photosynthetic oxygen → increases aerobic degradation • Uptake of nutrients
Roots and rhizomes in the sediment	• Stabilising the sediment surface → less erosion • Prevents the medium from clogging in vertical flow systems • Release of oxygen increase degradation (and nitrification) • Uptake of nutrients • Release of antibiotics

The vegetation cover in a wetland can be regarded as a thick biofilm located between the atmosphere and the wetland soil or water surface in which significant gradients in different environmental parameters occur. Wind velocities are reduced near the soil or water surface as compared to the velocities above the vegetation, which reduces re-suspension of settled material and thereby improves the removal of suspended solids by sedimentation. A drawback of reduced wind velocities near the water surface is, however, the reduced aeration of the water column.

Light is attenuated, hindering the production of algae in the water below the vegetation cover. This property is used in duckweed-based systems, as algae die and settle out beneath the dense cover of duckweed (Ngo, 1987). Another important effect of the plants is the insulation that the cover provides during winter especially in temperate areas (Smith et al., 1996). When the standing litter is covered by snow it provides a perfect insulation and helps keep the soil free of frost. The litter layer also helps protecting the soil from freezing during winter, but on the other hand, it also keeps the soil cooler during spring (Haslam, 1971a; Haslam, 1971b; Brix, 1994).

Effects on soil hydraulic conductivity

In constructed wetlands with subsurface horizontal water flow, the flow of water in the bed is intended to be largely subsurface through channels created by the living and dead roots and rhizomes as well as through soil pores. As the roots and rhizomes grow they disturb and loosen the soil. Furthermore, when roots and rhizomes die and decay, they may leave behind tubular pores and channels (macropores), which are thought by some to increase and stabilise the hydraulic conductivity of the soil (Kickuth, 1981). The structure of the macropore system is dependent on the plant species and the conditions of growth, and can be very effective in channelling water through a soil bed (Beven and Germann, 1982). Claims have been made that after a period of three years (three full growing seasons) any soil will develop a hydraulic conductivity of 10^{-3} m sec^{-1} and, once developed, the hydraulic conductivity will stabilise and maintain itself (Kickuth, 1981).

Data concerning development of hydraulic conductivity in soil-based constructed reed beds in Austria, Denmark and in the UK have, however, failed to prove this statement (Schierup et al., 1990; Haberl and Perfler, 1990). On the contrary, the hydraulic conductivity often decreases (McIntyre and Riha, 1991; Marsteiner et al., 1996) and usually stabilises in the range of 10^{-5} to 10^{-6} m sec^{-1}. Therefore, hydraulic dimensioning of constructed wetlands with subsurface flow should not be based on the assumption that the hydraulic conductivity will increase as a consequence of root and rhizome growth.

In vertical flow constructed wetlands and sludge mineralization beds, the development and growth of plants are important to counteract clogging (Fig. 3). The root growth and the physical presence of the stems that moves by the action of wind keeps the bed substrate permeable to water.

Figure- 3
In sludge mineralization beds with vertical flow the presence of plants are important to keep the substrate permeable to water.

Surface area for attached microbial growth

The stems and leaves of macrophytes that are submerged in the water column provide a huge surface area for biofilms (Gumbricht, 1993a; Gumbricht, 1993b; Chappell and Goulder, 1994). The plant tissues are colonised by dense communities of photosynthetic algae as well as by bacteria and protozoa. Likewise, the roots and rhizomes that are buried in the wetland soil provide a substrate for attached growth of microorganisms (Hofmann, 1986). Thus, biofilms are present on both the above and below ground tissue of the macrophytes (Fig. 4). These biofilms, as well as the biofilms on all other immersed solid surfaces in the wetland system, including dead macrophyte tissues, are responsible for the majority of the microbial processing that occurs in wetlands.

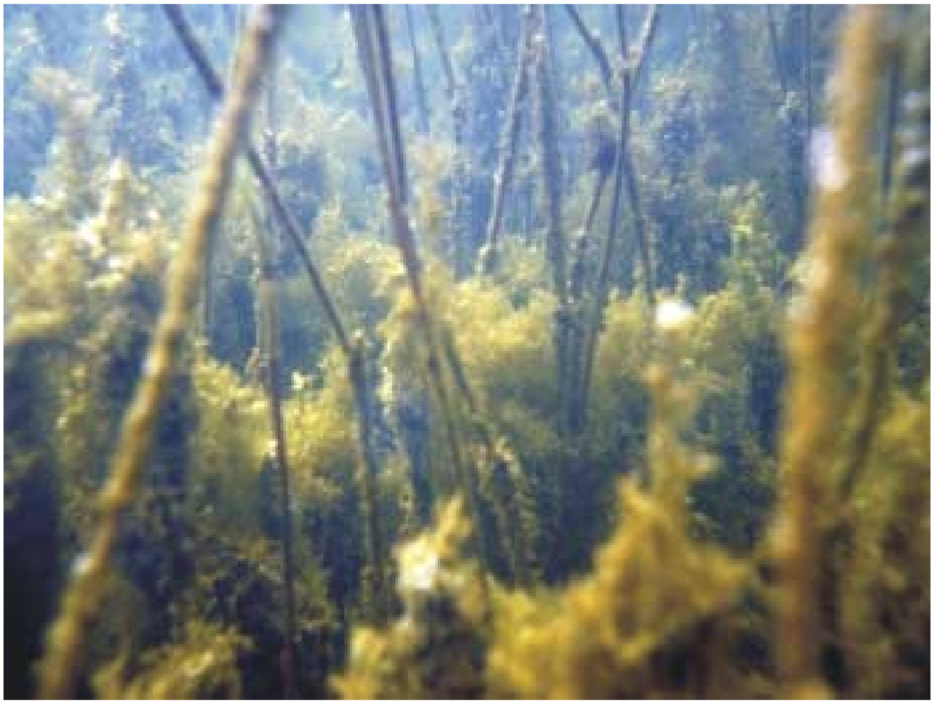

Figure- 4
Biofilm on submerged parts of emergent wetland plants.

Nutrient uptake

Wetland plants require nutrients for growth and reproduction, and the rooted macrophytes take up nutrients primarily through their root systems. Some uptake occurs also through immersed stems and leaves from the surrounding water. As wetland plants are very productive, considerable amounts of nutrients can be bound in the biomass. The uptake capacity of emergent macrophytes, and thus the amount that can be removed if the biomass is harvested, is roughly in the range 30 to 150 kg P ha^{-1} year^{-1} and 200 to 2500 kg N ha^{-1} year^{-1} (Brix and Schierup, 1989; Gumbricht, 1993a; Gumbricht, 1993b; Brix, 1994). The highly productive *Eichhornia crassipes* (Water Hyacinth) has a higher uptake capacity (approx. 350 kg P and 2000 kg N ha^{-1} year^{-1}) whereas the capacity of submerged macrophytes is lower (<100 kg P and 700 kg N ha^{-1} year^{-1}). However, the amounts of nutrients that can be removed by harvesting is generally insignificant compared to the loading into the constructed wetlands with the wastewater (Brix, 1994; Geller, 1997). If the wetlands are not harvested, the vast majority of the nutrients that have been incorporated into the plant tissue will be returned to the water by decomposition processes. Long-term storage of nutrients in the wetland systems results from the undecomposed fraction of the litter produced by the various elements of the biogeochemical cycles as well as deposition of refractory nutrient-containing compounds (Kadlec and Knight, 1996).

Root release

It is well documented that aquatic macrophytes release oxygen from roots into the rhizosphere and that this release influences the biogeochemical cycles in the sediments through the effects on the redox status of the sediments (Barko et al., 1991; Sorrell and Boon, 1992). Qualitatively this is easily visualised by the reddish colour associated with oxidised forms of iron on the surface of the roots and experimentally by submerging a root system into a reduced solution containing methylen blue (Fig. 5). But the quantitative magnitude of the oxygen release under *in situ* conditions remains a matter of controversy (Bedford et al., 1991; Sorrell and Armstrong, 1994).

Oxygen release rates from roots depend on the internal oxygen concentration, the oxygen demand of the surrounding medium and the permeability of the root-walls (Sorrell and Armstrong, 1994). Wetland plants conserve internal oxygen because of suberized and lignified layers in the hypodermis and outer cortex (Armstrong and Armstrong, 1988). These stop radial leakage outward, allowing more oxygen to reach the apical meristem. Thus, wetland plants attempt to minimise their oxygen losses to the rhizosphere. Wetland plants do, however, leak oxygen from their roots. Rates of oxygen leakage are generally highest in the sub-apical region of roots and decrease with distance from the root-apex (Armstrong, 1979). The oxygen leakage at the root-tips serve to oxidise and detoxify potentially harmful reducing substances in the rhizosphere. Species possessing an internal convective throughflow ventilation system have higher internal oxygen concentrations in the rhizomes and roots than species relying exclusively on diffusive transfer of oxygen (Armstrong and Armstrong, 1990), and the convective throughflow of gas significantly increases the root length that can be aerated, compared to the length by diffusion alone (Brix, 1994). Wetland plants with a convective throughflow mechanism therefore have the potential to release more oxygen from their roots compared to species without convective throughflow.

Studies on individual roots have been done using oxygen micro-electrodes to measure radial oxygen losses in oxygen-depleted solutions (Armstrong, 1967; Laan et al., 1989). The oxygen release rates obtained by this technique vary from less than 10 to 160 ng oxygen cm^{-2} root surface min^{-1} depending on species. Oxygen release from fine laterals at the base of roots can be significant, but generally, no release of oxygen from old roots and rhizomes is detected (Armstrong and Armstrong, 1988). The nonhomogeneity of the oxygen release pattern of wetland roots makes it difficult or impossible to extrapolate from results obtained by the oxygen micro-electrode technique to *in situ* release rates. Using different assumptions of root oxygen release rates, root dimensions, numbers, permeability, etc., Lawson calculated a possible oxygen flux from roots of *Phragmites* up to 4.3 g m^{-2} day^{-1} (Lawson, 1985) . Others, using different techniques, have estimated root oxygen release rates from *Phragmites* to be 0.02 g m^{-2} day^{-1} (Brix and Schierup, 1990; Brix, 1990), 1-2 g m^{-2} day^{-1} (Gries et al., 1990), and 5-12 g m^{-2} day^{-1} (Armstrong and Armstrong, 1990). Root oxygen release rates from a number of submerged aquatic plants are reported to be in the range of 0.5 to 5.2 g m^{-2} day^{-1} (Sand-Jensen et al., 1982; Kemp and Murray, 1986; Caffrey and Kemp, 1991) and from free-floating plants 0.25-9.6 g m^{-2} day^{-1} (Moorhead and Reddy, 1988; Perdomo et al., 1996). The wide range in these values is caused by species specific differences, by the seasonal variation in oxygen release rates, and by the different experimental techniques used in the studies. Recently, the importance of providing an external oxygen sink during experiments attempting to quantify the oxygen release from entire root systems has been demonstrated (Sorrell and Armstrong, 1994). The study concludes that oxygen release rates reported in earlier studies may have been underestimated.

Figure- 5
Root release of oxygen by *Phragmites australis*. The blue colour around the roots is formed by radical oxygen release from the roots oxidising the reduced form of methylen blue.

Root systems also release other substances besides oxygen. In some early studies Dr. Seidel from the Max-Planck Institute in Germany showed that the bulrush *Schoenoplectus* released antibiotics from its roots ((Seidel, 1964; Seidel, 1966). A range of bacteria (coliforms, salmonella and enterococci) obviously disappeared from polluted water by passing through a vegetation of bulrushes. It is also well known that a range of submerged macrophytes releases compounds that affect the growth of other species. However, the role of this attribute in treatment wetlands has not as yet been experimentally verified. Plants also release a wide range of organic compounds by the roots (Rovira, 1965; Rovira, 1969; Barber and Martin, 1976). The magnitude of this release is still unclear, but reported values are generally in the range of 5-25% of the photosynthetically fixed carbon. This organic carbon exuded by the roots may act as a carbon source for denitrifiers and thus increase nitrate removal in some types of treatment wetlands (Platzer, 1996).

Table- 2

Relative importance of the macrophytes in different designs of constructed wetlands (from Brix 1994). Number of +'s increase with increasing importance of the process. "-" designate no importance.

	Surface Flow	Subsurface Flow	Vertical Flow	Combined Systems
Area use	>20 m^2/PE	~10 m^2/PE	~5 m^2/PE	2-5 m^2/PE
Stabilise bed surface	+++++	+++++	+++	+++
Prevent clogging	-	-	+++++	+++++
Reduce current velocity	+++	-	-	-
Attenuate light	+++++	++	+	+++
Insulation	+++	+++	+++	+++
Attached microbes	+++++	+++	+	+
Uptake of nutrients	+++++	+	-	+
Oxygen transfer	+	++	+	+
Habitat for wildlife	+++++	+++	+	+
Aesthetics	+++++	+++++	+++	+++++

Other roles

The relative roles of macrophytes in different designs of constructed wetlands are summarised in table 2. The macrophytes in constructed treatment wetlands may have functions that are not directly related to the water treatment processes. In large systems, the wetland vegetation may support a diverse wildlife, including birds, reptiles, etc. (Worrall et al., 1996; Kadlec and Knight, 1996; Knight, 1997). This may be of importance, as natural wetlands and thereby the wetland habitat has been destroyed at a high rate in many places. Another point that is perhaps most important in small systems serving single houses, hotels, etc., is the aesthetic value of the macrophytes. It is possible to select nice-looking wetland plants *Iris pseudacorus* (Yellow Flag) or *Canna* spp. (Canna Lilies), and in this way make the sewage treatment system have a nice appearance (Fig. 6).

Figure- 6
Constructed wetland system for a single household. The system is planted with canna lilies.

ESTABLISHMENT OF THE COMMON REED

As *Phragmites australis* (the Common Reed) is the most commonly used macrophyte in the European constructed wetlands, this species will be dealt with here. However, similar techniques and similar precautions must generally be taken when propagating other wetland species. The information given here are based on experimental work performed in the UK (Cooper et al., 1996), information from the literature (Haslam, 1971a; Haslam, 1971b; Rodewald-Rudescu, 1974; Véber, 1978; Weisner and Ekstam, 1993) and experience obtained from constructors in Denmark and other European countries.

There are four distinct kinds of material which can be used to establish the desired vegetation of *Phragmites* in a constructed wetland:

(i) *Transplanted rhizomes*. These may be relatively small sections of vertical or horizontal rhizome, or larger clumps of material. In both cases, the material is carefully planted in the bed in a regular pattern. Alternatively, large quantities of soil containing rhizomes may be roughly distributed over the whole bed (the 'rhizome soil' technique).
(ii) *Stem cuttings*. These may be used to produce rooted plantlets in glasshouses for transplanting out, or cuttings may be planted directly into the beds. A variation of this method is the layering of growing stems to produce rooted plants at the points where stem nodes contact the ground.

(iii) *Seedlings*. Cultivated in glasshouses from seed and later transplanted.

(iv) *Seed*. Sown directly onto the soil.

Much of this section discusses methods of collecting or propagating these four kinds of material. However, propagation cannot be considered in isolation from problems of growth and establishment in reed beds. Hence, this section also deals with the factors which may affect establishment (e.g. soil type, water levels, weed control, nutrient levels, planting methods, date of planting).

Seed production in natural reed stands

The seed production in reed stands varies considerably among sites (or clones). Some clones produce no seed, and the seed production in other clones may vary from <100 to >1000 seeds per flower (Haslam, 1973). The reason for this is unknown, but abnormal pollen formation, injury to seed and panicles by insects and fungi, and unfavourable weather conditions during the flowering and ripening, are all possible factors. The reed stand may be infected with ergots, sausage shaped growths of fungus (*Claviceps* sp.), which develop in the place of seeds and, in some reed stands, may be responsible for low seed yields. Seed production seems not to be correlated with soil type, stand density or the height of the shoots. There is, however, more seeds in larger seed heads. Seeds for seedling propagation can be collected from late October till March or even later. However, the seeds are gradually shed during the winter, so the best time is probably late November. Seed can easily be stored at a dry and cold place for several years with little loss of viability.

Figure- 7
Propagation of seedlings of *Phragmites australis* in pots to be used in constructed wetlands

Germination of seeds from *Phragmites*

The percentage germination of seeds may vary from 2-96% among panicles from a small plot of reeds (Haslam, 1973). Fresh seeds may need to be chilled and stored at 5°C for several months to enhance germination. Seeds germinate successfully on damp soil or moist filter paper under controlled laboratory conditions, with a day night temperature regime of 30°C/20°C (Haslam, 1973; Cooper et al., 1996). A high and fluctuating temperature is apparently preferred and this can occur in the top soil in spring. Under these conditions seeds will germinate after 5 or 6 days, and germination will usually be completed within 7 to 9 days. The final percentage of seed germination ranges between 30 and 100%. Under a light regime of 16 hours light to 8 hours dark germination is highest when a day temperature of 25 to 30°C is combined with a fall in the night temperature of at least 10°C. Light is not necessary to ensure germination. Under constant darkness, fluctuating temperatures are sufficient to stimulate germination. Seeds should not be buried below the soil surface as the young seedlings are so small that they may not be able to break the surface. For best germination the seeds should be on a moist surface, but not flooded, as they do not germinate under 5 and 15 cm of water (Haslam, 1973).

Establishment from rhizome

Horizontal and vertical rhizomes with at least one shoot or bud can be planted directly in the reed bed. The success of this technique depends on the developmental stage of the shoots and on the degree of damage to them during sampling and planting (Véber, 1978). Experience show that the survival of planted rhizomes are roughly 50% and seems to be greater at low water levels (5 cm below the soil surface) compared to high water levels (5 cm above the soil surface). Splitting rhizomes into smaller fragments will decrease survival. Rhizomes fail to grow under completely flooded conditions because of inadequate oxygen supply, despite the fact that the water may be saturated with oxygen. For the same reason, in flooded soils it is vital not to break or damage the rhizomes in order to maintain the aerial connection between the atmosphere and the developing buds. Rhizomes have to be planted obliquely, with some part aboveground and above the water level.

The shoots from transplanted rhizomes are taller and wider than those from other materials (seed, seedlings and cuttings). This is because the width of the original bud determines the potential shoot height (Haslam, 1972). Above ground, *Phragmites* shows little tendency to spread into bare areas during the first summer, despite substantial rhizome growth below ground. This is because buds forming after the emergence period in spring, accumulate near the soil surface until emergence begins in the following spring. Hence the cover of shoots during the first year is largely dependent on the initial planting density. For this reason planting clumps at a density of 1 m^{-2} gives a less uniform cover of shoots, than planting the same material as four or five separate pieces of rhizomes. In neither case will the cover of shoots or rhizomes be as uniform as that obtained from the same density of seedlings, which spread during the first year.

In general, clumps of rhizomes have very high survival rates (close to 100%) in all types of soils. Large clumps (20 cm by 20 cm clumps) transplanted in spring will almost certainly establish successfully. The rhizomes and shoots within the clumps suffer little disturbance and grow almost as well as those in the original stand. However, the lack of a suitable supply of *Phragmites* and the high cost of excavating and transplanting clumps, make this method practical only in small beds. Furthermore, a fairly high density of clumps (2-4 m^{-2}) is necessary to get a good cover of plants in the first year. In gravel-based systems, the plants may suffer from lack of nutrients, especially nitrogen. Initial reed growth in such systems can be increased by supplying a nitrogen fertiliser.

However, in general there should be no need to fertilise, as the waste water usually supplies adequate nutrients. Shoot production from rhizomes transplanted in May and June, after shoots have begun to grow, is greatest if the shoots are left intact.

Rhizome soil can also be used to establish a vegetation of reeds. To improve the change of success, after spreading onto the surface of the reed bed, the rhizome soil must be kept continually moist without allowing the water level to cover the rhizomes. Irrigation may be necessary to prevent the rhizomes from becoming desiccated.

Establishment from cuttings

Stem cuttings can be successfully planted directly into a water-saturated bed under field conditions in mid-May at a survival rate of approximately 35%. This avoids the expense of glasshouse propagation and minimises the disturbance due to transplanting growing plants. Stem cuttings need to be at least two nodes long, but should not include the immature nodes at the base of the stem. Trimming of the upper leafy part of the stem will increase the percentage success. Later in the season, the percentage will be less. Thus stem cuttings can only be taken during a short part of the year (May and June). Where an alternative source of *Phragmites* is unavailable (e.g. seedlings or rhizomes), direct planting of stem cuttings may be a relatively cheap option with a good chance of success, provided that the soil is kept saturated and a sufficiently high planting density (10-15 plants m^{-2}) is used to allow for the failure of more than 50% of the cuttings. Although it should be possible to obtain sufficient quantities of cut stems to do this, the labour involved in planting and the need to plant the stems almost immediately after cutting, makes the method impractical on a large scale

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The use of cuttings in glasshouses to produce potted plants for later transplantation is best done by using cuttings from the upper part of the stem containing at least 3 nodes. Hormone rooting powder has no effect on the establishment. The quality of potted plants produced from cuttings is very variable. The rate of growth of plants rooted from cuttings is generally poor. Only few of the plants produce rhizomes during the first growing season which is necessary in order to survive through to the next spring. Furthermore, the use of stem cuttings is far less convenient, less guaranteed of success and likely to be more expensive in comparison with producing plants from seeds

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Layering of stems by bending them over to make contact with the soil can be used to create new *Phragmites* plants. One method is to bend over the thickest stems and cover them with soil, leaving the apical leaf bearing parts exposed. The layered shoots become rooted within three to four weeks and new tillers begin to sprout after another two to three weeks (Véber, 1978). New separate *Phragmites* plants are then obtained by cutting off the layered shoots. Because the stems remain attached to the parent plant, the chance of nodes successfully producing rooted plants are high. However, the technique requires the use of established plants and is likely to be expensive and make poor use of space compared to either seedling or cuttings. Furthermore, the rooted plants will not have produced rhizomes by the autumn (Véber, 1978).

Establishment from seedlings

Germination and survival of *Phragmites* seedlings in natural habitats is poor (Haslam, 1971b; Haslam, 1973). Even if the seed germinates successfully, the young seedlings are vulnerable to weed competition, lack of light, low nutrient, frost, drought and flooding. However, under glasshouse conditions all these factors can be controlled and seedling mortality is negligible. Seedlings can be produced by germination in a glasshouse during winter, by scattering pieces of fertile flower heads onto the surface of moist seedling compost and pressing the material into firm contact with the soil. Under conditions with day temperatures of 25-30°C and night temperatures of down to 10°C the germination will be initiated within a week. Because of the small size of *Phragmites* seeds the young seedlings are very small and have very low absolute growth rates. Seedlings doubles their shoot weight every 5 to 6 days, but despite this, it will take about two months before the seedlings have reached a height of 20 cm (Haslam, 1971b). Seedlings should be transplanted into individual 5-cm pots after 40-50 days, when they are approximately 10 cm high. After about three months, by which time the seedlings have produced some rhizome growth, they can be transferred to 7-cm plastic pots for further propagation.

Seedlings planted in May generally show a 100% survival by September. After 5 months of growth a seedling may produce a belowground root and rhizome biomass of 40-50 g, and a total rhizome length per plant of several meters, which is better that the yield from transplanted rhizome sections. The yield of shoots and roots is highest at a water level 5 cm above the bed surface. Seedlings can be transplanted as late as July without any significant effect on the final yield. Planting in August will lead to a lower final yield. Although young seedlings cannot survive complete flooding (Weisner and Ekstam, 1993), once they have reached a height of 20 cm they will grow best when the water table is 5 cm above ground level.

There are two additional advantages of seedling over rhizome transplants. First, there is no seedling mortality and all seedlings produce some rhizomes during the first growing season, and secondly seedlings spread more quickly. Frost may kill plants too small to have horizontal rhizomes (Haslam, 1971b; Haslam, 1973). Young plants with 10 shoots are large enough to have rhizomes and to overwinter successfully. Even seedlings produced from seeds sown in May are large enough to have rhizomes. In contrast, rhizome production from transplanted old rhizomes is very variable, and in some cases no rhizomes are produced. In addition to greater rhizome growth, seedlings have a greater tendency to spread during the first year and consequently a more even cover of shoots will occur in a bed planted with the same number of seedlings as rhizomes. Seedlings are much easier to handle and plant that are rhizomes. Furthermore, a collection of *Phragmites* seedlings will have a much greater genetic variation than rhizomes collected from a single stand. In the long term, this may have an advantages as the best adapted genotypes will eventually dominate. Presently, the use of potted seedlings are the most commonly used technique in northern Europe. A density of 4 plants m^{-2} is generally used (Fig. 8).

Figure- 8
Planting of potted seedlings in a sludge mineralization bed.

Direct seeding as a method of establishment

In theory there is no reason why *Phragmites* beds should not be established directly from seeds. Indeed, for very large areas it may be the only practical method. Establishment from seeds should be almost as rapid as from seedlings or rhizomes. The seeds may be left in the panicles because they germinate just as well there. Seeds can germinate under field conditions in mid May and by autumn the seedlings may have produced up to 140 cm of rhizome each. In practice, establishment from seeds is likely to be difficult unless the preparation of the site and its subsequent management is stringently controlled. The soil bed must be kept moist, and if possible covered with a clear plastic sheet to enhance germination and early seedling growth rate. A good supply of water and nutrients must be available throughout establishment because seedlings are sensitive to drought and lack of nutrients. But they are also vulnerable to flooding, frost, high salt concentrations, shade and inadequate soil aeration (Haslam, 1971b; Haslam, 1973; Weisner et al., 1993; Weisner and Ekstam, 1993; Cooper et al., 1996). However, the most stringent requirement is that the bed should be kept completely weed free for the first four to six weeks. Young seedlings of *Phragmites* are very small and therefore vulnerable to competition, particularly under dry soil conditions (Haslam, 1971b). On gravel substrates weeds should not be a problem, but the bed must be covered with a thin layer of peat (weed free) to provide a suitable medium for seed germination. On top-soils a covering of sterile sand or peat may be sufficient to suppress the germination and growth of weeds for long enough to enable the *Phragmites* seedlings to establish. In the longer term, weeds can be controlled by flooding. Although young seedlings of *Phragmites* cannot survive prolonged flooding, tolerance increases in the older seedlings. Hence, once the plants have reached a height of 10-20 cm, weed germination and growth can be inhibited by flooding the bed to a height of 5 cm.

Subsequent management

Whatever kind of material is used to plant a constructed wetland, the subsequent management will be crucial if establishment is to be successful.

Control of water level: As previously explained, young rhizomes or seedlings may not be too deeply flooded (Weisner et al., 1993). However, if the soil is allowed to dry this will inhibit growth, increase weed competition and may lead to plant mortality. Provided the roots and rhizomes of the plants are aerated through standing aerial stems, shallow flooding is beneficial for bud development and, providing insulation, may allow shoot emergence earlier than in unflooded beds.

Addition of nutrients: The productivity of natural stands of *Phragmites* is often related to the fertility of the soil in which they grow. It follows that in order to establish quickly, Phragmites needs a good supply of nutrients in their growing medium. Seedlings are particularly sensitive to low nitrogen levels. Nutrient levels in most top-soils should initially be sufficient for reed growth, but if no nutrients are added to the bed (either as fertiliser or effluent) then growth may be reduced later in the season. In gravel media, nutrient supplies may be severely limited and unless they are added continually throughout the growing season, plant growth might be reduced. If effluent is not fed to the beds, the *Phragmites* should be fertilised during establishment with a commercial NPK fertiliser.

Weed control: During the early years of establishment of *Phragmites* beds, weeds may make excessive growth, particularly on soil based beds. The most prevalent species are common weeds of agriculture including broadleaf species such as *Rumex* spp. and *Polygonum persicaria*, and grasses such as *Holcus lanatus* and *Poa* spp. Provided the beds are kept sufficiently wet, in the long term *Phragmites* will out-compete all these agricultural weeds. In natural *Phragmites* stands, pure *Phragmites* monoculture only occurs in areas which are flooded for at least two months of the year (Haslam, 1972). In drier habitats and in the inner part of littoral *Phragmites* stands other species are not excluded. Weeds decrease the rate of establishment of *Phragmites* as well as the short-term growth. Studies from the Czech Republic have shown that sparsely planted beds (rhizomes spaced 5 to 10 m apart in rows 5 m apart) will be covered in 3-4 years, compared to 4-6 years in slightly weed infested beds (Véber, 1978). If water and nutrients are limiting, competitive interference from weeds will be more severe and may lead to an early failure of establishment. The extent to which weed species inhibit the treatment processes is largely unknown. Experience from Danish soil-based systems shows no effects on performance (Brix, 1998). However, the weeds spoil the appearance of reed beds, and this may be particularly important in pilot schemes where a good visual impression needs to be made. The most effective method of weed control is flooding. However, *Phragmites* does not tolerate excessive depths of water, particularly during early establishment (Weisner et al., 1993). It is therefore essential that beds are flat or nearly flat, so that flooding with 30 cm of water will flood the entire bed. Where gravel is used as a medium, weeds are generally not a problem during the time in which the bed is becoming established. However, the seeds used at the banks of the beds may be washed onto the gravel, resulting in considerable growth of grasses.

Grazing by Mammals: In spring, young shoots of *Phragmites* are a favoured food of deer and rabbits. Although the *Phragmites* will recover from severe defoliation, continual grazing will result in poor establishment. Therefore, particularly in rural areas where a grazing problem is anticipated, it is necessary to fence off the reed bed.

Figure- 9
Insulation of distribution system with woodchips in a vertical flow constructed wetland.

Frost damage: Frost may kill many shoots in natural *Phragmites* stands. Although unemerged buds are only infrequently killed, growing shoots become increasingly sensitive through the year and it is possible for light frosts to kill growing shoots in May and June. Frost tends to kill the earlier, larger buds and shoots, and these are replaced by more numerous smaller shoots (Haslam, 1971b). The net result of frost is to produce a denser stand. Although the losses due to frosts are easily replaced in mature beds, the consequences during establishment of constructed reed beds may be more severe. Frost kills plants too small to have horizontal rhizomes and therefore seedlings planted out too early may be completely destroyed. However, experiences have shown that seedlings planted out in early May survived the frosts during that month. In order to avoid losses of plant material due to frosts, transplanting of rhizomes or seedlings should not begin until May or early June. In vertical flow constructed wetlands, it is advisable to insulate the distribution system against frost (Fig. 9).

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