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TREATMENT OF WASTEWATER IN THE RHIZOSPHERE OF WETLAND PLANTS — THE ROOT-ZONE METHOD

Hans Brix

Botanical Institute, University of Århus, Nordlandsvej 68, DK-8240 Risskov, Denmark

ABSTRACT

The present paper describes the theoretical basis of wastewater treatment in the rhizosphere of wetland plants, the so-called "root-zone method", along with the first working experiences from eight treatment plants in Denmark.

Mechanically treated wastewater is led horizontally through the rhizosphere of wetland plants. During the passage of the wastewater through the rhizosphere, the wastewater is cleaned by microbiological degradation and by physical/chemical processes. The wetland plants supply oxygen to the heterotrophic microorganisms in the rhizosphere and stabilize the hydraulic conductivity of the soil. Nitrogen is removed by denitrification and phosphorus and heavy metals are bound in the soil.

The first working experiences from Denmark show, that as far as BOD is concerned root-zone treatment plants are very nearly up to conventional secondary treatment standards already from the first growing season (removal efficiency: 51-95%). For the nutrients nitrogen and phosphorus the results vary (total-N removal: 10-88%; total-P removal: 11-94%). The removal efficiencies depended mainly on the composition of the soils and the degree of surface runoff in each treatment plant.

It is concluded that root-zone treatment plants seem to be a viable alternative to conventional wastewater treatment technology, especially suitable for single households and small to medium sized communities. There is, however, still very little information on the removal processes for nitrogen (denitrification), on the effect of soil type and on the required surface area to load ratio.

KEYWORDS

Wastewater treatment; the root-zone method; wetlands; macrophytes; rhizosphere; *Phragmites australis*; biochemical oxygen demand; nitrogen; phosphorus.

INTRODUCTION

In recent years increasing production and disposal of wastewater have caused an accelerated eutrophication of receiving waters. Therefore, in order to alleviate the detrimental impact of wastewater discharge, there is an increasing demand for removing the main nutrients, nitrogen and phosphorus, as well as the organic content of the wastewater prior to disposal. This is effec-

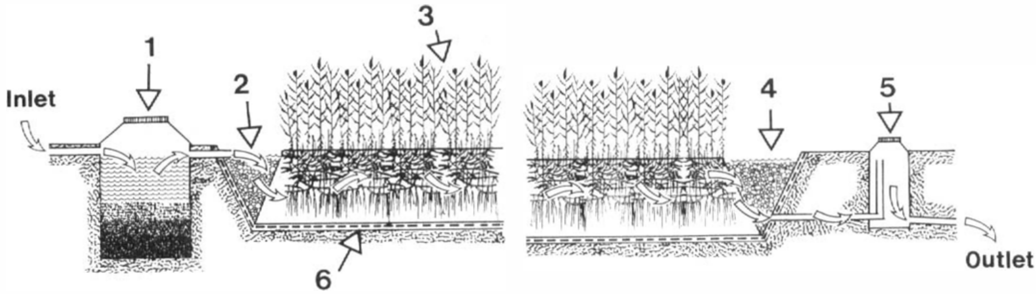

Fig. 1. Schematic representation of a root-zone treatment plant. 1: Sedimentation tank;, 2: Inlet channel; 3: Wetland plants; 4: Outlet channel; 5: Outlet weel with vertical tube for control of water level in outlet channel; 6: Watertight membrane.

tively achieved by extended conventional treatment technology. However, the working expenses and energy requirements of such advanced treatment systems are rather high. Furthermore, in sparsely populated areas the wastewater must be pumped over long distances to centralised treatment facilities. So, in many cases economic constraints will hinder an effective purification of wastewater.

Recently, considerable attention has been directed towards the capacity of natural or artificial wetlands to treat municipal and industrial wastewater (e.g. Fetter et al., 1976; Wattenhofer, 1980; Finlayson and Mitchell, 1982; Radoux, 1982; Wolverton, 1982; Bowner, 1985). Several investigations have shown that wetlands may act as efficient water purification systems and nutrient sinks (e.g. Tilton and Kadlec, 1979; Dolan et al., 1981; Nichols, 1983). In addition, such macrophyte based systems have certain advantages compared to conventional treatment systems:

- low working expenses
- low energy requirements
- low maintenance requirements
- they can be established at the very location where the wastewater is produced
- being a "low-technology" system, they can be established and run by relatively untrained personnel.

Therefore the disposal of wastewater into wetland based systems may be a viable alternative to conventional wastewater treatment technology, especially suitable for small to medium sized communities, in sparsely populated areas and in developing countries.

This paper describes a relatively new method of wastewater treatment based on wetland plants, the socalled "root-zone method" (German: Wurzelraumentsorgung). The concept of the method was developed a decade ago in West-Germany (Kickuth, 1977). In 1983 the first root-zone treatment plants were established in Denmark. Since then this type of wastewater treatment system has propagated rapidly, and at present (October 1985) there are approximately 30 root-zone treatment plants in Denmark ranging in sizes from 5 to 6000 p.e. (person equivalents). This paper describes the functioning of root-zone treatment plants, the major cleaning processes, and the first working experiences from the treatment plants in Denmark.

THE ROOT-ZONE METHOD

Design and working principles

A root-zone treatment plant is basically an artificial wetland consisting of a plastic-lined excavation containing emergent vegetation growing in soil (Fig. 1). The treatment plant is built with a slight inclination (1-3%) between inlet and outlet. According to Kickuth (1984) the demand on surface area to load ratio in root-zone treatment plants are 2-5m^2/p.e. depending on the sewerage of the catchment area. Mechanically treated wastewater is led into one end of the root-zone treatment plant where it runs into a transverse channel filled with broken stones. From there the wastewater flows horizontally through the rhizosphere of the wetland plants. The wastewater must penetrate through the soil and no surface runoff must occur. During the passage of the wastewater through the rhizosphere, the wastewater is cleaned by binding/precipitation processes in the soil and by microbiological degradation. The involved cleaning processes correspond to the processes in conventional mechanical biological chemical treatment systems with denitrification. The effluent is collected at the opposite end of the treatment plant, either in an open channel or in a channel filled with coarse gravel and may be discharged directly into the receiving water bodies.

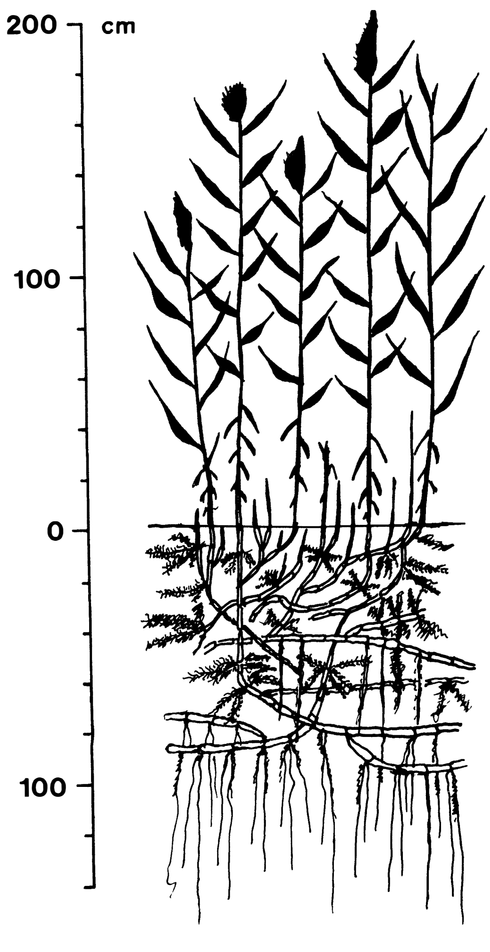

Fig. 2. Drawing of the vegetative propagation of Phragmites australis showing the vertical distribution of roots and rhizomes.

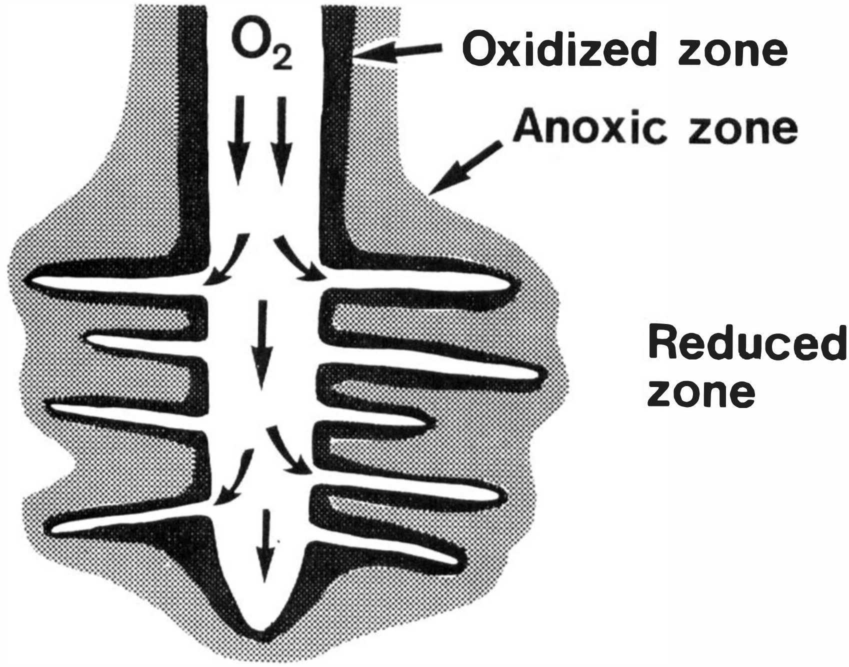

Fig. 3. Simplified representation of the redox-conditions around roots of wetland plants. Oxygen is transported from the atmosphere to the roots via the aerenchyma. A part of the oxygen diffuses into the substrate creating an oxidized zone (+oxygen) and an anoxic zone (-oxygen, +nitrate) around the roots in the otherwise reduced substrate (-oxygen, -nitrate).

The role of the macrophytes

The macrophytes have a key role in the functioning of root-zone treatment plants. Virtually all species of wetland plants may be used. However, the common reed (Phragmites australis (Cav.) Trin. ex Steudel) has several properties which renders this species especially suitable. The most conspicuous one is the strikingly deep roots and rhizomes (down to more than 1 m) which create a great volume of active rhizosphere per surface area (Fig. 2). The direct role of the macrophytes by their nutrient uptake is negligible as the nutrients taken up during one growing season constitute only a few percent of the total contents introduced into the treatment plant by the wastewater. Moreover, the nutrients bound in the plant tissues are recycled in the system upon decay of the plant material. The wetland plants do, however, have two important functions:

- To supply oxygen to the heterotrophic microorganisms in the rhizosphere
- To increase/stabilize the hydraulic conductivity of the soil.

Wetland plants are morphologically and anatomically adapted to growing in a water saturated substrate by virtue of well-developed internal gas spaces (aerenchyma) throughout the plant tissues. The functional significance of the aerenchyma is to supply oxygen to the buried plant parts. The roots and rhizomes, however, leak oxygen into the substrate (e.g. Armstrong, 1979) thereby creating oxidized microzones in an otherwise reduced substrate (Fig. 3). The presence of these oxidized and anoxic zones around the roots create a favourable environment for aerobic and facultative anaerobic microorganisms in the rhizosphere.

The number of macropores in soils have an important effect on the hydraulic conductivity (Beven and Germann, 1982). Maeseneer et al. (1982) have shown that percolation through soils is very much furthered by the presence of roots and rhizomes of Phragmites. As the roots and rhizomes penetrate through the soil, they loosen the soil creating increased porosity by forming pores of tubular shape. Upon decay the roots and rhizomes will leave horizontally interconnected channels behind, which are frequently filled with loosely packed organic material primarily derived from the decaying roots and rhizomes themselves (Beasley, 1976; Mosley 1979). According to Kickuth (1980) these macropores will stabilize the hydraulic conductivity in the rhizosphere at a level equivalent to coarse sand within 2 to 5 years regardless of the initial porosity of the soil.

The role of the microorganisms

The degradation of organic matter and the denitrification of nitrogen in a root-zone treatment plant are mediated by microorganisms. The leakage of oxygen from the roots of the macrophytes creates oxidized zones around the roots. Most of the organic content in the wastewater is decomposed to carbondioxide and water in these zones using oxygen as the terminal electron acceptor. In addition, ammonia is oxidized to nitrate by nitrifying bacteria in these zones. At some distance from the root-surface the free oxygen is depleted, but nitrate is still present (the anoxic zone). Here degradation of organic matter can take place by denitrifying bacteria. By these processes nitrate is converted to free nitrogen (N_2), which evaporates into the atmosphere. In the reduced areas in the rhizosphere, organic matter may be decomposed anaerobically to carbon-dioxide and methane by fermentative processes. The simultaneous existence of oxidized, anoxic and reduced zones, and the interaction between the different kinds of microbial degradation processes in these zones, is essential for an efficient decomposition of organic matter and nutrient removal in root-zone treatment plants. In addition, such interactions may be favourable for the decomposition of rather persistent compounds, such as chlorinated hydrocarbons (Kobayashi and Rittmann, 1982; Tiedje et al., 1984).

The role of the soil

The soil in a root-zone treatment plant provides a stable surface area for microbial attachment, a solid substrate for plant growth, and functions directly in the purification of the wastewater by way of physical and chemical processes. Soils are very effective in removing suspended solids, pathogenic bacteria and viruses by filtration and sorption (Lance et al., 1976; Taylor, 1981). Nutrients are removed from water flowing through soil in several ways. Ion exchange can remove significants amounts of positively charged ions, such as NH_4^+, K^+ and others, and anions such as PO_4^{3-} may be sorbed onto charged surfaces of humic substances. In general, organic soils and clay minerals have higher exchange capacities than coarsely textured mineral soils (Kadlec and Tilton, 1979; Rock et al., 1984). This is why it is inadvisable to use soils with coarse textures in order to secure a high hydraulic conductivity from the very establishment of the treatment plant. Binding of nutrients to the soil particles by sorption processes is not a permanent removal mechanism, but may buffer and thereby stabilize the system.

Precipitation processes in the soil are a more permanent manner by which certain ions are removed from the wastewater. Coprecipitation of phosphate with iron, aluminium and calcium can remove significant quantities of phosphorus (Arvin and Petersen, 1980; Scheffer et al., 1980). Heavy metals may be precipitated with sulfide in zones where sulphate reduction occurs. The formation of organo-metallic phosphates may be an additional form of nutrient removal in the soil. Phosphorus and persistent toxic substances, such as heavy metals, are accumulated in the soil, and may be one of the factors determining the lifetime of a root-zone treatment plant.

Seasonal variation in the cleaning efficiency

The temperature has a significant effect on the microbiological activity. According to Kickuth (1984) the purification efficiency of a root-zone treatment plant will decrease by approximately 20% during winter. However, recent results from an experimental plant in Austria have shown, that the cleaning processes may cease completely during very cold winters, and also that it will take approximately three months after the end of the frost-period before the treatment efficiency is fully recovered (Riegler, 1985). Especially the microbiological degradation of organic matter, and the rate of nitrification and denitrification will be affected by low temperatures. The optimum temperature for nitrification is 25-35°C (Focht and Verstraete, 1977; Fillerey, 1983), and at temperatures below 5°C the rate of nitrification and denitrification will be extremely slow and of no quantitative significance for the removal of nitrogen in a root-zone treatment plant. The abiotic processes in the rhizosphere which remove phosphorus and heavy metals will probably be less affected.

There are a number of factors which will tend to keep a relatively high temperature in the rhizosphere during winter:

- The plant cover and the litter on the surface will have an insulating effect.
- The production of heat from the microbial activity will increase the temperature in the rhizosphere.
- The influx of wastewater will in most cases have a higher temperature than the surroundings.

These factors will secure the infiltration area and the rhizosphere against freezing during winter.

THE FIRST EXPERIENCES FROM ROOT-ZONE TREATMENT PLANTS IN DENMARK

At present there are approximately 30 root-zone treatment plants in Denmark of which the oldest ones were established during the winter 1983-84. This paper describes the working experiences from eight of these.

TABLE 1. Some basic data for eight root-zone treatment plants

Treatment plant	Size (m) (width x length)	Planted species	Organic load (p.e.)	Area to load ratio (m^2/p.e.)
(1) Moesgård	25 x 20	Typha latifolia Carex acutiformis Phragmites aust.	180	2.8
(2) Hjordkær	87 x 13	Phragmites aust.	600	1.9
(3) Ingstrup	8.5 x 13.5	Phragmites aust.	5	23
(4) Rugballegård	8 x 12	Phragmites aust.	5-25	3.8-19
(5) Lunderskov	60 x 25	natural wetland	(200)	(7.5)
(6) Knudby	19 x 19	Phragmites aust.	65	5.6
(7) Borup	30 x 48	Phragmites aust.	200	7.2
(8) Kalø	38 x 20	Phragmites aust.	300	2.5

Treatment plants (1)-(5) were established before the growing season 1984, and (6)-(8) before the growing season 1985. All treatment plants were supplied with mechanically treated wastewater except the treatment plant at Lunderskov which received secondarily treated wastewater. (p.e.: person equivalent).

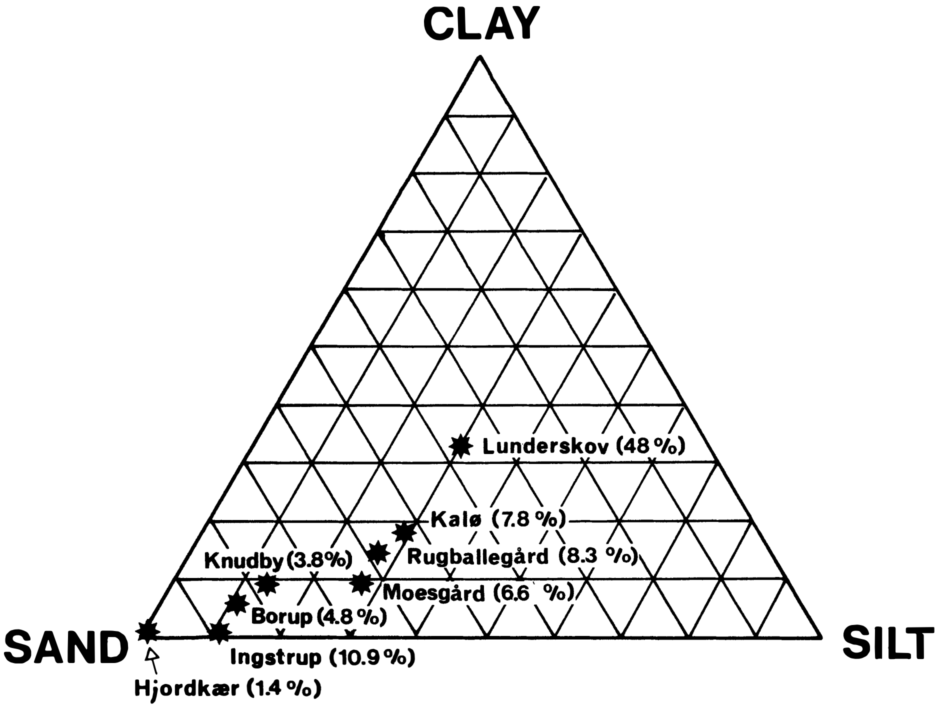

Fig. 4. Grain size distribution of the eight soils used in the root-zone treatment plants. Numbers in brackets give the organic content (%) of the soils. Clay: < 0.002 mm; silt: 0.002-0.06 mm; sand: 0.06-2 mm. At Hjordkær 94.4% of the soil particles were larger than 2 mm (gravel).

The root-zone treatment plants included in this paper are all established as full-scale treatment facilities, which means that natural variations in e.g. amount and composition of the wastewater make difficult a direct comparison of the recorded purification efficiencies of the treatment plants. The data, however, show the actual purification efficiencies under realistic conditions, and so too what efficiencies might be expected from full-scale operation during the first two growing seasons.

Table 1 lists some of the basic data for the root-zone treatment plants. One of the plants (Lunderskov) is a natural wetland receiving secondarily treated municipal wastewater. The other seven are artificial wetlands planted with Phragmites as the only macrophyte, or planted with a combination of different species of macrophytes (Moesgård). In most cases the original soil at the site of the excavation was used. In one case, however, the Phragmites were planted in gravel (Hjordkær). Fig. 4 shows the grain size distributions and the organic contents of the eight soils. The fraction of clay varies from 0% at Hjordkær to 33% at Lunderskov, and the organic content varies from 1.4% at Hjordkær to 48% at Lunderskov.

Removal efficiencies

Biochemical oxygen demand (BOD). In table 2 are the mean removal efficiencies for BOD, total-nitrogen and total-phosphorus listed. The mean removal efficiency for BOD varied between 51% and 95% for the eight treatment plants. The low removal efficiency recorded at Kalø is probably due to the fact that the vegetation cover was very sparse throughout the period of investigation

TABLE 2. Mean inlet and outlet concentrations (mg/l) and removal efficiencies for Biochemical Oxygen Demand (BOD), total-nitrogen and total-phosphorus in the eight root-zone treatment plants

Treatment plant	Period	BOD In	BOD Out	BOD %	Total-nitrogen In	Total-nitrogen Out	Total-nitrogen %	Total-phosphorus In	Total-phosphorus Out	Total-phosphorus %
Moesgård	Aug 84-Oct 85	106	22	80%	45	30	30%	6.6	3.8	38%
Hjordkær	Jul 84-Aug 85	149	54	66%	41	29	29%	14.1	11.7	17%
Ingstrup	Jun 84-Sep 85	368	18	95%	112	12	88%	51	3.2	94%
Rugballegård	Jun 84-Sep 85	470	39	82%	89	33	62%	17.8	3.0	83%
Lunderskov	Sep 84-Sep 85	52	23	52%	14	6	53%	4.2	2.4	45%
Knudby	Apr 85-Aug 85	142	29	76%	38	27	23%	12.9	7.8	31%
Borup	Apr 85-Aug 85	98	39	59%	30	23	25%	11.7	10.4	18%
Kalø	Mar 85-Aug 85	75	36	51%	45	40	10%	9.3	8.8	11%

(first growing season), and that the clayish soil in this treatment plant had a very low hydraulic conductivity. Most of the wastewater did not penetrate into the soil, but spread on the soil surface as overland flow.

The highest removal efficiency for BOD was recorded in the plant at Ingstrup. This plant only receives the wastewater from one household (5 p.e.). The surface area to load ratio was very high during the period of investigation ($23m^2$/p.e.), and in the summer period there has been no outlet from the treatment plant except in connection with precipitation.

Nitrogen. The mean removal efficiency for total-nitrogen varied, and was generally less than 30% for the majority of the root-zone treatment plants (Table 2). Higher removal efficiencies were recorded in the natural wetland at Lunderskov (53%), and also at Rugballegård (62%) and at Ingstrup (88%) probably due to the relatively high surface area to load ratios in these plants. In each case the concentrations of nitrite and nitrate in the effluents remained very low (generally less than 0.1 mg/l), indicating a low nitrification rate. The removal efficiencies for inorganic nitrogen (ammonia) were generally equivalent to the removal efficiencies for total-nitrogen. No direct evidence of denitrification in the treatment plants was observed. The main process responsible for the removal of nitrogen was probably adsorption of ammonia to the soil particles.

Phosphorus. The mean removal efficiencies for total-phosphorus in the root-zone treatment plants varied between 11% and 94% (Table 2). This variation is probably due mainly to two factors: (a) Different degree of surface runoff in the treatment plants, and (b) different composition of the soils. The removal efficiency was low (11%) at Kalø, where most of the wastewater spread on the surface of the soil and did not penetrate into it. At Ingstrup and Rugballegård, however, the most if not all of the wastewater penetrated into the soil. At these plants the wastewater was rather concentrated and the surface area to load ratio was high. In addition, these soils are characterized by a relatively high organic content, which means that adsorption to humic and fulvic substances in the rhizosphere were extremely important for the removal of phosphorus. At the gravel based treatment plant at Hjordkær the removal efficiency for phosphorus was low.

Seasonal variations in removal efficiencies

Fig. 5 illustrates the mean removal efficiencies during the first summer period (May-October 1984), the first winter period (November 1984 - April 1985), and the second summer period (May-October 1985), respectively, for the five root-zone treatment plants which have now been working for two growing

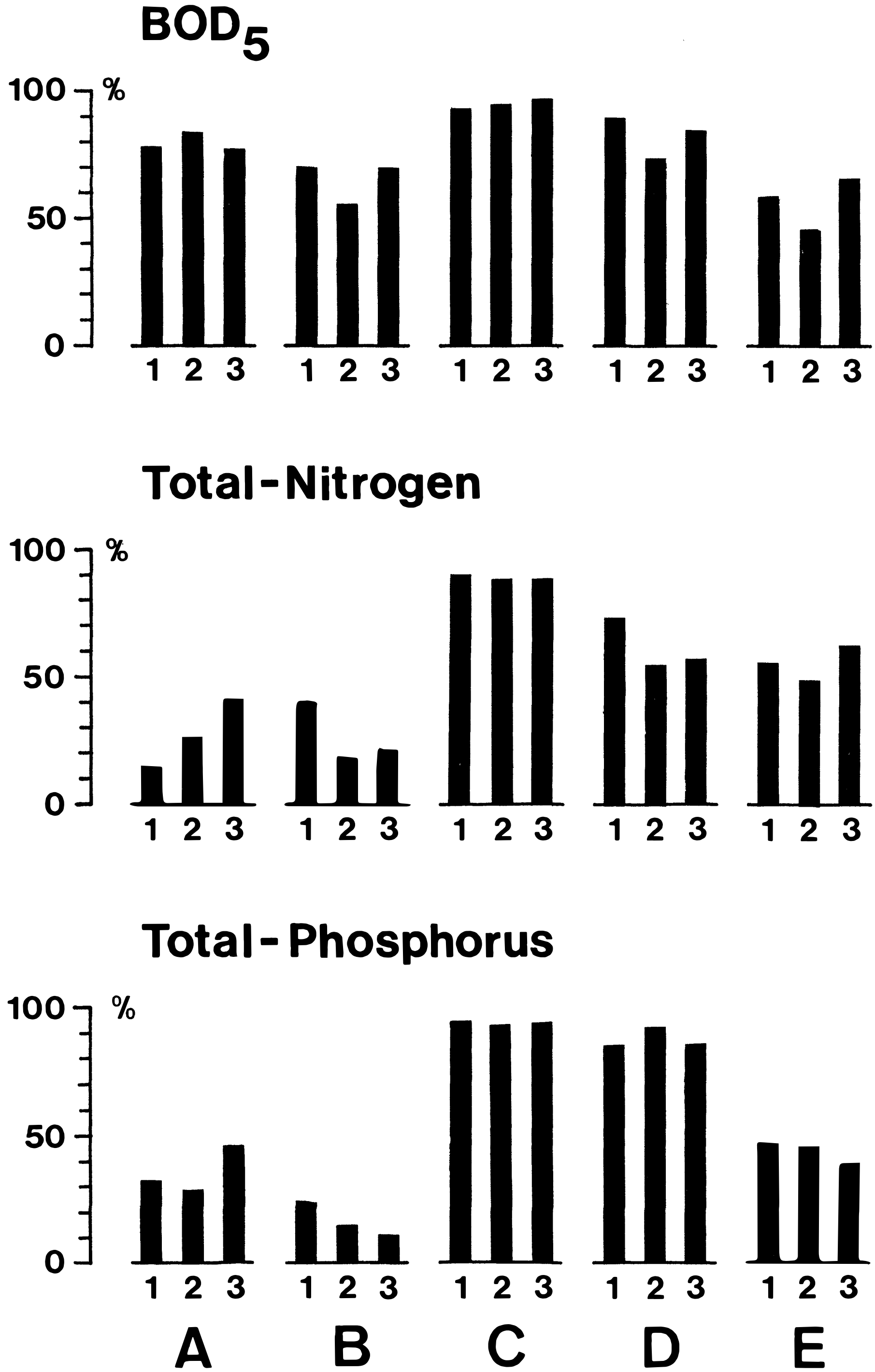

Fig. 5. Mean removal efficiencies (%) for BOD, Total-N and Total-P during (1) the first summer period (May-October 1984), (2) the first winter period (November 1984-April 1985), and (3) the second summer period (May-October 1985). A: Moesgård; B: Hjordkær; C: Ingstrup; D: Rugballegård; E: Lunderskov.

seasons. In three of the plants a slight reduction (approx. 15%) in removal of BOD during winter was observed, whereas BOD removal in the other two treatment plants either increased (Moesgård) or remained unaffected (Ingstrup). The removal efficiencies observed the second summer were not significantly different from those recorded the first summer.

For total-nitrogen no general seasonal trend could be observed. The removal efficiency increased with time at Moesgård, decreased with time at Hjordkær, and remained constant at Ingstrup. At Rugballegård and Lunderskov a slight reduction in removal efficiency during winter was observed.

The total-phosphorus removal efficiency showed no seasonal pattern. At Moesgård the efficiency increased slightly the second summer and at the gravel based treatment plant at Hjordkær the efficiency decreased with time. The recorded efficiencies at the three other treatment plants were nearly constant.

The observed seasonal pattern for BOD shows that removal of BOD might decline slightly during winter. The data for total-nitrogen indicate that removal of nitrogen was based mainly on physical/chemical processes (adsorption, deposition) and not microbiological decomposition (denitrification). The removal efficiencies for total-nitrogen and total-phosphorus at Moesgård increased the second summer probably in response to increased hydraulic conductivity of the soil. The vegetation was at this time abundant and had created an increased porosity of the soil. This means that a larger proportion of the wastewater penetrated into the rhizosphere the second summer. A similar improvement in purification efficiency was not observed at the other treatment plants. At Hjordkær the efficiency in fact decreased slightly probably because the binding sites on the soil particles (gravel) were saturated.

CONLUSIONS

The data presented in this paper show that root-zone treatment plants can very nearly attain secondary treatment quality for BOD already from the first growing season. For the nutrients nitrogen and phosphorus the data vary and the removal processes were almost exclusively based on physical/chemical binding in the rhizosphere. There was no indication of quantitatively significant denitrification during the period of investigation. Gersberg et al. (1984) have, in an artificial wetland on gravel, found that the removal efficiency for total-nitrogen was less than 25% when the system received primary effluent. When the system, however, received a blend of primary effluent and secondary effluent in a ratio of 1:2, the latter containing nitrogen in the form of nitrate, the removal efficiency was 80% for total-nitrogen. This indicates that the rate of nitrification is the factor that limits nitrogen removal in such systems.

The main problem in the first years after the establishment of a root-zone treatment plant is the low hydraulic conductivity of the soil. Overland flow occurred in all treatment plants examined in this investigation except in plants where the rooting medium was gravel or where the hydraulic load per surface area was low. The results from Moesgård, however, indicate that the hydraulic conductivity may increase as an effect of root development. It is unadvisable to use sand or gravel based systems in order to obtain a high hydraulic conductivity from the very beginning. The removal of phosphorus and toxic substances such as heavy metals will be very low in such systems.

In conclusion, root-zone treatment plants seem to be a viable alternative to conventional wastewater treatment technology, especially suitable for single households and small to medium sized communities. Their design is relatively simple and they require little tending. However, information is still sparse especially on the microbiological removal of nitrogen (denitrification), on the effect of soil type and plant cover, and on the required surface area to load ratio. Further research on experimental treatment systems together with long term experiences from full-scale operations are needed in order to throw light on and optimize these factors, and in order to establish the applicability of the root-zone method in general.

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