Advanced Treatment of Wastewater by Using Filter Materials and Plants with Resource Reuse and Amenity Functions

2001.3

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CONTENTS

Summary

The increase in wastewater production that is coinciding with the increase in the human and livestock population in rural areas is causing the eutrophication of aquatic ecosystems. It is thus necessary to develop low cost and energy saving wastewater treatment systems suited to rural areas. It is also desirable to add resource reuse and amenity functions to the wastewater treatment facilities in order to make them attractive and acceptable. In this study, optimum conditions for a system consisting of an aerobic soil column and an anaerobic contact column for the livestock wastewater treatment were studied. For domestic wastewater and eutrophic pond or lake water treatment, the plant bed filter system was developed and optimum conditions including selection of plant species were studied.

The author attempted to modify a combination aerobic - anaerobic soil column system for livestock wastewater treatment in order to improve treatment efficiency of this system by using several materials reusable in agriculture as the column packing media. This system consists of two columns mounted in series: an aerobic soil column where organic matter is decomposed, phosphorus is sorbed onto clay minerals of soil in the column, and ammonium is oxidized to nitrate by nitrifying bacteria, and an anaerobic soil column where nitrate in the influent is converted to nitrogen gas by denitrification bacteria. In the aerobic column, the addition of 20% crushed limestone was effective for preventing the acidification of the column packing medium and promoting nitrification for a long period of time. In the anaerobic column, carbonized rice husks and charcoal chips were more suitable materials for packing media of the column than volcanic ash soil in terms of permeability of the influent through the medium. The addition of straw to the column packing medium accelerated denitrification, but this effect decreased as the concentration of added methanol in the influent rose. The denitrification of 1 g of NO_3-N required about 3 g of methanol.

It is important to add functions of resource reuse and amenity to wastewater treatment systems by introducing crops and flowers. A bench scale experiment was conducted to compare the effectiveness of three kinds of bed filters (zeolite, zeolite+shell fossil, charcoal chips) and five plant species. Pots ($0.05m^2$) filled with bed filter materials were prepared as experimental systems and artificial domestic wastewater was fed into these systems. The addition of higher plants to the

bed filter enhanced the nitrogen and phosphorus removal from wastewater as plant species had considerably affected the P and N removal efficiency. Although the effectiveness of adding plants to the system on removal of total organic carbon was not conclusive, zeolite and zeolite+shell fossil bed filters were superior to charcoal chips for P and N removal.

Since the majority of useful plants are terrestrial species, I constructed a plant bed filter ditch in which terrestrial and aquatic plants can be utilized for nitrogen and phosphorus removal from wastewater. The experimental ditch (4.0 m long, 0.4 m wide, 0.4 m high) contained baskets filled with bed filter material (zeolite) and were planted with higher plants to match the ability of the plant species to endure saturation. The height of the zeolite packed in baskets was varied. The bed filter surface was about 0.05-0.1 m higher than the water level for terrestrial species and the same as the water level for aquatic species.

Screening studies were conducted to evaluate and compare the effectiveness of 20 kinds of plant species which are economically important or have aesthetic value, including 13 terrestrial species , for domestic wastewater treatment. Artificial wastewater containing 20 mgL^{-1} of N and 3.3 mgL^{-1} of P, was supplied to the ditch at a rate of about 1.41 - 2.08 $gm^{-2}d^{-1}$ for N and 0.20-0.33 $gm^{-2}d^{-1}$ for P. The addition of higher plants to the ditches enhanced the removal of nitrogen and phosphorus from wastewater. N and P removal rates of the ditches mainly depended on the N and P absorption rates of the plants. The maximum value of the N removal rates of the papyrus (*Cyperus papyrus* L.), kenaf (*Hibiscus cannabinus* L.), sorghum (*Sorghum vulgare* Pers.), and Italian ryegrass (*Lolium multiflorum* Lam.) ditches were 1.3-1.7 $gm^{-2}d^{-1}$ and the maximum value of the P removal rates were 0.24-0.26 $gm^{-2}d^{-1}$. It was found that N and P removal rates could be maintained at 0.8 $gm^{-2}d^{-1}$ and 0.15 $gm^{-2}d^{-1}$, respectively except in the winter, by cultivating papyrus, kenaf, sorghum, Italian ryegrass, and barley and so on in an appropriate combination in the ditches.

It was also found that the addition of plants to the ditch promoted microbial activity.

Nitrification proceeded more actively in the system containing papyrus and reeds in the winter and the role of aeration by these aquatic plants was analyzed. N balance data of the plant bed filter ditches suggested that denitrification contributed to N removal in addition to N absorption by the plants.

Eutrophication of ponds for agricultural use has begun to adversely affect rice production and residential environments in Japan. I evaluated the ability of several plant species, which had already been found effective for domestic wastewater treatment, to remove nitrogen and phosphorus from polluted pond water whose N and P concentrations were much lower than those of domestic wastewater. Artificial pond water containing 2.5 mg L^{-1} of N and 0.5 mg L^{-1} of P was supplied to ditches. All the plants examined were effective for lowering N and P concentrations in the artificial pond water, especially Italian ryegrass, papyrus, and kenaf.

In order to determine the N and P concentration range in which plants can be efficiently used for wastewater treatment,I studied the influence of N and P wastewater concentrations on N and P removal rates of Italian ryegrass, papyrus, kenaf, sorghum, African marigold and peppermint. Concentrations at a removal rate of zero were 0.19 mg L^{-1}(papyrus)- 0.50 mg L^{-1}(sorghum) for N and 0.01 mg L^{-1}(papyrus, Italian ryegrass) - 0.06 mg L^{-1}(sorghum) for P. In the case of papyrus, N and P removal rates were low and significantly affected by the concentration when the N concentration did not exceed 0.57 mg L^{-1} and the P concentration did not exceed 0.45 mg L^{-1}. Thus N and P removal rates at such low concentrations are considered to be much smaller than those determined from the experiments on the treatment of artificial domestic wastewater and pond water. At high N and P concentrations, the removal rates were high and hardly affected by the concentration. Thus the ditch size at the site could be estimated roughly based on the N and P removal rates determined in the preceding experiments. The concentration range from 1.0 to 20 mgL^{-1} for N and from 0.5 to 4 mgL^{-1} for P was regarded as the ranges in which the removal rates of all plant species examined were sufficiently high and unrestricted.

I conducted a more practical experiment based on the results obtained from the experiments using artificial wastewater and evaluated the effectiveness of plant bed filter ditches in the treatment of real eutrophic pond water containing particulate N and P. Experimental ditches were planted with the species which were effective in removing N and P from artificial wastewater and could be used by rural communities for handicrafts and ornamental purposes. The plant-free ditch was effective for removing particulate P, but PO_4-P was dissolved from particulate P accumulated in the bed filter. The addition of plants to the ditches removed PO_4-P successfully. Plant uptake and filtration by bed filters played an important role in P removal in the ditches containing plants. The plant-free ditch removed particulate N perfectly and NO_3-N to some extent. The ditch containing plants removed NO_3-N and particulate N quite well in summer. The N balance indicated that N was removed mainly by denitrification and plant absorption. This suggests that denitrification was promoted by using suspended solids (SS) accumulated in the bed filter as a hydrogen donor. The planted ditches purified eutrophic pond water resulting in a T-N concentration below 0.3 mgL^{-1} and T-P below 0.02 mgL^{-1} - the minimum N and P concentrations required for water bloom formation. The addition of organic matter to the ditch was effective for improving N removal efficiency by 0.1 - 0.2 $gm^{-2}d^{-1}$ in winter and spring.

When we apply the plant bed filter ditch to an actual site, the ditch needs some modifications or improvements depending on the quality of the wastewater. The ratios of N to P absorption rates by plants observed in this study were 3:1 to 20:1. The excess component, N or P, was not absorbed by plants when the ratio of N to P concentration in the influent was extremely high or low. In such cases, the functions of N or P adsorption and promotion of denitrification should be given to the bed filter to remove the excess component. In the treatment of wastewater containing SS, the removal of SS before plant bed filter treatment or removing SS accumulated in the bed filter periodically is necessary to prevent ditch clogging.

I believe that the plant bed filter ditches should be constructed as flower and crop gardens around the wastewater treatment plants in rural areas, farmyards and ponds. Based on a rough estimation, the plant bed filter ditch should cover an area of approximately 1000-1300 m^2 in order to treat about 70 % of N and P in the secondary effluent from the wastewater treatment plant for 200 people. I found that the ditches planted with papyrus, marigold, peppermint, or Italian ryegrass purified eutrophic pond water resulting in a T-N concentration below 0.3 mgL^{-1} and T-P below 0.02 mgL^{-1}. The plant-bed filter ditches could be used to supply clear water for ornamental streams in parks, where children could play in the water.

The plant bed filter ditch provides for resource reuse and amenity in addition to wastewater treatment. Now many local governments are interested in and want to introduce our system for improving aquatic ecosystems. In such cases, the ditches need some volunteers who will harvest, transplant and maintain the plants. Recently, there have been many activities organized by local residents to improve aquatic ecosystems close to their homes. Thus it would be desirable for residents to actively take care of flowers and crops cultivated on the plant bed filter system. Further more, in order to popularize the plant bed filter ditches and operate them for a long time, the municipalities must help in constructing the ditches and providing the infrastructure for their management.

Chapter 1

General Introduction

Water pollution problem in rural areas

The eutrophication of aquatic ecosystems has become a serious problem for fisheries, agriculture, water supplies and residential living environments, etc., in Japan. Lakes and ponds which supply irrigation water have been polluted (Fujita et. al. 1986, Shigematstu and Ookubo 1993). Irrigation using such polluted water has adversely affected rice production, causing easy lodging, straight heads, serious decrease of ripe grains, deterioration of rice quality, and increase of disease injury (Morikawa 1982, Hidaka 1990, Kitahara et.al. 1993).

The increase of wastewater production coinciding with the increase of population and livestock raising in rural areas has led to the eutrophication of aquatic ecosystems. Most of the nitrogen and phosphorus load going into Lake Kasumigaura, one of the largest lakes in Japan, and a supply of irrigation water, comes from domestic and livestock wastewater (Tabuchi and Takamura 1985). However, it is uneconomical and energy consuming to introduce urban-type sewage systems into rural areas because the pollution sources in rural areas are very disperse. Treating pollutants near the pollution source is more important in rural areas. Thus it is necessary to develop low cost, energy saving wastewater treatment techniques suited to rural areas.

Today in Japan, most of food and feed are imported from other countries. This means that N and P in domestic and livestock wastewater come from other countries, accumulate in Japan, and cause eutrophication of aquatic ecosystems (Miwa and Iwamoto 1988, Wakatsuki 1988). Reusing and recycling N and P in the wastewater is desirable to reduce N and P accumulation in Japan.

Generally, people do not want to construct sewage treatment plants near their homes, though they need wastewater treatment. It is thus necessary that the wastewater treatment plants have some other, attractive functions, such as adding amenity and reusing resources.

Problems of livestock wastewater treatment

Livestock wastewater is rich in nitrogen and phosphorus which induce the eutrophication of lakes and other aquatic ecosystems. In order to alleviate the detrimental impact of wastewater discharge, it is necessary to remove nitrogen and phosphorus as well as organic matter from the wastewater prior to disposal. The activated sludge process, though widely adopted for wastewater treatment, does not adequately remove nitrogen and phosphorus from livestock wastewater. In addition, the equipment and maintenance of such a treatment system are expensive. It is difficult, therefore, for most of the small livestock farmers to introduce this system for livestock wastewater treatment. There is presently an increasing awareness of the need for developing new low cost technologies for advanced treatment of livestock wastewater.

Livestock wastewater treatment using soil

Some attention has been directed toward wastewater treatment that uses soil columns (Moritani et al. 1982, 1983; Morishita, T. and Minami, U. 1983a, 1983b; Yoshida et al. 1983; Yamaguch and Teranisi 1988; Wakatsuki et al. 1989).

A combination aerobic - anaerobic soil column system (Watahiki et al. 1981; Fukushi and Aida 1988; Harada and Aida 1989) based on Kakishima and Aida's model (Kakishima and Aida 1980) was reported to be effective for removing nitrogen, phosphorus and organic matter from livestock wastewater. This system consists of two columns mounted in a series, an aerobic soil column and an anaerobic soil column. The wastewater from which suspended solids (SS) is removed and led into the aerobic column where organic matter is decomposed, phosphorus is sorbed onto clay minerals of the soil in the column, and ammonium is oxidized into nitrate by nitrifying bacteria. The effluent from the aerobic column flows into the anaerobic column (submerged condition) where nitrate in the influent is converted to nitrogen gas by denitrification bacteria.

Problems of domestic wastewater treatment

Most of the domestic wastewater, that does not contain urine and excrement, of rural communities in Japan that does not have sewage systems, is being discharged into water without prior treatment. The increase of the production of wastewater coinciding with the growth of the population in such areas partly contributes to the eutrophication of aquatic ecosystems.

Unfortunately, conventional sewage treatment processes, such as the general activated sludge and trickling filter processes, do not sufficiently remove nitrogen and phosphorus from wastewater.

Secondary treated sewage is one of the major sources of eutrophication of aquatic ecosystems. Thus, there is an increasing need for developing energy-saving and cost effective methods for domestic wastewater and secondary effluent treatment suited to rural areas.

Wastewater treatment by using plants

Considerable attention has been directed toward using N and P absorption by plants for wastewater treatment because of the low cost, energy saving, and ease of operation. Many studies on water hyacinths, which have high N and P removal efficiency, have been reported (Wolverton and McDonald 1976, Reddy and Stutton 1984, Debusk and Reddy 1987 etc.). However, the water hyacinth has some problems: while they grow prolifically in tropical and sub-tropical areas, their growing period is quite restricted in temperate zones ; biomass is not effectively used; and plants are sometimes washed away (Brix 1993, Zakova et. al.1994).

Recently, there has beed many reports on systems of wastewater treatment consisting of bed filters planted with emergent plans. These systems have been called plant rock filters (Wolverton 1982, 1983, 1986), helophyte-beds (Bucksteek 1987), macrophyte beds (Boutin 1987), and root zone method (Brix 1987a, 1987b; Cooper and Boon 1986, Cooper and Hobson 1989). They are generally referred to as constructed wetlands (CW) (Hammer 1989, Cooper and Hindlater 1990, Moshiri 1993). These systems aim to combine functions of plants, bed filters, and microbes living in beds. Soil, sand and gravel are used as bed filters. Emergent plants such as reeds and cattails, which grow wild in temperate zones, are generally planted in this system. In the constructed wetland systems, the major mechanism of N removal is microbial ammonification - nitrification - denitrification and that of P removal is adsorption to the soil and precipitation. Plant N and P uptake is an insignificant function there (Wood 1995, Brix 1994, 1997, Reilly et. al. 2000). Since the plants are generally not harvested, the majority of the nutrients they take will be released to the water again when the plants decompose (Brix 1999). It is therefore important to include the function of resource reuse in wastewater treatment systems, using nitrogen and phosphorus contained in wastewater as resources, to promote the nutrient cycle in rural areas (Ozaki and Abe, 1993).

In Japan, a Kanumatsuchi and zeolite bed filter planted with Chinese water spinach (a vegetable, *Ipomea aquatica* Forskal), called biogeofilter, was studied by Hashimoto et. al.(1987).

Plant N and P uptake played an important role in this system. The author belives that it is possible to add functions of resource recovery and reuse to such systems by selecting suitable bed filter materials reusable in agriculture and higher plant species useful for human life. As plants are constantly harvested, nitrogen and phosphorus which are recovered by plants, are taken out from these systems, and recycled in rural areas. Such plants should be used for other process except for food due to the risk of accumulation of heavy metals in the plants and contamination by bacteria etc.

Furthermore, giving amenity function to the wastewater treatment system is desirable in order to make the system more attractive and acceptable by local residents. Wastewater treatment systems including flowers and ornamental plants can function as flower gardens or ornamental plantings.

Though most crops, flowers and ornamental plants are terrestrial species, there are few studies on the wastewater treatment efficiency of terrestrial plants.

Aim of this research

A combination aerobic - anaerobic soil column system based on Kakishima and Aida's model (Kakishima and Aida 1980) was reported to be effective for treating livestock wastewater. In order to improve the treatment efficiency of this system, the author modified this system by including several materials reusable in agriculture. Then they tried to obtain fundamental information on the operational conditions of the system. The study was carried out to analyze the effect of calcium carbonate addition to the packing medium of the aerobic column on the treatment efficiency. Recently, some studies and practical experiments have been reported using charcoal for wastewater treatment (Arafune 1991, Yatagai 1995). I also considered the possibility of using carbonized rice husks or charcoal as a packing medium of the anaerobic column, and determined the organic matter requirements for denitrification.

Using crops and flowers for wastewater treatment helps to recycle N and P in rural areas and also to give amenity functions to wastewater treatment systems. Most crops and flowering plants are terrestrial species, so I developed a plant bed filter ditch where terrestrial species could grow. Screening studies were carried out to evaluate bed filter materials and useful plants for the removal of N and P from domestic wastewater. The bed filter material should be able to be reused in agriculture as soil conditioners and plants should be economically important species or have an aesthetic value.

Generally, N and P concentrations of eutrophic pond water are low, about one tenth those of domestic wastewater. I therefore also evaluated the ability of useful plants to remove nitrogen and phosphorus from wastewater with low N and P concentrations such as eutrophic pond water. In order to determine the N and P concentration range in which these plants can be efficiently used for wastewater treatment, the influence of N and P wastewater concentrations on N and P removal rates of the plants was studied. I also conducted a more practical experiment to evaluate the effectiveness of the plant bed filter ditches on the treatment of eutrophic pond water in Tsukuba, Japan. The pond water, unlike artificial wastewater used in our previous experiments, contained particulate N and P such as algae and soil particles. I studied the efficiency of the removal of total N and P including particulate N and P by the ditches and the fate of particulate N and P during their passage through the ditches. I also attempted to formulate a guide for making plant bed filter ditches, especially about recommended plantings (plant species and planting season) and estimating ditch size.

Chapter 2

Advanced Treatment of Livestock Wastewater Using an Aerobic Soil Column and an Anaerobic Contact Column

The author conducted to modify a combination aerobic - anaerobic soil column system (Watahiki et al. 1981; Fukushi and Aida 1988; Harada and Aida 1989) for livestock wastewater treatment in order to improve treatment efficiency of this system by using several materials reusable in agriculture as column packing medium. This system consists of two columns mounted in series, an aerobic soil column and anaerobic soil column. The wastewater, from which suspended solids (SS) has been removed, is led into the aerobic column where organic matter is decomposed, phosphorus is sorbed onto clay minerals of soil in the column, and ammonium is oxidized to nitrate by nitrifying bacteria. The effluent from the aerobic column flows into the anaerobic column (submerged condition) where nitrate in the influent is converted to nitrogen gas by denitrifing bacteria.

The present study was carried out to analyze the effect of calcium carbonate addition to the packing medium of the aerobic column on the treatment efficiency. I also considered the possibility of using carbonized rice husks or charcoal chips as packing medium of the anaerobic column, and determined the organic matter requirements for denitrification.

2-1 Effect of calcium carbonate addition to the packing medium on the treatment efficiency of Aerobic column.

Materials and Methods

The aerobic column, with an effective zone volume of 6.4 liters (Fig. 2-1), was packed with volcanic ash soil (Humic Andosol at Kannondai, Tsukuba, Japan) for phosphorus sorption and with zeolite (clinoptilolite at Iwami, Japan, CEC 150 meq/100g, 3-5 mm) for intensifying ammonium adsorption. In order to examine the effect of calcium carbonate addition on wastewater treatment (especially ammonium oxidation), four types of columns were prepared according to the rate and the particle size of calcium carbonate: column 1, 0% (w/w) $CaCO_3$; column 2, 1.5% (w/w) $CaCO_3$; column 3, 20% (w/w) $CaCO_3$; column 4, 2% (w/w) crushed lime stone (0.5-3 mm).

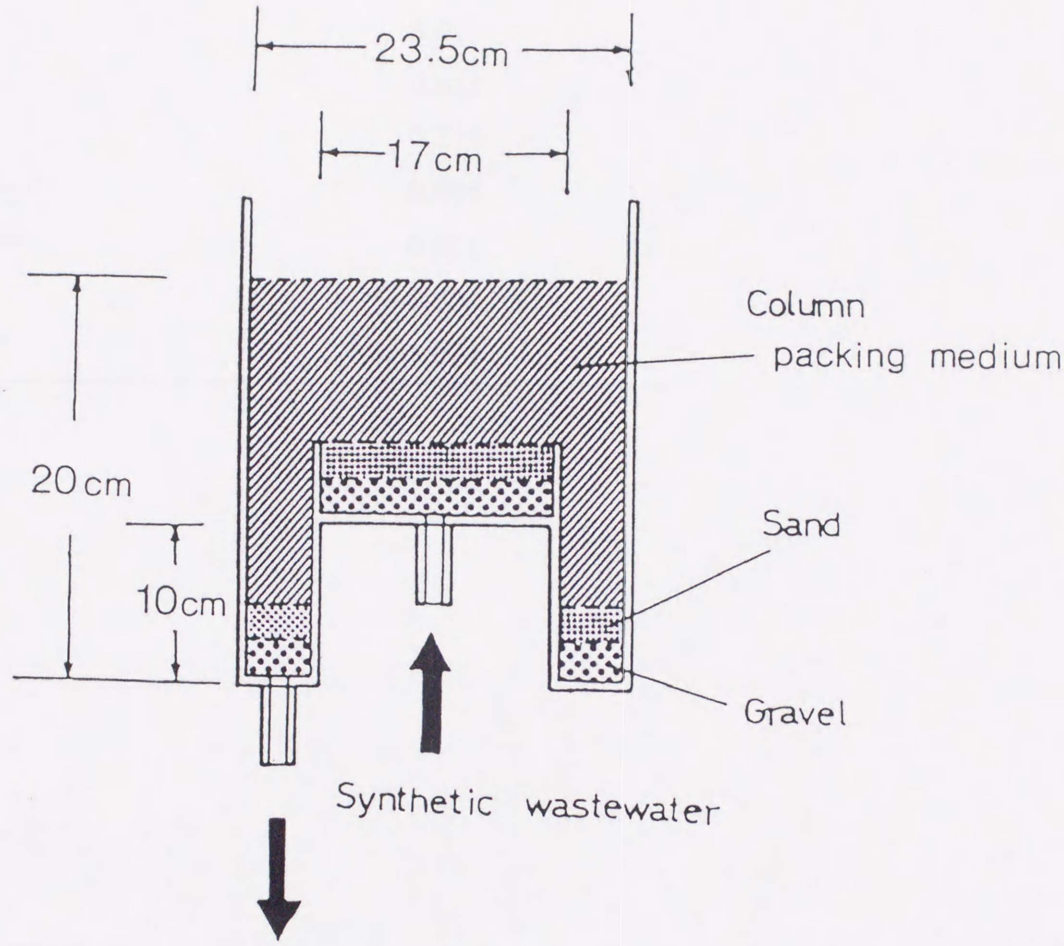


Fig. 2-1 Aerobic column (cross section).

Table 2-1. Composition of synthetic wastewater (gL^{-1})

NH_4Cl	0.8
Glucose	0.42
Peptone	0.05
Beef extract	0.05
Urea	0.05
NaCl	0.015
Na_2HPO_4	0.275
$MgSO_4$ $7H_2O$	0.005
$FeCl_3$ $6H_2O$	0.004
KCl	0.004
CaCl $2H_2O$	0.004

Table 2-1 shows the composition of the synthetic wastewater which contained 209 mgL^{-1} NH_4-N, 250mgL^{-1} T-N, 60 mgL^{-1} PO_4-P, and 200 mgL^{-1} TOC (total organic carbon). The wastewater was infiltrated intermittently by upward flow to the aerobic column and flowed out from the bottom of the column.

The wastewater fed was 0.5 L/day (NH_4-N & organic N loading rate, 18.1 $gm^{-3}d^{-1}$) for the first 63 days and 1 L/day (NH_4-N&organic N loading rate, 36.2 $gm^{-3}d^{-1}$) thereafter. The retention time of wastewater was 6 to 3 days.

All the column experiments were performed at 25℃.

Effluents were collected periodically and the concentrations of NH_4-N, NO_3-N, and PO_4-P were measured by using a Technicon Auto Analyzer 2, while the concentration of TOC was measured by using a Beckman TOC Analyzer Model 102.

After the completion of the experiments, soils packed in each column were divided into three layers and the number of ammonium-oxidizing bacteria in the soil samples was counted according to the most probable number method (Alexander and Clark 1965).

Results and Discussion

The efficiency of the ammonium treatment depended on the concentration and the particle size of calcium carbonate added to the column packing medium. Changes in the NO_3-N concentration of the effluent indicated that ammonium oxidation (nitrification) was accelerated in order of 0% $<$ 1.5% $<$ 20% $CaCO_3$=20% crushed lime stone addition at the end of the experiment (Fig. 2-2). Ammonium was not detected in the effluent from the 20% crushed limestone column. However, the NH_4-N concentration of the effluent from the 0 and 1.5% $CaCO_3$ increased markedly after 80-85 days. The NH_4-N concentration of the effluent from the 20% reagent $CaCO_3$ column was high, 20-30 mgL^{-1} after 45 days. Some cracks were found in the 20% $CaCO_3$ column packing medium. The reason why ammonium flowed out from the 20% $CaCO_3$ column is considered that some part of the wastewater passed through cracks in the packing medium.

The distribution of the ammonium-oxidizing bacteria, pH values, and inorganic nitrogen concentration in the column is shown in Fig. 2-3. Both the pH and the number of ammonium-oxidizing bacteria increased with the rise in the calcium carbonate concentration in the column packing medium (Fig. 2-3). On the contrary, the residual NH_4-N decreased with the rise in the concentration of added calcium carbonate (Fig. 2-3). These results indicated that the addition of a large amount of calcium carbonate prevented the acidification, increased the number of nitrifying bacteria, and accelerated nitrification in the aerobic soil column. The influent ammonium was efficiently converted to nitrate in the 20% crushed limestone column. On the other hand, as the nitrification did not proceeded adequately in the 0 and 1.5% $CaCO_3$ columns, the unconverted ammonium absorption sites of the column packing medium were saturated.

The PO_4-P concentrations were less than 0.06 mgL^{-1} in the effluents from the three columns except for that containing 20% $CaCO_3$ (Fig.2-2), indicating that the PO_4-P removal efficiency was more than 99.9% (PO_4-P removal rate, 8.6 $gm^{-3}d^{-1}$) in the 0% $CaCO_3$ column, 1.5% $CaCO_3$ column, and 20% crushed limestone column throughout the experimental period. The leakage of PO_4-P from the 20% $CaCO_3$ column may be attributed to the produce of many small cracks in the column packing medium which were caused by the addition of a large amount of $CaCO_3$.

The concentration of TOC of the effluent decreased below 10 mgL^{-1} within 1 week. The removal efficiency for TOC remained at more than 94.5% (TOC removal rate, 27.3 $gm^{-3}d^{-1}$) in every column throughout the experimental period (data not shown).

Conclusions

The addition of 20% crushed limestone was effective for preventing the acidification of column packing medium and promoting nitrification for a long period of time. Ammonium, phosphorus, and TOC in the wastewater were successfully treated by the aerobic column packed with 60% volcanic ash soil, 20% zeolite, and 20% crushed limestone.

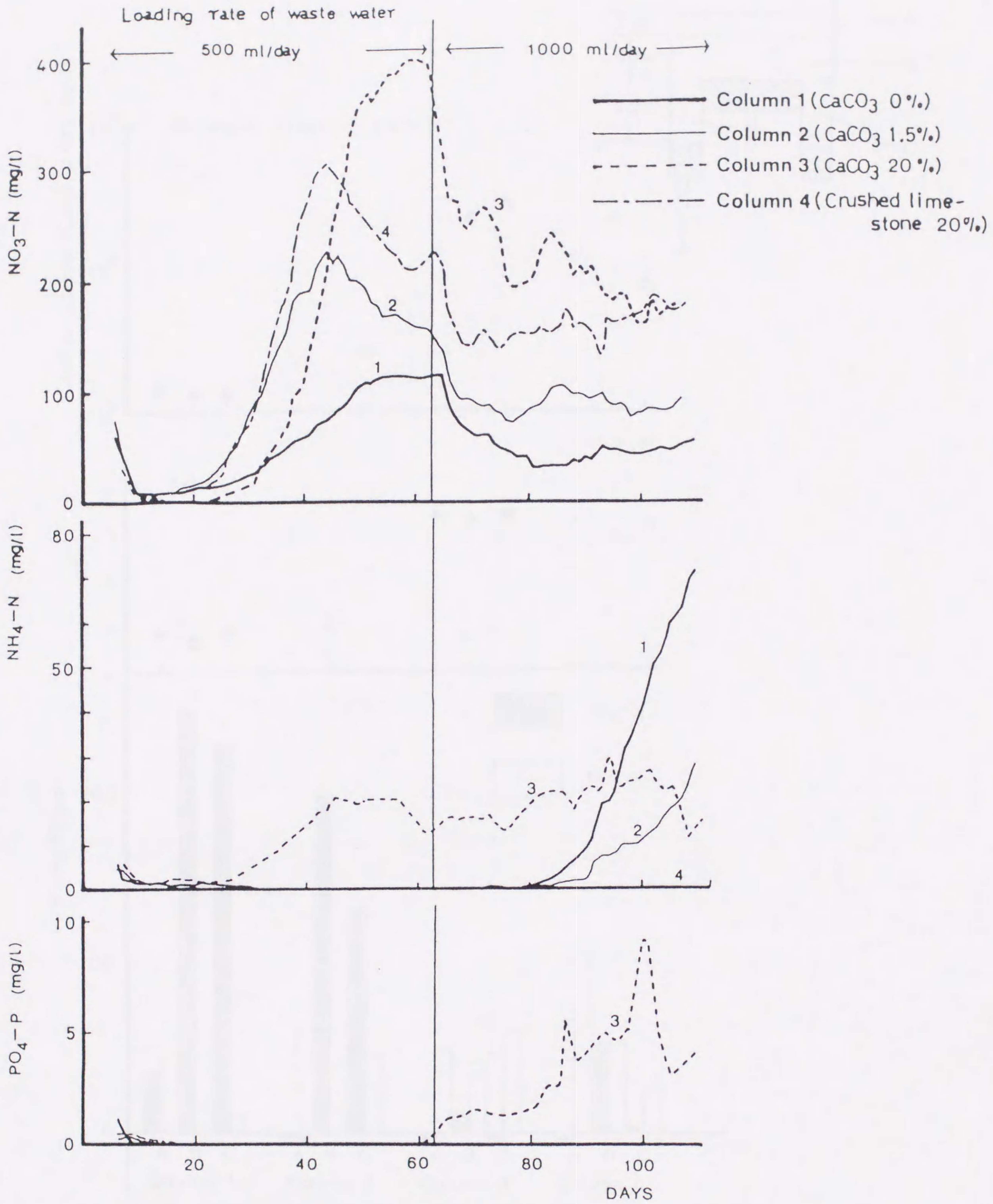


Fig. 2-2 Temporal changes in NO_3-N, NH_4-N, and PO_4-P concentrations of the effluent from the aerobic column.

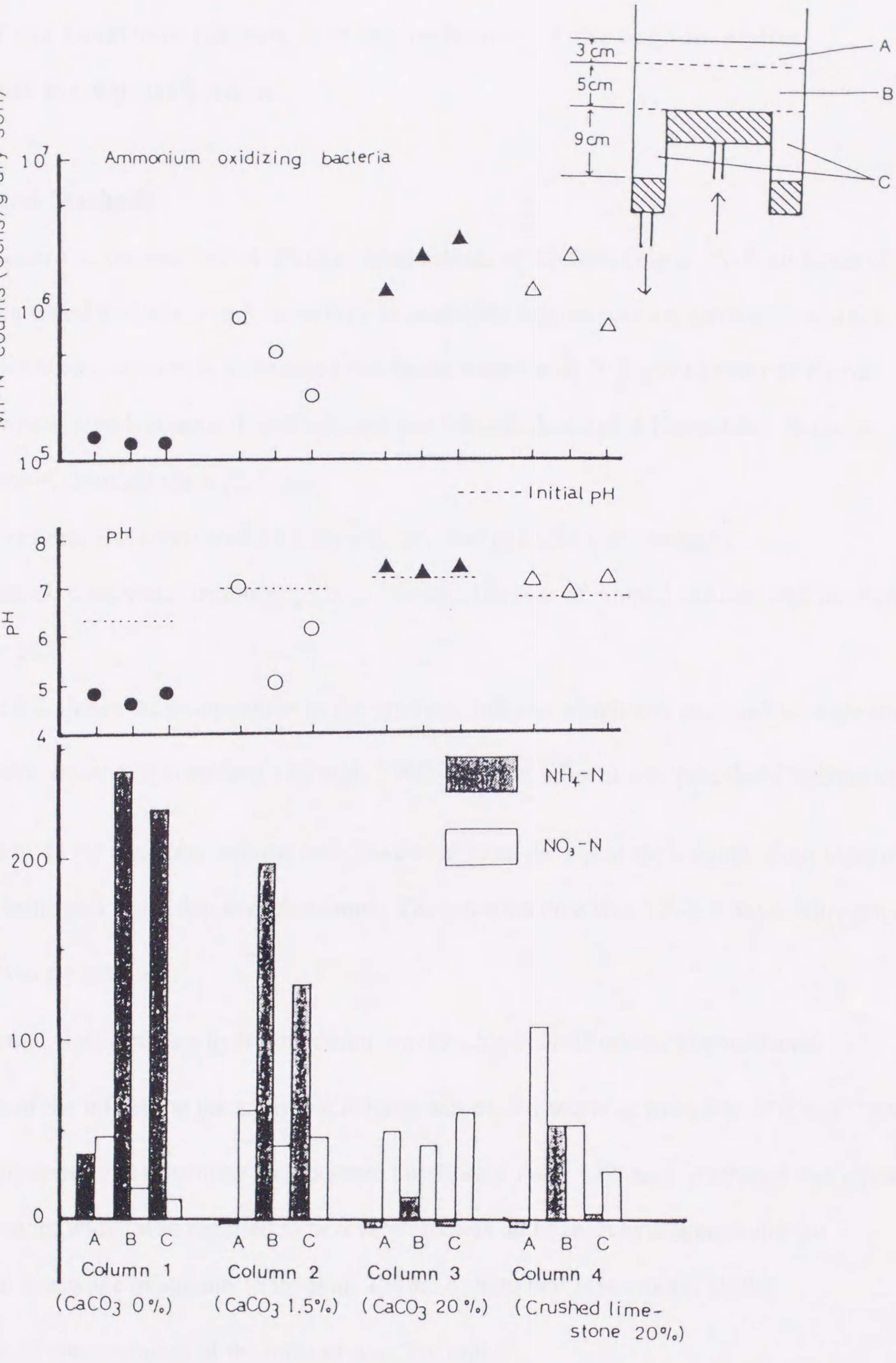


Fig. 2-3 Distribution of ammonium oxidizing bacteria, pH value, and residual N in the packing medium in the aerobic column

2-2 The possibility of using carbonized rice husks or charcoal chips as packing medium of the anaerobic column, and determination of the organic matter requirements for denitrification.

Materials and Methods

The anaerobic column had an effective zone volume of 12 liters (Fig.2- 4). Four kinds of materials were tested to evaluate their suitability as anaerobic column packing medium: column 1, carbonized rice husks; column 2, carbonized rice husks mixed with 20% (w/w) straw (10% rice straw, 10% wheat straw); column 3, volcanic ash soil (Humic Andosol at Kannondai, Tsukuba, Japan); column 4, charcoal chips (2-5 mm).

Each column was inoculated with the activated sludge (1.57 g dry weight) from the livestock wastewater treatment plant at National Institute of Animal Industry and incubated for 1 week at 25℃.

Table 2-2 shows the composition of the synthetic influent which was assumed to originated from the aerobic column. It contained 183 mgL^{-1} NO_3-N. The influent was percolated intermittently by upward flow to the anaerobic column and flowed out from the top of the column. Four liters of the influent was infiltrated every day to each column. The retention time was 1.8-2.6 days. Nitrogen loading rate was 64 $gm^{-3}d^{-1}$.

Methanol was used as a hydrogen donor required for denitrification. The methanol concentration of the influent to the anaerobic column was varied stepwise from 0 to 550 mgL^{-1} every 2 weeks approximately to determine the optimum conditions. After 142 days, methanol was replaced with fumaric acid, which was reported to be a very efficient additive as hydrogen donor for denitrification in sewage treatments (Sato et al. 1989a, b, Sato and Matsumoto, 1990). The fumaric acid concentration of the influent was 350 mgL^{-1}.

This experiment was performed at 25C.

Effluents were collected periodically and the concentrations of NH_4-N, NO_3-N, PO_4-P, and TOC were measured.

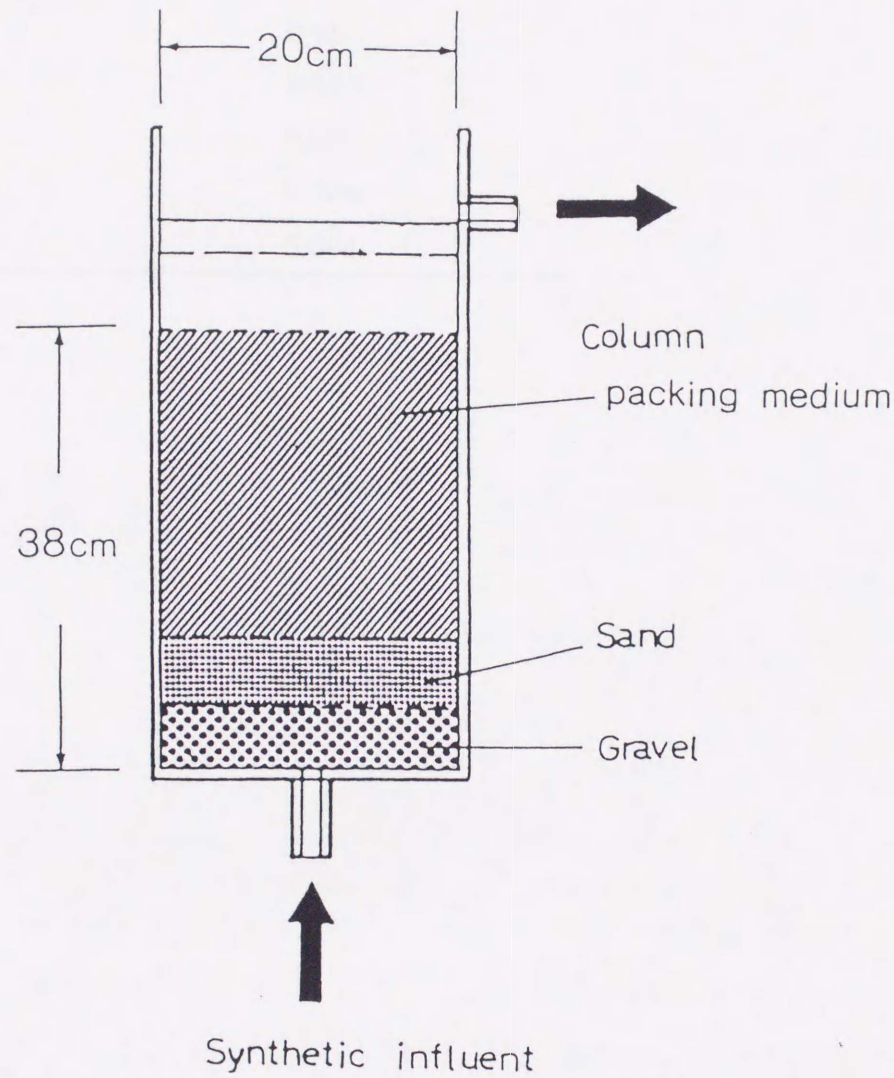


Fig. 2-4 Anaerobic column (cross-section)

Table 2-2. Comparison of synthetic influent (gL^{-1})

KNO_3	1.38
Methanol	0-0.055
Peptone	0.05
Beef extract	0.05
NaCl	0.015
$MgSO_4$ $7H_2O$	0.005
$FeCl_3$ $6H_2O$	0.004
CaCl $2H_2O$	0.004

Results and Discussion

The decrease of the NO_3-N concentration of the effluent suggests that the NO_3-N removal efficiently increased in proportion to the rise of the concentration of added methanol (Figs. 2-5 , 2-6 and Table 2-3). The NO_3-N concentration of the effluent from the column packed with carbonized rice husks and straw was lower than that from the other three columns which did not contain straw throughout the experimental period(Figs. 2-5 , 2-6 and Table 2-3). This observation suggested that straw was utilized as hydrogen donor for denitrification. The effect of straw addition on NO_3-N removal decreased with the rise in the methanol concentration, and the initial level was recovered gradually after methanol addition was discontinued (Fig. 2-5 and Table 2-3). These data suggested that denitrifers utilizing methanol predominated over those utilizing straw only with the increase of the methanol concentration.

It was found that excessive methanol addition to the influent resulted in the increase of the TOC concentration of the effluent (Table 2-3).

In order to determine the amount of methanol required for complete denitrification, the relationship between the methanol concentration of the influent and NO_3-N concentration of the effluent was examined (Fig. 2-6). Based on the reading of three regression curves, except that for the column containing 20% straw (Fig. 2-6), it was found that the denitrification of 1g NO_3-N required 2.8-3.1 g methanol. Theoretically, however it required 1.91 g methanol assuming that all the methanol was used for denitrification (Aida and Nomoto 1988). The ratio of the experimental value (2.8-3.1) to the theoretical value (1.91) was 1.5-1.6. The requirement of the fumaric acid for denitrification was calculated similarly. The ratio of the experimental value (5.9) which was calculated from the regression curves in columns 1 and 4 (Fig. 2-6) to the theoretical value (3.45) for fumaric acid was 1.7. It was concluded that the utilization efficiency of methanol for denitrification was almost the same as that of fumaric acid.

Since 67 days after the start of the experiment, the infiltration of 4 L $(day)^{-1}$ of wastewater to the column packed with volcanic ash soil became impossible due to clogging, the experiment in this column was discontinued.

Conclusions

In the anaerobic column, carbonized rice husks and charcoal chips were more suitable materials as packing medium of the column than volcanic ash soil in terms of permeability of the influent through the medium. The addition of straw to the column packing medium accelerated denitrification, whereas the effect of straw addition decreased with the rise in the concentration of added methanol in the influent.

The denitrification of 1 g of NO_3-N required about 3 g of methanol. The ratio of the experimental value (2.8-3.1) to the theoretical value (1.91) was 1.5-1.6. The utilization efficiency of fumaric acid for denitrification was 1.7, almost the same as that of methanol.

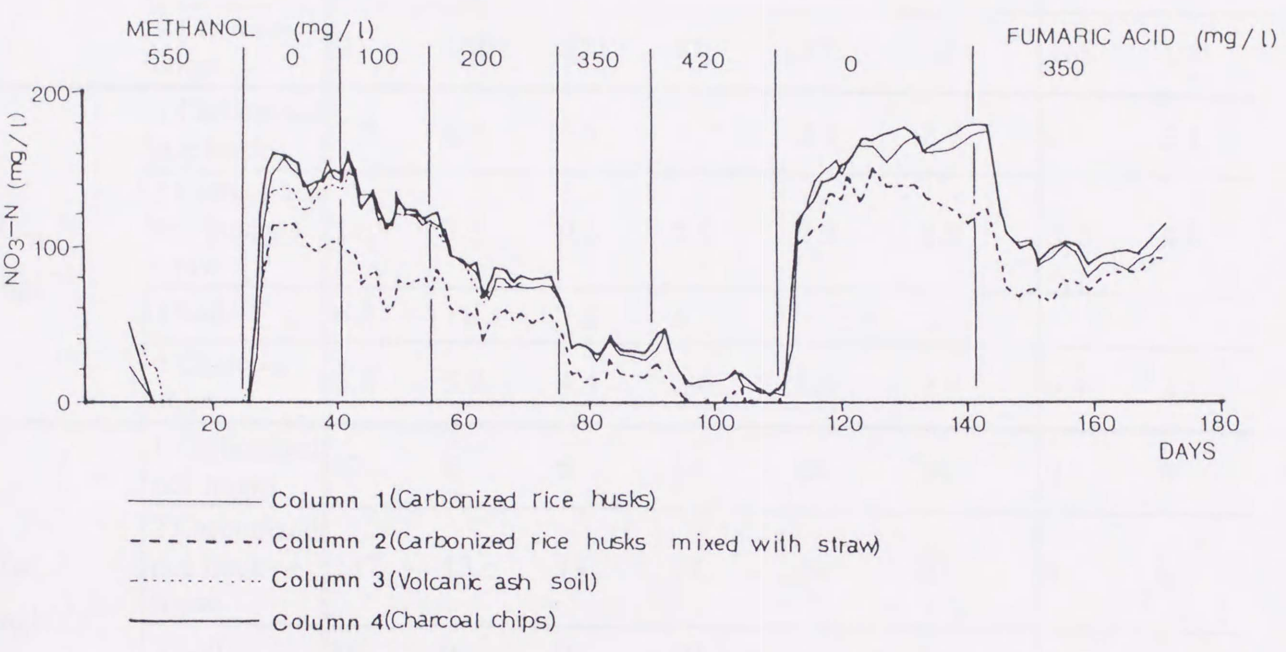


Fig. 2-5. Temporal changes in NO_3-N concentration of the effluent from the anaerobic column. The experiment in column 3 was discontinued 67 days after the start due to clogging.

Table 2-3. Relationship between added methanol concentrations and NO_3-N, NH_4-N, and TOC concentrations (mgL^{-1}) in the effluent from the anaerobic column

Components in the effluent	Packing medium	Methanol (mgL^{-1})						Fumaric acid (mgL^{-1})	
		550	0	100	200	350	420	0	350
NO_3-N (mgL^{-1})	1 Carbonized rice husks	0	145	119	75	32	9	159	93
	2 Carbonized rice husks + straw	0	104	72	52	22	2	132	77
	3 Soil	0	135	116	74	-	-	-	-
	4 Charcoal chips	0	150	122	81	37	12	168	100
NH_4-N (mgL^{-1})	1 Carbonized rice husks	7.5	6.4	6.9	4	2.6	2.7	6	3.1
	2 Carbonized rice husks + straw	11.9	7.5	9.6	5.9	2.3	2.9	5.7	4.6
	3 Soil	6.2	11.3	7.2	5	-	-	-	-
	4 Charcoal chips	6.8	5.9	4.4	2.6	1.9	2.9	6.4	3.1
TOC (mgL^{-1})	1 Carbonized rice husks	47	0	6	14	24	24	0	0
	2 Carbonized rice husks + straw	147	13	19	17	24	27	8	6
	3 Soil	19	0	0	10	-	-	-	-
	4 Charcoal chips	24	0	0	11	19	18	0	0

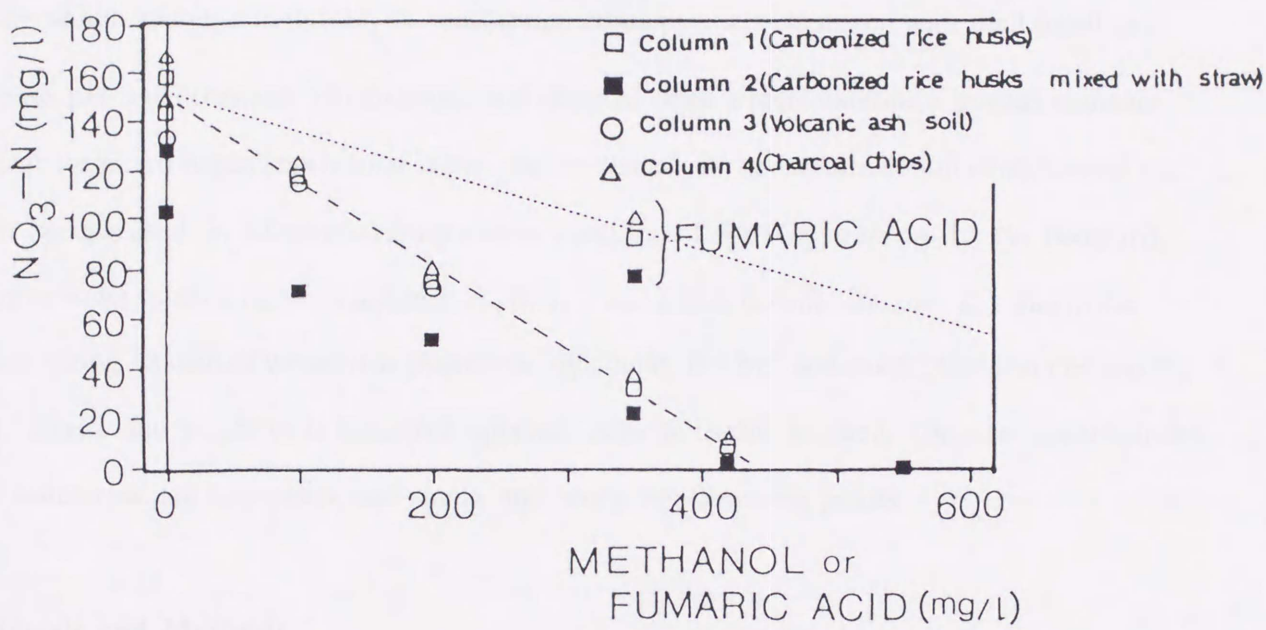


Fig. 2-6 Relationship between NO_3-N concentrations* of the effluent and concentration of added methanol or fumaric acid. *Average NO_3-N concentration during quasi-steady state for each concentration of methanol and fumaric acid. The values of NO_3-N concentrations in the absence of represent those during the periods of 25-40 and 110-140 days in each column except for column 3 in which data were available only in the initial period (Fig. 2-5).

Chapter 3

Use of Higher Plants and Bed Filter Materials for Domestic Wastewater Treatment

It is desirable to add resource reuse and amenity functions to the wastewater treatment system in order to make the system attractive and acceptable. Screening studies to evaluate and compare the effectiveness of three bed filter materials reusable in agriculture and five useful plant species for domestic wastewater treatment were described in this chapter. The bed filter materials consisted of zeolite which exhibits a high NH_4-N adsorption efficiency, zeolite mixed with shell fossil to increase pH and accelerate nitrification, and charcoal chips which exhibits a porous structure suitable for micro-organisms habitat. They can be reused in agriculture as soil conditionors etc. Plant species used in summer-autumn season consisted of rice (*Oryza sativa* L. cv. Takanari), Chinese water spinach (*Ipomea aquatica* Forskai), and zinnia (*Zinnia elegans* L.) and in the winter-spring season of watercress (*Nasturtiu officinale* R. Br.) and stock (*Matthiona incana* R. Br.). Zinnia and stock were terrestrial specied. Rice in useful as feed, Chinese water spinach and watercress are vegetables, and zinnia and stock are flowering plants.

Materials and Methods

(1) Wastewater treatment apparatus.

The experimental apparatus consisted of $0.05m^2$ pots, with of an effective zone volume of 7.5L, that were packed with filter materials planted with higher plants(Fig.1). Eleven combinations of bed filter materials and plants shown in Table 1 were tested to evaluate their efficiency for wastewater treatment The suitability as bed filter was compared among zeolite, a 1:1 mixture of zeolite and shell fossil(v/v), and charcoal chips.

In the summer-autumn season (June to December), seedlings of rice, Chinese water spinach, and zinnia were planted on each bed filter, on June 17, June 20 ,and July 14 1989, respectively(Table 1). Chinese water spinach and zinnia were partly harvested every 10 d and all their above-ground parts were harvested on December 17. Rice was harvested on October 17.

In winter-spring season (January to May), seedlings of watercress were planted on Decembr

28 on the bed where Chinese water spinach had been harvested and seedlings of stock were planted on January 6 1990 on the bed where zinnia had been harvested. Watercress and stock were harvested on May 17.

(2) Operational conditions

Table 3- 2 shows the composition of the artificial wastewater which simulated domestic wastewater(June 1989 to March 1990) and fully oxidized domestic wastewater(April to May, 1990). The concentration of domestic wastewater was cited from Inamori and Sudo(1983).

The wastewater was poured on to the surface of the bed filter, for vertical filtrating, and flew out from the bottom of the pot. The water level was controlled by the height of the effluent tube depending on the plant species, i.e.rice ,+1cm; Chinese water spinach, -2cm; zinnia, -5cm; watercress, -2cm; stock, -5cm.

Depending on the difference of evapotranspiration rate , 3 L of the wastewater was loaded per pot every 2 d in summer-autumn season and 2 L of the wastewater at 1.5 time concentration was loaded per pot every 2 d in winter-spring season. The loading rates of N, P, and total organic carbon (TOC) were 0.47, 0.13, and 1.26 $gm^{-2}d^{-1}$, respectively. In April and May when N was loaded as nitrate, P loading rate was 0.09 $gm^{-2}d^{-1}$, and TOC loading rate was 0 $gm^{-2}d^{-1}$.

These experiments were performed in a greenhouse. The windows were opened except January to March.

(3) Analysis

The volume of effluents were measured whenever wastewater was loaded.

Wastewater flowing in and out was collected periodically and the water quality was analyzed. Concentration of Total N (T-N) was measured using a Yanako T-N Analyzer, and the TOC content was determined using a Simadzu Total Organic Carbon Analyzer TOC 500. Total P (T-P) was measured by ascorbic acid method (APHA, AWWA and WPCF 1989) after persulfate digestion.

The contents of N and P in the above-ground parts of plants and the bed filter materials were measured by using Technicon Auto Analyzer 2 after digesting by salicylate acid-thiosulfate, a modification of the Kjeldahl method (Bremner and Mulvaner 1982).

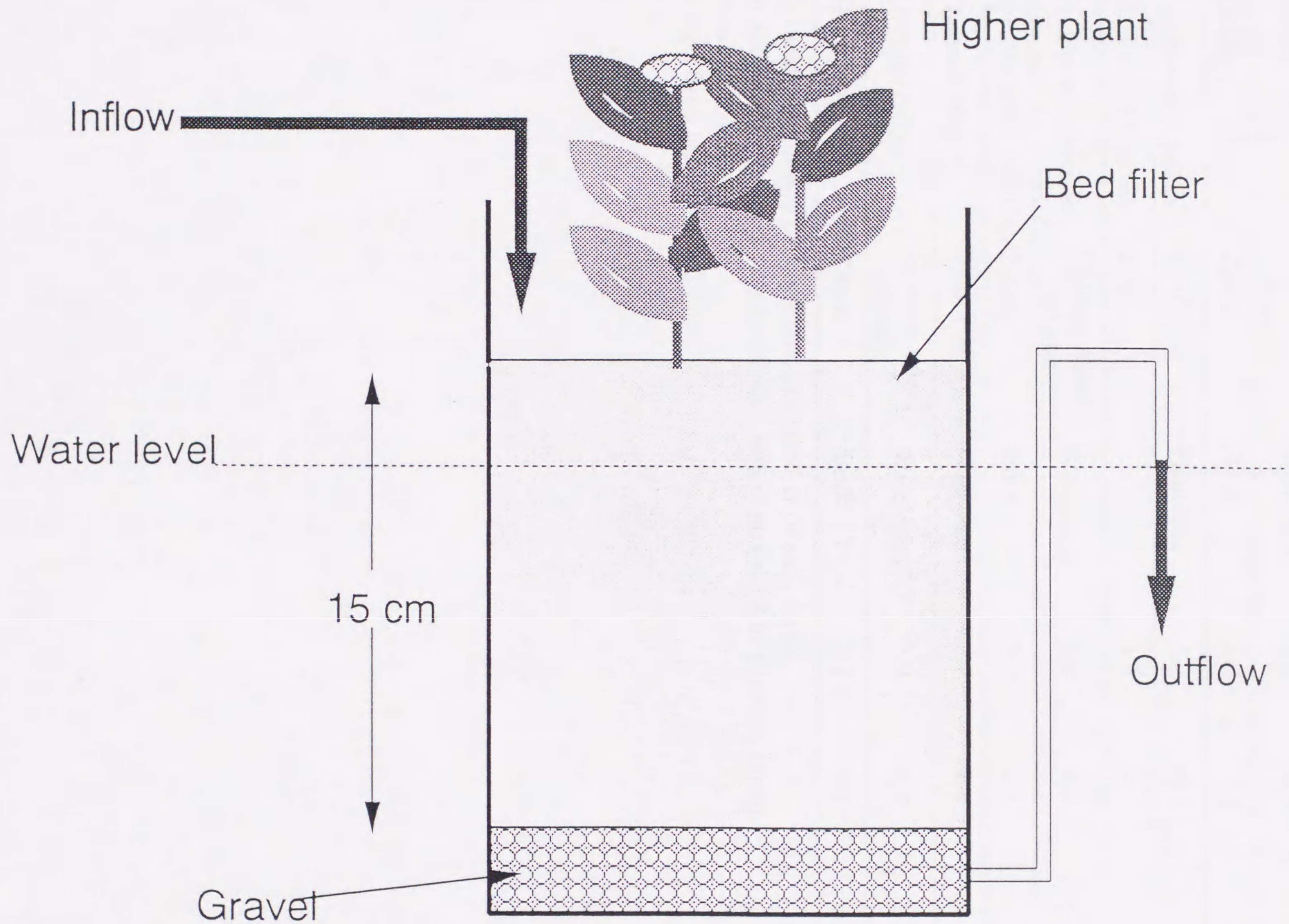


Fig.3-1. Experimental apparatus (plant bed filter).

Table 3-1 Plants and bed filters.

No.	Bed filter material	Plant		Retention time (d)		Water level[d] (cm)
		Jun.-Dec.	Jan.-May	Jun.-Dec.	Jan.-May	
1	Zeolite	Plant-free	Plant-free	2.7	4.1	-5
2	Zeolite	Rice	-	3.3	-	+1
3	Zeolite	Chinese water spinach	Watercress	2.9	4.4	-2
4	Zeolite	Zinnia	Stock	2.7	4.1	-5
5	Zeolite+shell fossils[b]	Plant-free	Plant-free	2.7	4.1	-5
6	Zeolite+shell fossils	Rice	-	3.3	-	+1
7	Zeolite+shell fossils	Chinese water spinach	Watercress	2.9	4.4	-2
8	Zeolite+shell fossils	Zinnia	Stock	2.7	4.1	-5
9	Charcoal chips[c]	Plant-free	Plant-free	2.7	4.1	-5
10	Charcoal chips	Chinese water spinach	Watercress	2.9	4.4	-2
11	Charcoal chips	Zinnia	Stock	2.7	4.1	-5

a Zeolite mainly composed of moldenite, produced in Iwami, Japan.
b Zeolite mixed with the same volume of shell fossils produced in Toyama, Japan.
c Particle size: 2-5mm.
d Water level from top of the bed filter.

Table 3-2 Concentration of components in artificial wastewater and loading rate.

Component	Concentration (mgL^{-1})			Loading rate ($gm^{-2}d^{-1}$)
	Jun.-Dec.	Jan.-May	Apr.-May	
T-N	15.6	23.4	23.4	0.47
NH_4-N	2.8	4.2	0	
NO_3-N	2.4	3.6	23.4	
Org-N	10.4	15.6	0	
T-P	4.2	6.3	4.5	0.13^{a}
PO_4-P	3.0	4.5	4.5	
Org-P	1.2	1.3	0	
TOC	42.0	63.0	0	1.26^{b}

a Loading rate (Apr.-May): 0.09 $gm^{-2}d^{-1}$

b Loading rate (Apr.-May): 0 $gm^{-2}d^{-1}$

Removal efficiency of each pollutant was expressed as the ratio of the amount of the pollutant removed by each system to the amount of the pollutant in the effluent.

Resuls

(1)T-P removal efficiency

Among the plant-free systems, the zeolite and the zeolite+shell fossil filter were more efficient for T-P removal than the charcoal chips filter (Figs. 3-2 and 3-3).

When plants were added to the system, the T-P removal efficiency increased markedly and the difference among the kinds of bed filter material was less appreciable in the summer-autumn (Jun.-Dec.) season (Fig. 3-2).

Planted species had a considerable influencs on the T-P removal efficiency. The systems including rice or Chinese water spinach (hereafter referred to as rice+ or Chinese water spinach+systems) removed more than 88 or 93% of P in the inflow during the experimental period and were more efficient than the system including zinnia (hereafter referred to as zinnia+systems) which removed 70-76% of P in the inflow. The T-P removal efficiency of the Chinese water spinach+systems remained at more than 89% until November, while that of the zinnia+system decreased from October onward (Fig.3-2).

In the winter - spring season, the addition of plants to the system became effective about two months after transplanting. In January and February when plants were in early growth stage, the T-P removal efficiency of the systems including plants was lower or slightly higher than that of the plant-free systems except for zeolite+shell fossil filter planted with watercress. From March onward, the removal efficiency of the systems including plants containing increased markedly with the plant grew (Fig. 3-3). The T-P removal efficiency of the plant-free zeolite system and the plant-free zeolite+shell fossil system rose markedly after the T-P loading rate decreased to 0.09 $gm^{-2}d^{-1}$, as the T-P removal rate did not decrease in both systems (Fig. 3-3).

The zeolite+shell fossil and the charcoal chips filter systems containing watercress (hereafter referred to as watercress+systems) showed the higher T-P removal efficiency than the systems including stock (hereafter referred to as stock+systems). The zeolite + shell fossil filter planted with watercress showed the highest T-P removal efficiency, more than 80% throughout the winter-spring season (Fig. 3-3).

Phosphorus balance data showed 36-48% of loaded P was absorbed by the above-ground parts of Chinese water spinach and watercress, and 24-27% by zinnia and stock(Fig. 3-6). The T-P removal efficiency was considerably influenced by the phosphorus absorption efficiency of the plants.

(2)T-N removal efficiency

Among the plant-free systems, T-N removal efficiency of the zeolite filter and the zeolite+shell fossil filter was superior to that of the charcoal chips filter. After N was laded as nitrate (without organic compound), the T-N removal efficiency of the zeolite filter decreased compared to that of the zeolite+shell fossil filter and the charcoal chips filter(Fig. 3-4, Fig. 3-5).

In the summer-autumn season, the T-N removal efficiency of the systems including plants became higher than that of the plant-free systems regardless of the type of bed filters, although the difference coming the system was not as significant as that for T-P(Fig. 3-4).

Plant species affected the T-N removal efficiency. In the summer-autumn season, the Chinese water spinach+systems and the rice+systems removed more than 84% and 89% of T-N in the inflow during the experimental period, respectively. The zinnia+systems were more efficient than the plant -free systems, which removed 74-83% of T-N in inflow, but less efficient than the systems including the other two species.

In the winter-spring season, the T-N removal efficiency of the watercress +systems was superior to that of the stock+systems and the plant-free systems regardless of any bed filters. On the other hand, the removal efficiency of the stock+systems was as the same as or lower than that of the plant-free system from January to March. From April onward, when nitrogen was loaded as nitrate, the removal efficiency of the plant-free system decreased markedly in zeolite and zeolite + shell fossil filters, and became lower than that of the stock+system(Fig. 3-5). The adding of stock to the systems was not effective for the N removal from wastewater with large amounts of organic nitrogen but effective for the N from nitrate-rich wastewater.

According to the nitrogen balance data, 34-39% of the N in the inflow was absorbed by the above-ground parts of Chinese water spinach and watercress, and 28-35% by zinnia and stock.

Thirty-one to 45% of N in the inflow was considered to be removed by denitrification in the systems including plants, while the amount of remaining nitrogen in the bed filter was lower than 21% in these systems(Fig. 3-7). These data suggested that N removal mainly depended on the plant absorption capacity and denitrification process.

(3)TOC removal efficiency

In summer-autumn season, the plant-free systems removed 69-74% of TOC in the inflow. The adding of Chinese water spinach, rice and zinnia to the systems, slightly improved TOC removal efficiency (Table 3-3).

In the winter-spring season, the plant-free systems showed higher TOC removal efficiency than the systems including plants. The TOC removal efficiency of the watercres+systems was lower than that of the stock+systems(Table 3-4).

Discussion

(1)Effect of bed filter materials of the wastewater treatment efficiency.

The results from the plant-free systems indicated that the zeolite filter and zeolite+shell fossil filters were more effective than the charcoal chips filter for P removal.

Nitrogen removal efficiency of the plant-free zeolite and zeolite+shell fossil filters was higher than that of charcoal chips filter when wastewater contained N mainly as organic compounds, because NH_4-N in the wastewater and NH_4-N derived from organic N in the wastewater were adsorbed by zeolite.

On the other hand, since the zeolite filter was not effective for the removal of N from the wastewater containing N as nitrate, the TOC concentration of the effluent from the zeolite filter was lower than that from the zeolite+shell fossil filter and charcoal chips filter(Table 3- 4). These results indicated that the amount of organic compounds (containing microorganisms) accumulated during the experiments in the zeolite filter were smaller than zeolite+shell fossil filter and charcoal chips filter. It was reported that the amount of organic compounds utilized as hydrogen donors for denitrification determined the NO_3-N removal efficiency in the anaerobic soil column and the anaerobic contact column systems (Aida 1989; Chapter 2). These observatios suggested that denitrification was not appreciably accelerated in zeolite filter by the lack of hydrogen donors when the concentration of the organic compounds (hydrogen donors) in the wastewater was low.

In the systems including plants except for watercress, zeolite, and zeolite+shell fossils were more effective as bed filters than the charcoal chips filter for P removal. The mechanism underlying the higher P removal efficiency of the zeolite+ shell fossil filter in the watercress+systems than that of zeolite and charcoal chips filter is being analyzed. Zeolite and zeolite+shell fossils were also effective as bed filter of plant-bed filter system for the removal of N from domestic wastewater (organic N rich). In stock+systems, the N removal efficiency of the zeolite filter was lower than zeolite+shell fossil filter and charcoal chips filter when nitrate-rich (containing the few organic conpounds) wastewater was loaded, because the nitrate absorption rate of stock was not sufficient to induce the decrease of the N removal efficiency of the zeolite filter.

(2)Effect of planting of the wastewater treatment efficiency.

When plants were added to the system, the P and N removal efficiency was enhanced. The effect of plant addition on P removal was more appreciable than that on N removal. Based on the N balance data, it was obsorbed that the percentage of removal by bed filters, denitrification and other process was decreased by the addition of plants to the systems. These findings indicated that plant absorption competed with microbial activities such as nitrification and denitrification, and the plants absorbed nitrogen adsorbed on the bed filters.

When root residues of previously grown plants were present (in the winter-spring season), the zeolite and zeolite+shell fossil filter systems including plants sometimes showed a lower P and N removal efficiency than the plant-free systems during the first 2 months of plant growth. This phenomenon may be ascribed to the fact that the P and N absorption rate of the plants was lower than the rate of supply of P and N from the root residues of previously grown plants when the plants were in early growth stage.

The effectiveness of the addion of plants to the system on TOC removal was not conclusive. A negative effect was obserbed in the watercress+systemis in the winter-spring season. It was considered that organic carbon was supplied from the root residues of the plants grown in the summer-autumn season. According to our observation, the root residues of Chinese water spinach (planted before watercress) were more abundant than those of zinnia (planted before stock).

The planted species affected the P and N removal efficiency. Rice and Chinese water spinach were more effective than zinnia, and watercress was more effective than stock. Rice, Chinese water spinach, and watercress are wetland plants, while zinnia and stock are terrestrial species. Wetland plants adapted to anaerobic conditions display an extensive internal lacunal system which can transport O_2 to the roots (Guntespergen 1989). Anaerobic conditions were created within the bed filter as O_2 was consumed by the decomposition of organic compounds in the wastewater. It is possible to consider the adaptability to anaerobic condition affected to some extent the plant growth and P and N absorption efficiency.

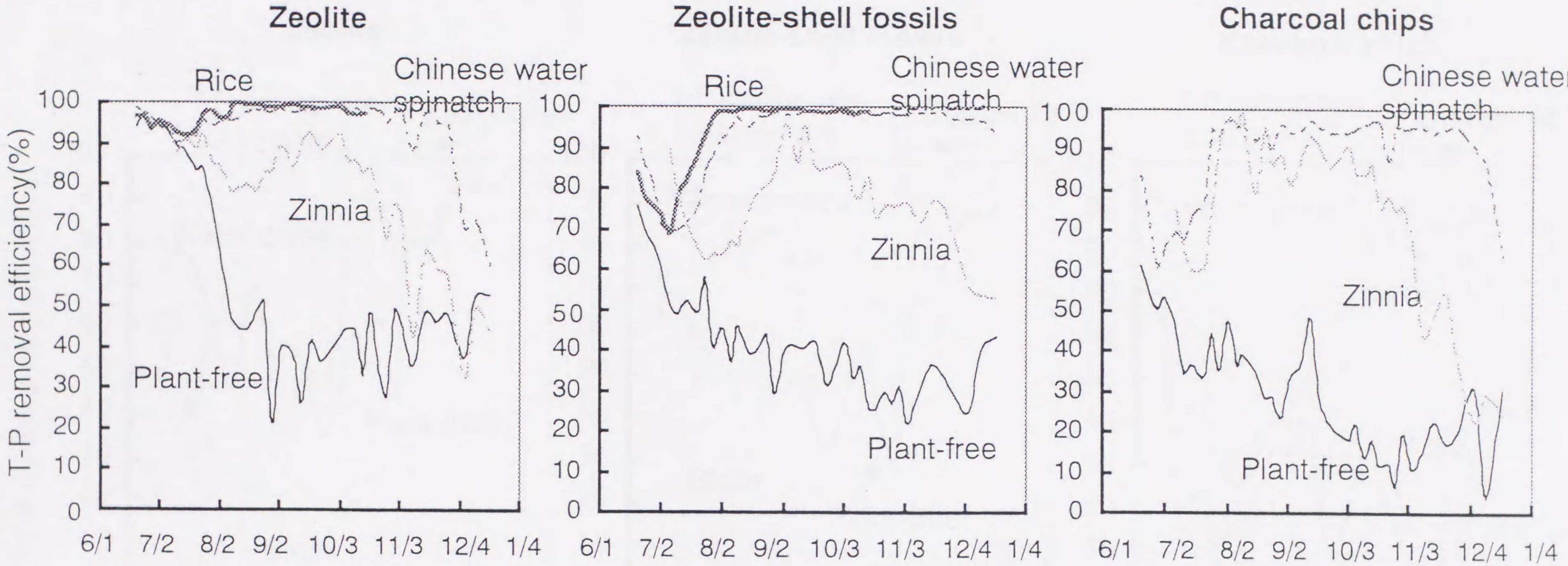
It was reported that O_2 supplying from the roots of reed also enhanced the microbial activity (ammonification and nitrification) which accelerated N removal from domestic wastewater (Wolverton 1983, Reddy 1988) . In our study, it remains to be determined whether denitrification was promoted in the systems including wetland plants. It may be considered that the O_2 supply from the roots of rice, Chinese water spinach, and watercress was not sufficient to accelerate nitrification, or that the N loading rate was low and microbial organisms and plants competed for nitrogen.

Conclusions

(1) Zeolite and zeolite+shell fossil was tended to be more effective as plant bed filter systems for the removal of P and N from domestic wastewater than charcoal chips.

(2) The addition of higher plants to the bed filters resulted in the enhancement of N and P removal from domestic wastewater, though the effectiveness of the addition of plants to the system on TOC removal was not conclusive. Plant species significantly affected the P and N removal efficiency. Rice, and Chinese water spinach were more effective than zinnia, while watercress was more effective than stock.

(3) The system consisting of a zeolite+shell fossil bed filter planted with Chinese water spinach in the June-December period and with watercress in January-May period showed highest P and N removal efficiency, i.e. more than 80% during experimental period. These systems removed 91% of P and 90% of N and the average removal rate of P and N was 0.11 and 0.42gm-2d^{-1}, respectively.



F1g.3-2. Changes of T-P removal efficiency during the summer-autumn season (June-December). T-P loading rate was 0.13 $gm^{-2}d^{-1}$.

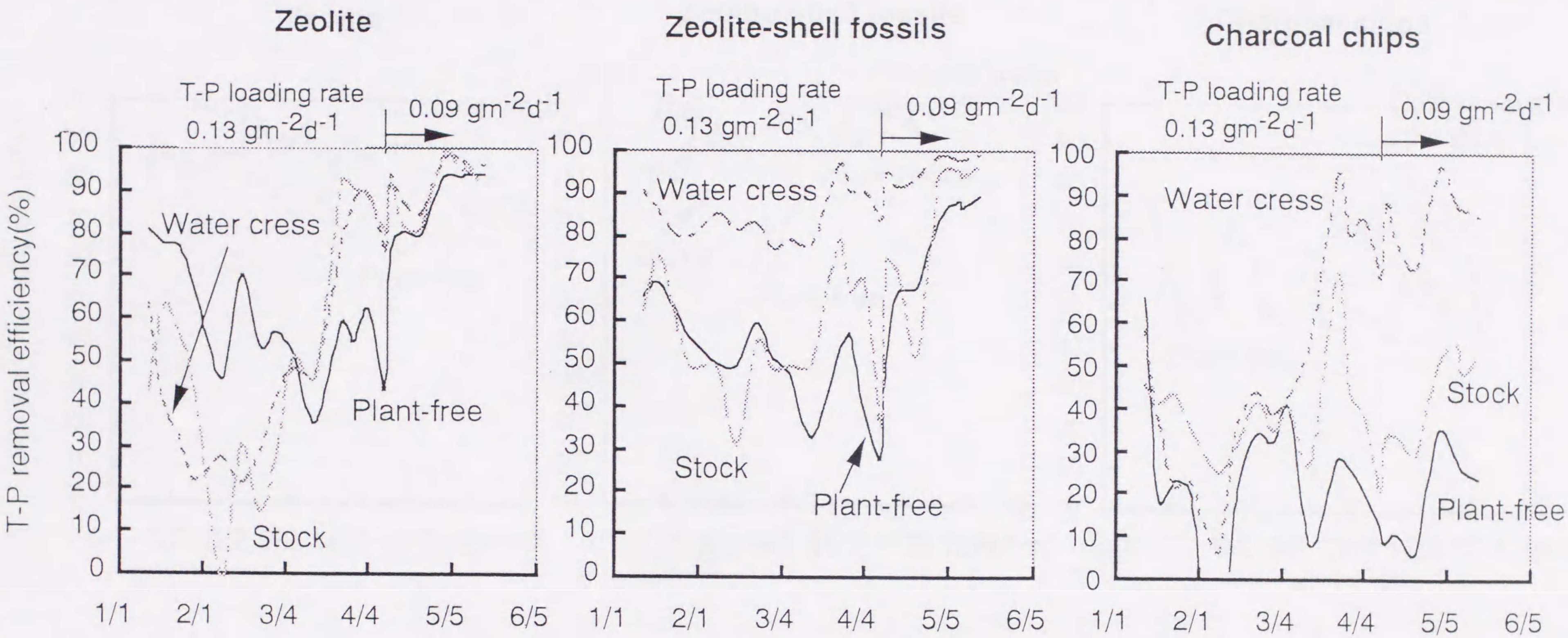
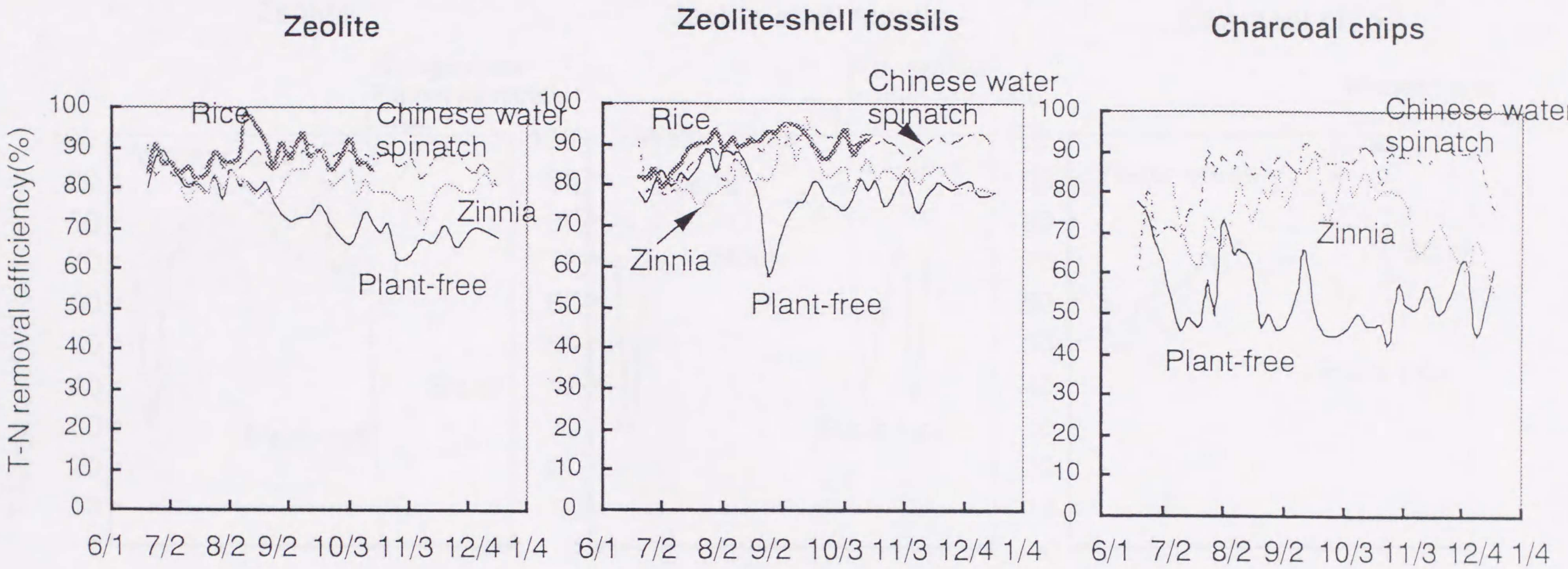
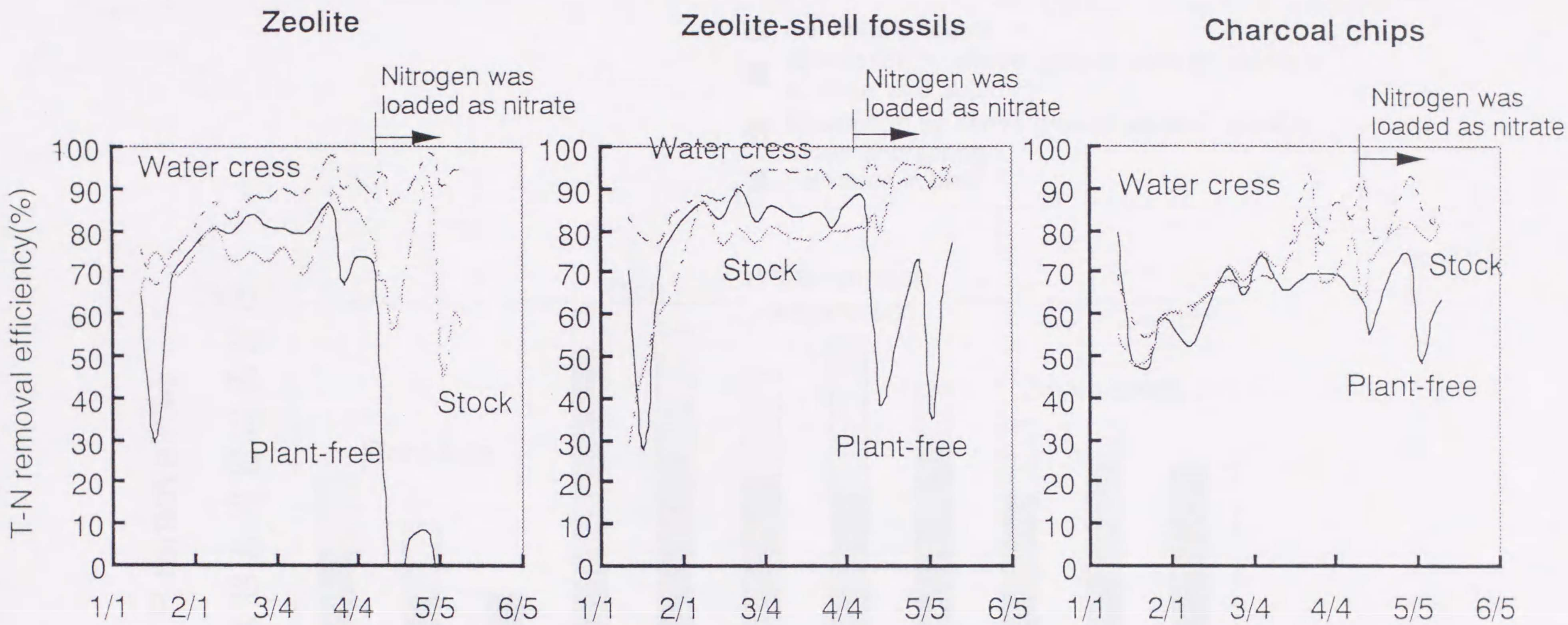


Fig.3-3. Changes of T-P removal efficiency during the winter-spring season (Jaunary-May). Watercress was planted in the bed where Chinese water spinach had been grown and stock was planted in the bed where zinnia had been grown.



F1g.3-4. Changes of T-N removal efficiency during the summer-autumn season (June-December). T-N loading rate was 0.47 $gm^{-2}d^{-1}$.



F1g.3-5. Changes of T-N removal efficiency during the winter-spring season (January-May). Watercress was planted in the bed where Chinese water spinach had been grown and stock was planted in the bed where zinnia had been grown. T-N loading rate was $0.47 gm^{-2}d^{-1}$.

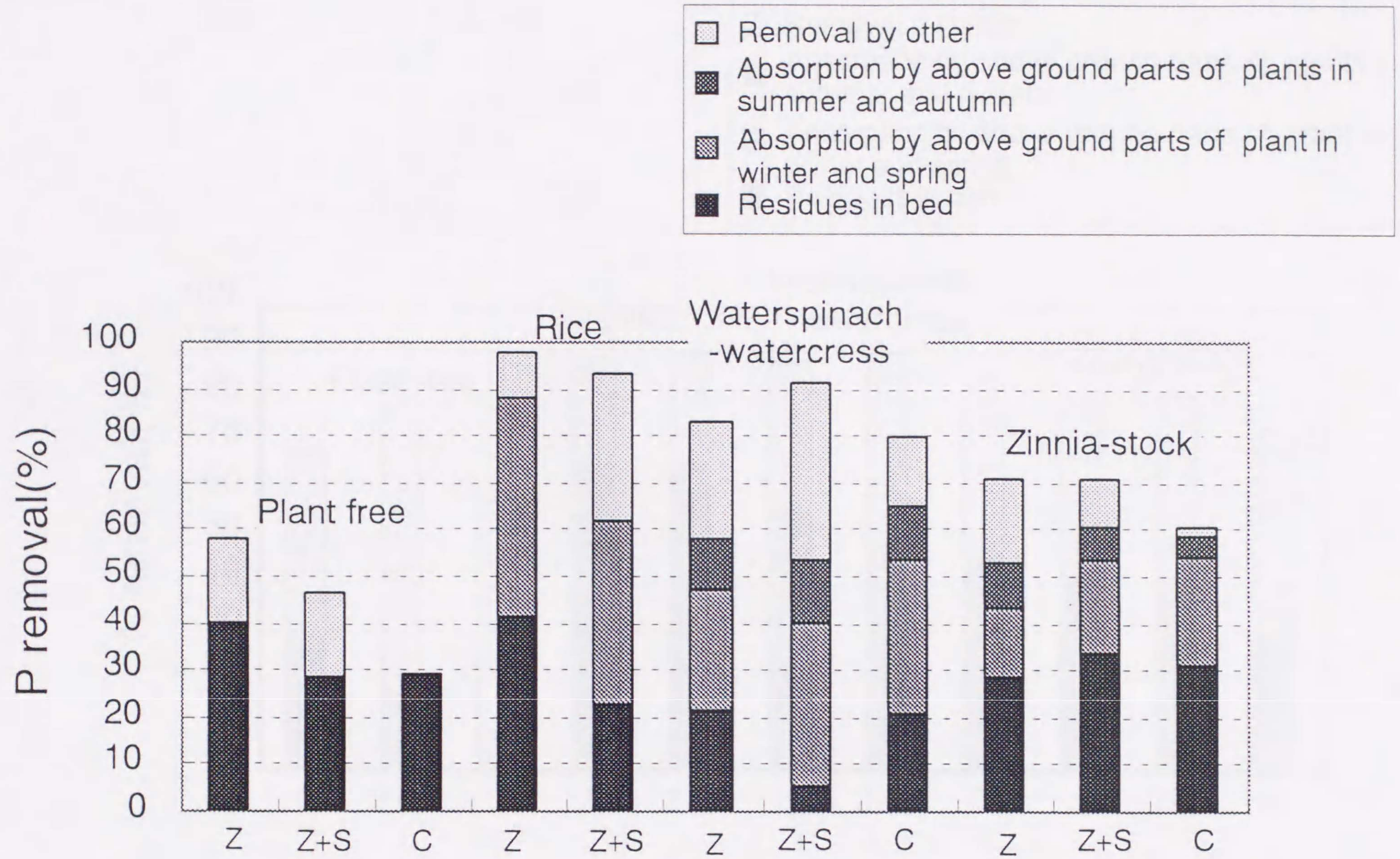


Fig.3- 6. Phosphorus balance.

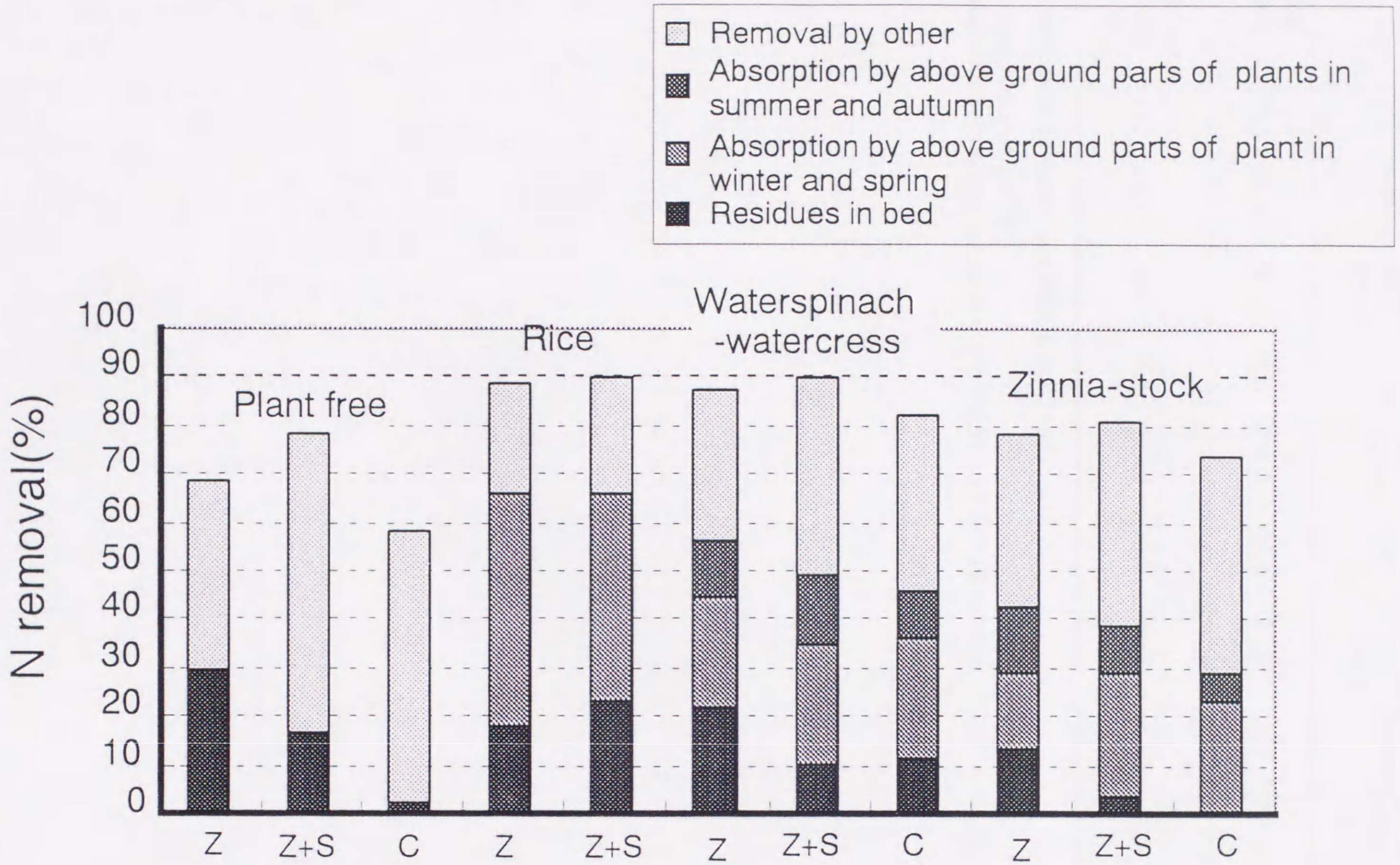


Fig.3- 7. Nitrogen balance.

Table 3-3 TOC removal efficiency(%) and concentration of effluent during the summer-autumn season (June to December).

	Zeolite				Zeolite+shell fossil				Charcoal chips		
	Plant free	Rice	Chinese water spinach	Zinnia	Plant free	Rice	Chinese water spinach	Zinnia	Plant free	Chinese water spinach	Zinnia
Removal efficiency (%)[a]	72.2	79.4	79.1	72.6	74.4	75.9	81.5	76.7	69.2	79.3	74.0
Concentration of effluent (mgL^{-1})	12.1	12.3	11.8	14.9	12.2	15.6	11.2	16.1	14.5	12.3	16.5

TOC concentration in wastewater flowing in 42 mgL^{-1}.

TOC loading rate 1.26 $gm^{-2}d^{-1}$

a Removal efficiency={(amount of TOC removal by each system)/(amount of TOC loaded)}x100.

Table 3-4 TOC Removal efficiency(%) during winter-spring season January to May)

		Zeolite			Zeolite+shell fossil			Charcoal chips		
		Plant free	Watercress	Stock	Plant free	Watercress	Stock	Plant free	Watercress	Stock
Jan.-May	Removal efficiency (%)	77.4	42.4	73.0	76.1	25.1	75.2	70.6	31.0	54.7
	Concentration of effluent (mgL^{-1})	15.0	42.6	19.0	15.4	56.0	16.4	20.2	52.1	31.5
Apr.-May	Concentration of effluent (mgL^{-1})	2.6	10.2	8.2	6.2	14.1	9.2	9.5	17.2	11.4

TOC concentration in wastewater flowing in Jan.-Mar.: 63.0 mgL^{-1}; Apr.-May: 0 mgL^{-1}

TOC loading rate Jan.-Mar.: 1.26 $gm^{-2}d^{-1}$; Apr.-May: 0 $gm^{-2}d^{-1}$.

a Removal efficiency={(amount of TOC removal by each system)/(amount of TOC loaded)}x100.

Chapter 4

Evaluation of Useful Terrestrial and Aquatic Plant Species for Removing Nitrogen and Phosphorus from Domestic Wastewater

It is important to add functions of resource reuse and amenity to wastewater treatment systems by introducing crops and flowering plants. Since the majority of such plants are terrestrial species, the author developed wastewater treatment ditches in which terrestrial species can grow. In Chapter 3, plant species significantly affected the P and N removal efficiency and the addition of plants to bed filter systems did not have good effects on organic compound treatment, compared with N and P removal. In this chapter, studies carried out to evaluate and compare the effectiveness of 20 kinds of economically important plant species and plants with an aesthetic value for the N and P treatment of the secondary effluent, containing less organic compounds, are described. In addition, the role of aeration by some kinds of aquatic plants is analyzed.

Materials and Methods

(1)Design of the plant bed filter ditches

Since the majority of the plants used for human life are terrestrial species, I designed a wastewater treatment ditch in which terrestrial species can grow. The ditch contained baskets filled with bed filter material and were planted with higher plants (Fig.4-1, Plates 4-1 and 4-2). The bed filter material was zeolite (particle size: 3 - 10 mm) due to its high NH_4-N adsorption efficiency, its suitability for plant culture in bench-scale experiments (Chapter 3) , and its reusability in agriculture as soil conditioners. The depth of zeolite in the baskets varied based on the saturation tolerance of the respective plant species. The bed filter surface was about 0.05-0.1 m higher than the water level for terrestrial species and the same as the water level for aquatic species.

The experimental ditches were small, 0.4 m wide, 0.4 m deep, and 4m long, and 0.5 m wide, 0.4 m deep, and 1m long. The baskets, which were 0.4m wide, 0.4m deep, and 0.3m long, were filled with zeolite (particle size 3 - 10 mm). Six baskets were placed in the 4 m long ditches and 2 baskets in the 1 m long ditches. Water depth was 0.3 m. The height of zeolite packed in the baskets was 0.3 m for aquatic species and 0.35 - 0.4 m for the terrestrial species. The weight of zeolite in each basket for terrestrial species was 26 - 29 kg and that for aquatic species, 22 kg. Generally, 6 seedlings were planted in one basket.

(2)Plant species

Thirteen terrestrial and 7 aquatic plant species (Table 7-1) that can be utilized by the rural communities were tested to evaluate their efficiency in removing N and P from the wastewater. Each ditch was planted with one species.

Seedlings of African marigold (*Tages electa* L.) , rice (*Oryza sativa* L. cv Takanari), adlay (*Coix lacryma-jobi* L. var. *mayuen* Stapf), sorghum (*Sorghum vulgare* Pers.), sun hemp (*Crotalaria juncea* L.), and kenaf (*Hibiscus cannabinus* L.) were planted in May or June. Their aboveground parts were harvested in October or November.

Seedlings of hanana (*Brassica campestris* L. var.), wheat (*Triticum aestivum* L.), stock (*Mattiora incana* R. Br.), safflower (*Carthamus tinctorius* L.), tall fescue (*Festuca arundinacea* Schreb.), barley (*Hordeum vulgare* L. cv. kankei b443), autumn poem (*Brassica* sp.), and Italian ryegrass (*Lolium multiflorum* Lam.) were planted in November. Their aboveground parts were harvested the following May.

The perennial plants, i.e., papyrus (*Cyperus papyrus* L.), reed (*Phragmites communis* Trin), iris (*Iris pseudacorus* L.), orchard grass (*Dactylis glomerata* L.), rush (*Juncus effusus* L. var. *decipiens* Buchen), and calla (*Zantedeschia aethiopica* Spreng) were cultivated for a period of one year. after which the aboveground parts of the papyrus, reed, and iris were harvested.

In addition, one ditch which was plant-free was monitored as the control. Hanana, tall fescue, barley, autumn poem, and Italian ryegrass were examined in the 1m long ditches, and the other species were examined in the 4m long ditches. The experiments were performed in a greenhouse.The windows were opened except from December to March.

(3)Operational conditions

To ensure the maintenance of constant N and P concentrations and loading rates, artificial wastewater simulating secondary effluent was continuously added from one end of the ditch and flowed out from the opposite end. The undiluted solution for artificial wastewater was diluted with tap water to 1/1000 automatically and supplied to each ditch at a constant flow rate using a Kaneki

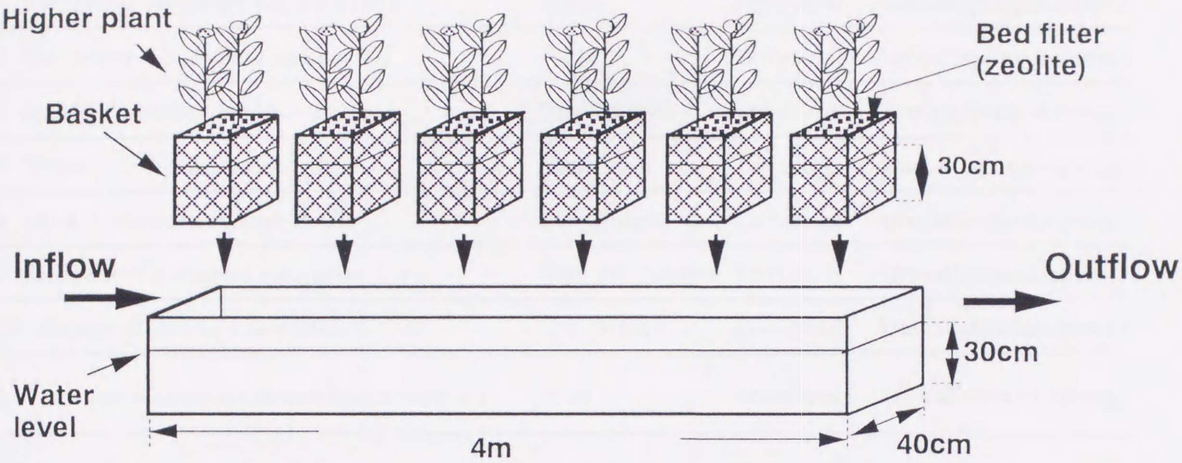


Fig.4-1. Plant bed filter ditch.

Table 4-1. Plants cultivated in the bed filter ditches and their use.

Plant	Use	Aquatic/ Terrestrial	Annual/Perennial
1. African Marigold (*Tages electa* L.)	Cut flowers	Terrestrial	Annual(spring-autumn)
2. Rice (*Oryza sativa* L. cv Takanari)	Feed	Aquatic	Annual(spring-autumn)
3. Adlay (*Coix lacryma-jobi* L. var. *mayuen* Stapf)	Feed, food, medical use	Aquatic	Annual(spring-autumn)
4. Sorghum (*Sorghum vulgare* Pers.)	Feed	Terrestrial	Annual(spring-autumn)
5. Sun hemp (*Crotalaria juncea.* L.)	Fiber	Terrestrial	Annual(spring-autumn)
6. Kenaf (*Hibiscus cannabinus* L.)	Fiber, Paper	Terrestrial	Annual(spring-autumn)
7. Wheat (*Triticum aestivum* L.)	Feed, food	Terrestrial	Annual(autumn-spring)
8. Stock (*Mattiora incana* R. Br.)	Cut flowers	Terrestrial	Annual(autumn-spring)
9. Safflower (*Carthamus tinctorius* L.)	Dye, cut flowers	Terrestrial	Annual(autumn-spring)
10. Hanana (*Brassica campestris* L. var.)	Cut flowers	Terrestrial	Annual(autumn-spring)
11. Tall fescue (*Festuca arundinacea* Schreb.)	Feed	Terrestrial	Annual(autumn-spring)
12. Barley (*Hordeum vulgare* L. cv. kankei b443)	Feed, food	Terrestrial	Annual(autumn-spring)
13. Autumn poem (*Brassica* sp.)	Vegetable	Terrestrial	Annual(autumn-spring)
14. Italian ryegrass (*Lolium multiflorum* Lam.)	Feed	Terrestrial	Annual(autumn-spring)
15. Papyrus (*Cyperus papyrus* L.)	Paper , handicrafts	Aquatic	Perennial
16. Reed (*Phragmites communis* Trin)	Handicrafts	Aquatic	Perennial
17. Iris (*Iris pseudacorus* L.)	Cut flowers	Aquatic	Perennial
18. Orchard grass (*Dactylis glomerata* L.)	Feed	Terrestrial	Perennial
19. Rush (*Juncus effusus* L. var. *decipiens* Buchen)	Tatami in Japan	Aquatic	Perennial
20. Calla (*Zantedeschia aethiopica* Spreng)	Cut flowers	Aquatic	Perennial

Table 4-2 . Concentration of components in artificial wastewater and loading rate (from August 1990 to April 1994).

Components	Concentration (mgL^{-1})	Loading rate ($gm^{-2}d^{-1}$)
T-N	20.0	1.41-2.08
NH_4-N	6.0	
NO_3-N	14.0	
T-P	3.3	0.20-0.33
TOC	2-3	

Loading rate of wastewater volume was 74-100 $Lm^{-2}d^{-1}$.

Plate 4-1. Plant bed filter ditch.

Plate 4-2. Basket filled with zeolite

diluter (Taiyo-kogyo). Table 2 shows the composition and loading rate of the artificial wastewater simulated as secondary effluent. The wastewater containing 20 mgL^{-1} of N and 3.3 mgL^{-1} of P, was supplied to the ditches. The loading rate of wastewater volume was 74-85 $Lm^{-2}d^{-1}$ during the period from September 1990 to May 1992, and 90-100 $Lm^{-2}d^{-1}$ during the period 1993 and 1994 (209 $Lm^{-2}d^{-1}$ in July 1990 and 104 $Lm^{-2}d^{-1}$ in August 1990). The retention time of the wastewater was about three days during the period except for July 1990. N and P loading rates were 1.41 - 2.08 $gm^{-2}d^{-1}$ and 0.20-0.33 $gm^{-2}d^{-1}$, respectively, during the period from August 1990 to April 1994. The concentration of the secondary effluent was based on Hidaka (1986).

(4)Measurement

The volume of wastewater flowing in and out was measured and the water quality was analyzed once a week. The concentration of Total N (T-N) was measured by using a Mitsubishikasei T-N analyzer, and Total P (T-P) content was measured by the ascorbic acid method (APHA, AWWA, and WPFC 1989) after persulfate digestion.

The removal rate was calculated as the difference between the rate of N and P in the wastewater entering and leaving the ditches divided by the area of the ditches. (N & P entering rate: N & P concentration x rate of influent water volume . N & P leaving rate: N & P concentration x rate of effluent water volume.)

The content of N and P in the aboveground parts of plants was determined using Technicon Traacs 800 after digestion with salicylate acid-thiosulfate as a modification of the Kjeldahl method (Bremner and Mulvaney 1982).

The temperature in the greenhouse was measured at 11:00 AM.

Results and Discussion

(1) Conditions of plants

Plants studied in this experiment grew vigorously with some of them (papyrus, kenaf, sun hemp, reed, sorghum etc.) reaching about 3m in height (see Plates 4-3 to 4-9). Plant roots grew out of the baskets and formed root mats in the water. Roots of kenaf ,sunn hemp, and sorghum (terrestrial species) were concentrated near the surface of the water. Papyrus and reeds (aquatic plants) extended their roots deeply into the water. Apparently, terrestrial species extended their roots to areas rich in oxygen, while aquatic plants extended their roots even to areas deficient in oxygen because they have an internal lacunal system which can transport oxygen from the atmosphere to the roots (Guntenspergen 1989).

(2) N and P removal by plant free ditch

In the plant-free ditch the T-N and T-P concentrations decreased only slightly (Fig.4-2). The decrease of the T-N concentration was apparently caused by NH_4-N adsorption onto zeolite. The plant-free ditch was efficient in reducing NH_4-N concentration to some extent (Fig.4-8). The average decrease of T-N and NH_4-N concentrations in the plant-free ditch was 1.4 mgL^{-1} and 3.3mgL^{-1}, respectively and the increase of the NO_3-N concentration was 2.8mgL^{-1} (Fig.4-8). These observations indicate that the reduction of the NH_4-N concentration was mainly due to nitrification. The incomplete removal of NH_4-N in the plant-free ditch was ascribed to the fact that the surface of the zeolite particles became gradually saturated with NH_4-N, or some part of the wastewater passed through the large void between the zeolite particles without making any contact with the zeolite, though further research is needed.

(3) Effect of plant species on N and P removal

Seasonal change

The use of higher plants in the ditches enhanced the N and P removal rates from the wastewater. Plant species in the ditches considerably affected the N and P removal efficiency (Figs.4-2 and 4-3).

The season and period when the ditches showed high N and P removal efficiency also depended on the plant species in the ditches. When a ditch was planted with annual plants in May or June, the T-P and T-N concentrations in the ditch effluent increased about one month after the transplanting as the plants grew. The T-P and T-N concentrations were the lowest from August to October, while in the case of the ditches with perennial plants such as papyrus and reed that were planted in the previous year, the concentrations became relatively low from May onward (Fig.4-2). It was observed that the temperature affected the changes of N and P removal rates of perennial plant ditches throughout the year since plant communities were fully established. Maximum values of N and P removal rates (maximum value of monthly average) in the case of the kenaf, papyrus, and sorghum ditches were higher than those of the other ditches in summer and autumn. Maximum observed P removal rate of the adlay ditches was also higher (Fig.4-3).

When the ditches were cultivated with annual plants (Italian ryegrass, barley, hanana) in autumn (November), the T-P and T-N concentrations in the ditch effluents started to decrease the following February when the plant biomass began to show a marked increase. The T-P and T-N concentrations in the effluents from most of the ditches were lowest in March and April. N and P removal rates of the Italian ryegrass ditch were the highest in the ditches planted in the spring. The effluent volume of the Italian ryegrass ditch was the lowest because of the high evapotranspiration rate, although T-N and T-P concentrations in the Italian ryegrass ditch effluent were not the lowest in the spring of 1994 . The barley ditch also showed a high T-N removal rate (Fig.4-3).

The T-P concentration in the papyrus ditch was 1.5 - 2.0 mgL^{-1} lower than that in the reed ditch during the period from January to March, 1992. T-P removal rate of the papyrus ditch decreased to 0.10 -0.14 $gm^{-2}d^{-1}$ during the period from January to April (1992) when T-N concentrations in both ditches were almost same as that in the plant-free ditch (Figs 4-2 and 4-3). Thus the P removal rate of the papyrus ditch was 2 times higher than that of the reed or plant-free ditches. It remained to be determined whether papyrus absorbed phosphorus during the winter or whether the high removal rate was due to one or more other physico-chemical mechanisms.

Among the plant species with an aesthetic value, African marigold, hanana and calla were most effective for N and P removal (Figs.4-2 and 4-3).

Maximum values of N removal rates obtained for the papyrus, kenaf, sorghum, and Italian ryegrass ditches were 1.3-1.7 $gm^{-2}d^{-1}$ and maximum values of the P removal rate were 0.24-0.26 $gm^{-2}d^{-1}$ (Fig.3). These values were comparable to those obtained for water hyacinth (N: 0.5-1.6 $gm^{-2}d^{-1}$, P: 0.1-0.3 $gm^{-2}d^{-1}$) (Ozaki et al. 1993).

Biomass and N, P removal

Figure 4-4 shows nitrogen balance during the period from May to October, 1991 calculated for the ditches planted in May, 1991 (kenaf, papyrus, sunn hemp and plant-free ditches). According to these data, 51.5% of N in the inflow was removed by the kenaf ditch , 48.1% by the papyrus ditch, and 29.3% by sunn hemp ditch. Approximately 58.4% of removed N was absorbed by kenaf, 44.5% of removed N was absorbed by sunn hemp and 46.1% of removed N was absorbed by the above ground part of papyrus.

Figure 4-5 showed phosphorus balance during the period from May 17 to November 6, 1991 calculated for the ditches planted in May, 1991 (kenaf, papyrus, sunn hemp, and plant-free ditches). Based on these data, 65.2% of P in the inflow was removed by the kenaf ditch , 60.5% by the papyrus ditch, and 31.8 % by the sunn hemp ditch. Approximately 64.9% of removed P was absorbed by kenaf and 51.9% of removed P was absorbed by sunn hemp, while 47.3% of removed P was absorbed by the above-ground part of papyrus.

Based on the phosphorus and nitrogen balance data, it was found that at least a half of the N and P removed from wastewater by the plant bed filter system depended on plant absorption. The data also indicated that the N and P removal efficiency of the system was significantly affected by the N and P absorption rates of the plant species.

The ditches which showed high N and P removal rates were cultivated with plants which displayed high biomass production rates. Biomass production rates of papyrus, kenaf, sorghum, and Italian ryegrass were 17-25 $gm^{-2}d^{-1}$ (2.33 - 4.31 kgm^{-2}). N and P removal efficiency of the ditches was affected significantly by the N and P absorption rates (aboveground part of plants) (Figs.4-3, 4-6, 4-7). Plants with high biomass production rates showed high N and P absorption rates (Figs.4-6 and 4-7).

The average ratio of N to P removal rate was approximately 5 : 1 (range of 4:1 to 8:1), that for the adlay ditch was 4:1 and for the barley ditch, 8:1 (Figs.4-3, 4-6, and 4-7). These findings indicate that the excess component, N or P, was removed only partially by the plant bed -filter ditch and remained in the ditch effluent when the ratio of N to P concentration in the wastewater was significantly different from 5:1.

(4)Effect of plantings on nitrification and denitrification

Figure 4-8 shows the changes in the nitrogen compound concentrations of the influents and effluents. NH_4-N concentration of the planted ditches decreased as the plants grew and became lower than that of the plant- free ditch. In the ditches with perennial plants, papyrus and reeds, the NH_4-N concentration remained lower than that in the plant-free ditch during the period from December to February when the T-N removal efficiency of these ditches decreased to the same level as that of the plant-free ditch. The NH_4-N concentration of the reed ditch remained especially low (almost under 1.0 mgL^{-1}) after the above-ground parts of the plants died and were removed. Based on the T-N and NO_3-N concentration data, nitrification proceeded more actively in the papyrus and reed ditches than in the plant-free ditch even in the winter when almost no nitrogen was removed from wastewater in these ditches and the above-ground part of the reeds had withered.

Based on the increase of the NO_3-N concentration in the effluent, the nitrification rate was estimated at about 0.22 $gNm^{-2}d^{-1}$ in the plant-free ditch and at about 0.39 $gNm^{-2}d^{-1}$ in the papyrus and reed ditches from December to February. It was found that the nitrification rate of about 0.17 $gNm^{-2}d^{-1}$ was accelerated due to the presence of plants. Emergent plants such as reeds and papyrus have an internal lacunal system which transports O_2 from aerial parts to roots (Guntespergen 1989, Merong 1995) , though some parts of O_2 transported to the roots are leaked out to the rhizosphere and accelerate nitrification (Armstrong 1988, Reddy 1989, Moorhead 1988, Steinberg 1994).

Yamasaki reported that most of the oxygen flux from reeds was derived from standing dead shoots and suggests that dead shoots of reeds played an important role in plant aeration (Yamasaki 1987). This in turn suggests that O_2 which was supplied from roots through the lacunae of papyrus and reed accelerated nitrification process in the ditch in the winter. The acceleration of nitrification even after the above-ground part of the reeds was removed was attributed to the fact that O2 was supplied through the remaining cut shoots sticking out of the bed filter surface.

In Figs.4-6 and 4-7, the difference between the removal rate and absorption rate of the plants (aboveground parts) was ascribed to the removal by the bed filter and absorption by the underground parts of the plants. The slope of the regression line for the P removal rates was 1.38 times larger than that for the P absorption rates, while the slope of the regression line for the N removal rate was 1.62 times larger than that for the N absorption rates (Figs.4-4 and 4-6). These observations suggest that denitrification contributed somewhat to N removal in addition to absorption by the plants. Roots release a considerable amount of organic carbon into the rhizosphere (Rovira 1965). The amount of organic carbon released via root systems varies from only a few percent to up to 40% of the dry matter produced by plants (Whipps 1987, Lynch and Whipps 1990). This is the major source of substrates for microbial activity in the rhizosphere (Rovira 1965). It appears that dead plant roots and exudate from roots are used as hydrogen donors for denitrification.

(5) Recommended plantings

Figure 4-9 shows the season when the monthly average of the N and P removal rates of the plant bed filter ditches was higher than 0.8 $gm^{-2}d^{-1}$ for N and 0.15 $gm^{-2}d^{-1}$ for P. N and P removal rates of the kenaf, papyrus, sorghum, Italian ryegrass, and barley ditches exceeded 0.8 $gm^{-2}d^{-1}$ for N and 0.15 $gm^{-2}d^{-1}$ for P from two to seven months. The Italian ryegrass ditch and barley ditch showed a high removal efficiency in early spring, the papyrus ditch from late spring to autumn, and the kenaf ditch and sorghum ditch from summer to autumn. N and P removal efficiency of the ditch planted with the perennial plant papyrus remained high for the longest period of time among the annual plants studied. In the case of flowering species such as hanana and calla, the N removal rate exceeded 0.8

$gm^{-2}d^{-1}$ in spring and in the case of African marigold the P removal rate exceeded 0.15 $gm^{-2}d^{-1}$ in summer and autumn.

Since N and P absorption by plants accounted for a considerable percentage of N and P removal by the ditch, the harvest of plants was necessary for the system to function steadily . Therefore, it is important that harvested plants be used for human life. Papyrus was used as writing material and other products (boats, sails, mats and cords) in ancient Egypt. Currently papyrus sheets are produced in a limited amount as souvenirs and as decorative items in Egypt (Ragab 1972). Recently, research has been carried out on the production of paper, fuel and fodder from papyrus (Jones 1983, Muthuri and Kinyamario 1989), and the author believe that papyrus could be used as a source of handicrafts. Kenaf is a fiber crop which has recently attracted considerable attention as a source of paper instead of wood (Robinson 1988), and could be used for newsprint in California, USA (Robinson 1988, Bosisio 1988).

I suggest that papyrus, kenaf, and sorghum should be used mainly in summer and autumn, and that Italian ryegrass and barley be used in winter and spring. They improved the N and P removal efficiency of the ditch considerably in addition to their resource recycling functions. Flowering species such as African marigold (summer and autumn) , and hanana and calla (winter and spring) are recommended for supplementary use with papyrus, kenaf, sorghum, Italian ryegrass,and barley to enhance the aesthetic value of the ditches and provide amenity functions. It appears that efficient wastewater treatment can be performed consistently except in the winter, by cultivating these plants in an appropriate combination in the ditches, to maintain the N and P loading rates of wastewater at about 0.8 $gm^{-2}d^{-1}$ and 0.15 $gm^{-2}d^{-1}$, respectively.

Conclusions

(1) The plant bed-filter ditches with plants which exhibited high biomass production rates showed high N and P removal rates. Maximum values of the N removal rates of the papyrus, kenaf, sorghum, and Italian ryegrass ditches were 1.3-1.7 $gm^{-2}d^{-1}$ and maximum values of the P removal rates were 0.24-0.26 $gm^{-2}d^{-1}$. Biomass production rates (aboveground parts) of the plants were 17-25 gm-

$2d^{-1}$ (2.33-4.31 kgm^{-2} at harvest time). N and P removal rates of the ditches were highly dependent on the N and P absorption rates of the plants.

(2) The average ratio of N to P removal rate of the plant bed-filter ditch was approximately 5 : 1 (but ranged from 4:1 to 8:1).

(3) The N and P removal rates of the papyrus ditch exceeded 0.8 $gm^{-2}d^{-1}$ for N and 0.15 $gm^{-2}d^{-1}$ for P from late spring to autumn, those of the kenaf ditch and sorghum ditch from summer to autumn, and those of the Italian ryegrass ditch and barley ditch exceeded these values in early spring.

(4) Nitrification proceeded more actively in the papyrus and reed ditches than in the plant-free ditch even in the winter. It was estimated that the nitrification rate of about 0.17 $gNm^{-2}d^{-1}$ was accelerated due to the presence of plants. N and P balance data of the plant bed filter ditches suggested that denitrification contributed somewhat to N removal in addition to N absorption by the plants.

(5) Kenaf, papyrus, and sorghum are recommended for use in plant bed filter ditches mainly in summer and autumn, while Italian ryegrass and barley are recommended for winter and spring because they improved the N and P removal efficiency considerably in addition to their resource recycling functions.

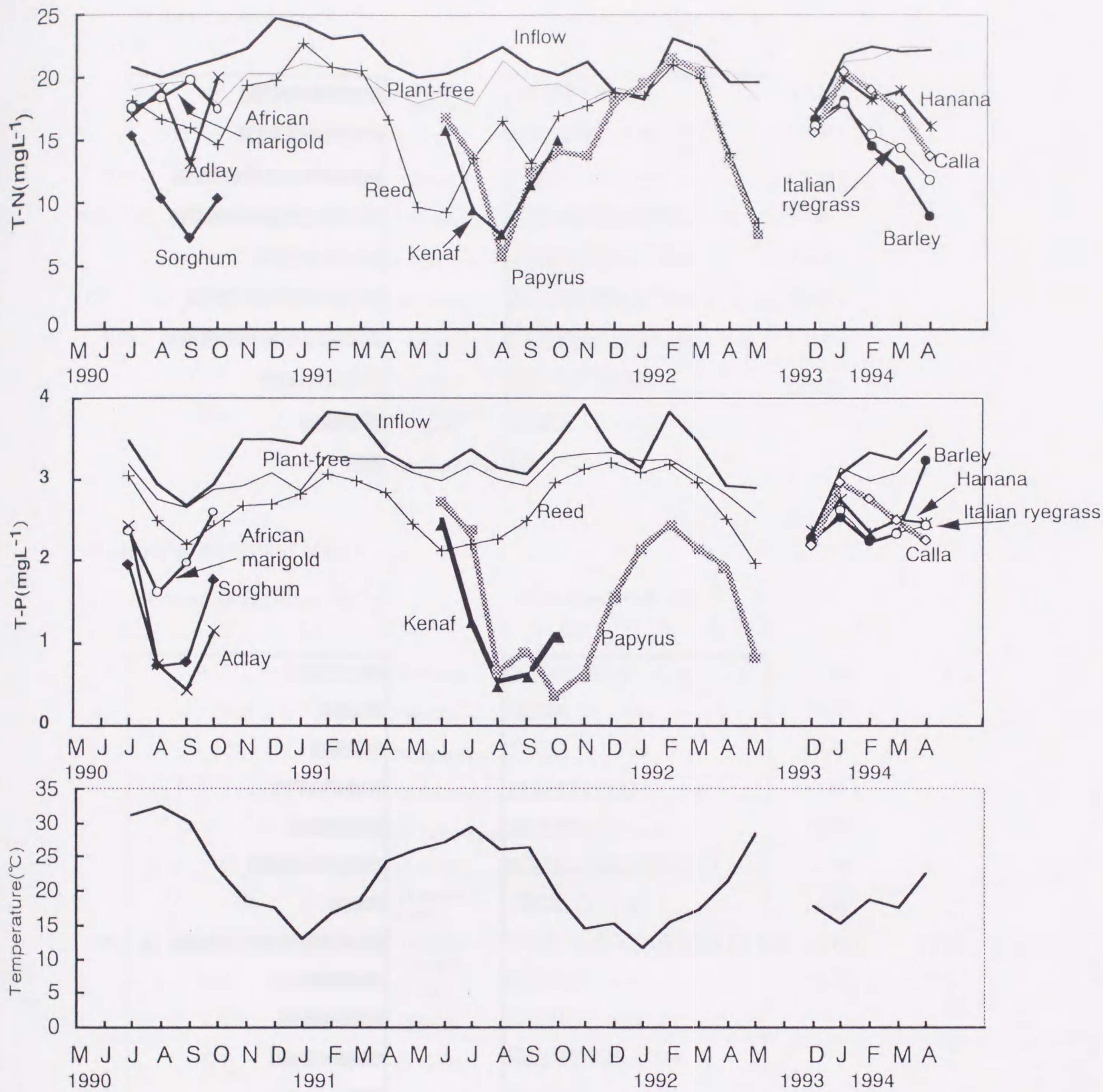


Fig. 4-2. Changes in T-N and T-P concentrations of ditch effluents and atmospheric temperature at 11:00 AM in the greenhouse (monthly average value).

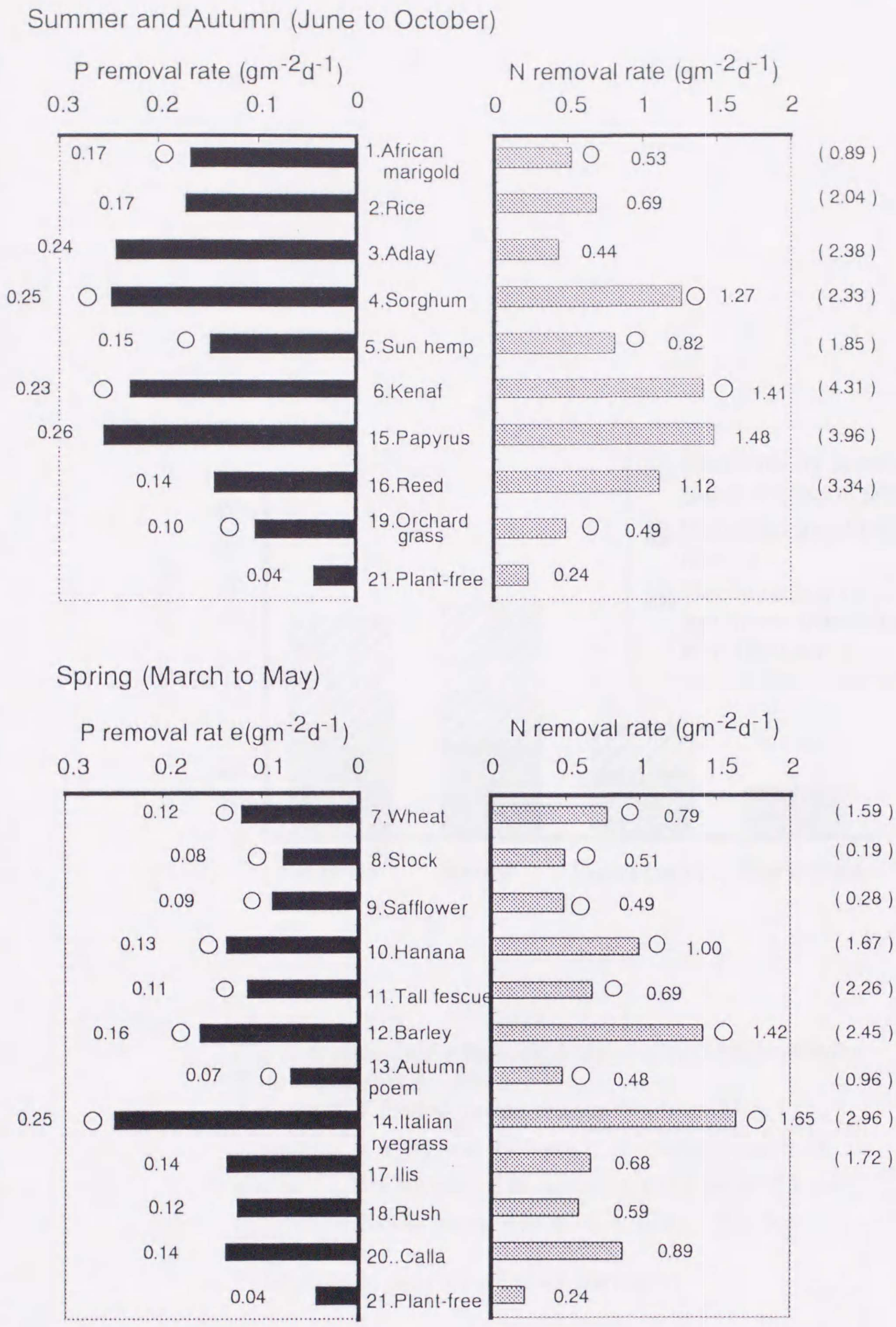


Fig.4-3. Maximum* values of N and P removal rates in the ditches cultivated with the useful plants.
10-14 plants were examined in the 1 m ditches. The others were examined in the 4 m ditches.
P loading rate: 0.20-0.33 ($gm^{-2}d^{-1}$), N loading rate: 1.41-2.08 ($gm^{-2}d^{-1}$).
○: terrestrial plants. ( ): Dry weight of plant aboveground parts (kgm^{-2}) at harvest time.
*Maximum value of monthly average

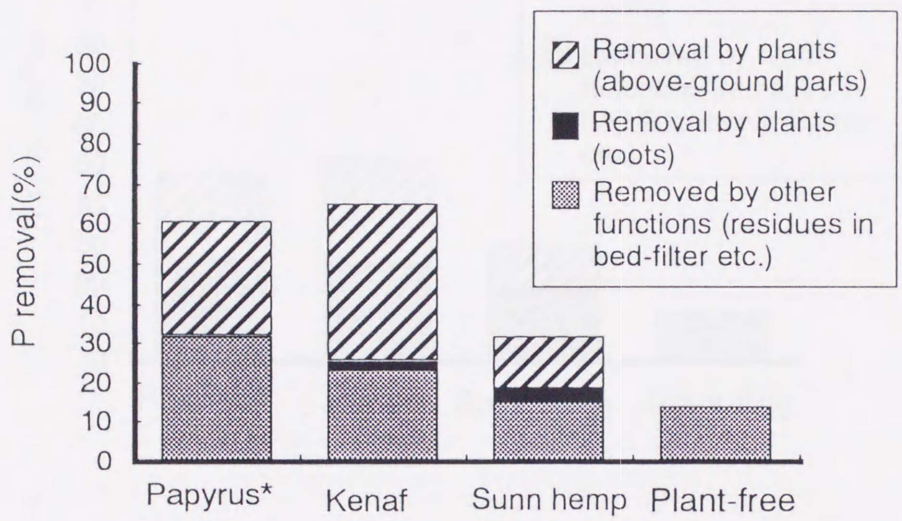


Fig. 4-4. Phosphorus balance during the periods from May 17 to November 6, 1991.
Amount of P loaded during the periods from May 17 to November 6, 1991 was 47.3 gm^{-2} (P loading rate: 0.28 $gm^{-2}d^{-1}$). Dry weight of the above-ground parts of kenaf, papyrus, and sunn hemp was 4.31, 3.96 and 1.85 Kgm^{-2}, respectively.
*The roots of papyrus were not harvested.

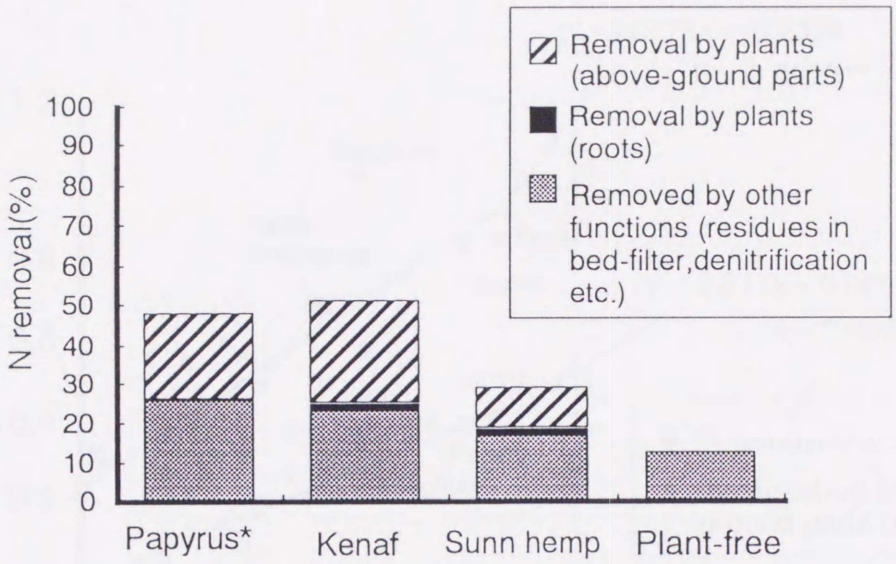


Fig.4-5. Nitrogen balance during the periods from May 17 to October 6, 1991.
The amount of N loaded during the periods from May 17 to November 6, 1991 was 289.9 gm^{-2} (N loading rate: 1.7 $gm^{-2}d^{-1}$). Dry weight of the above-ground parts of kenaf, papyrus, and sunn hemp was 4.31, 3.96 and 1.85 kgm^{-2}, respectively.
*The roots of papyrus were not harvested.

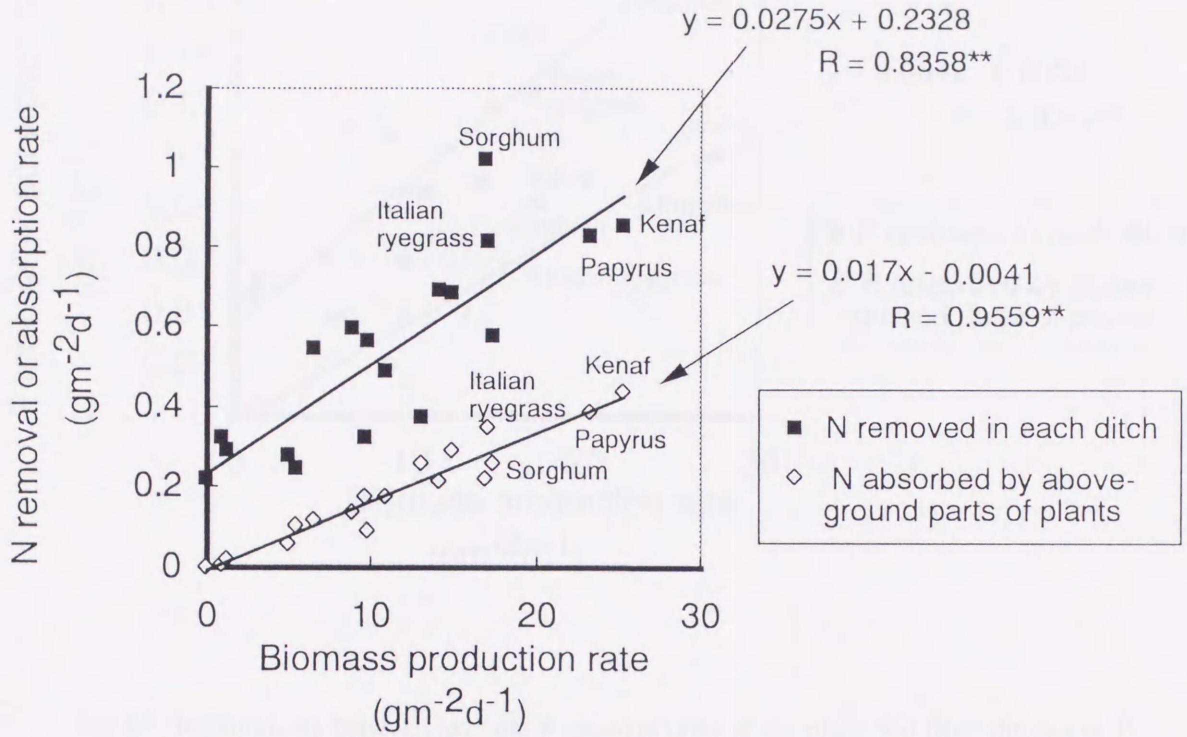


Fig.4-6. Relationship between average N removal rate of the plant bed filter ditches or N absorption rate of plant and plant biomass production rate during the experimental period.
The plant biomass production rate was expressed as dry weight of the aboveground parts divided by the number of days of culture.

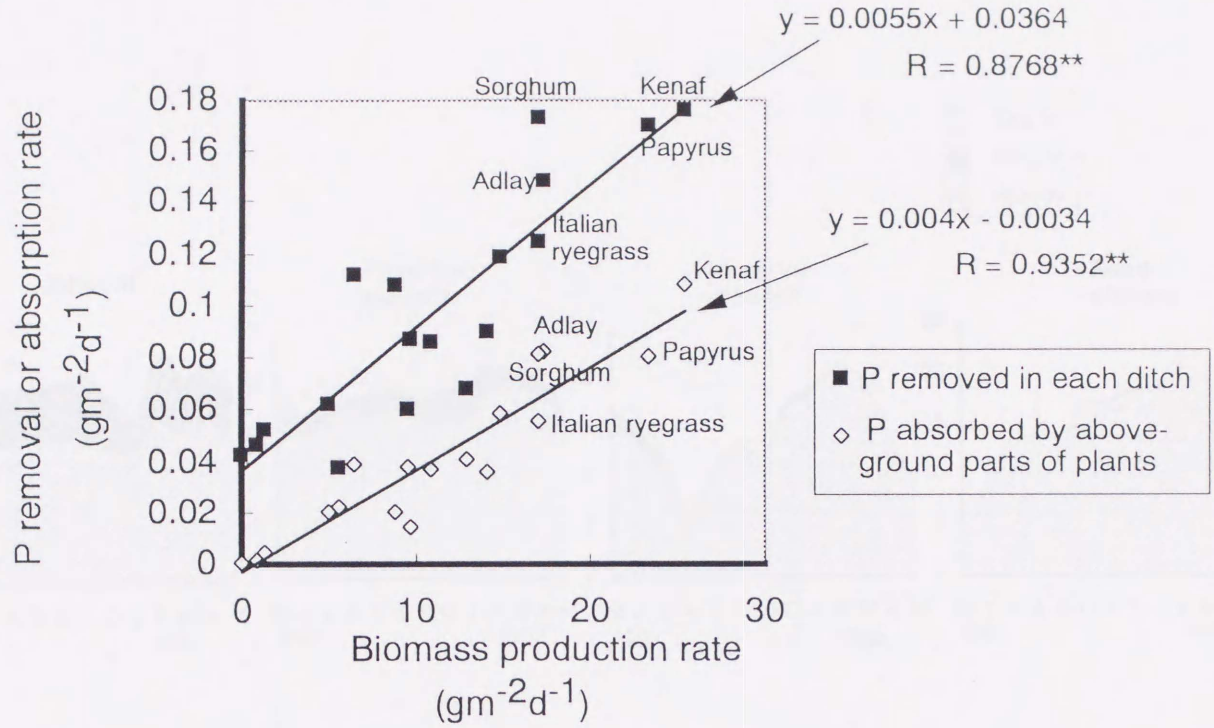


Fig.4-7. Relationship between average P removal rates of the plant bed filter ditches or P absorption rate of plant and plant biomass production rate during the experimental period. The plant biomass production rate was expressed as dry weight of the aboveground parts divided by the number of days of culture.

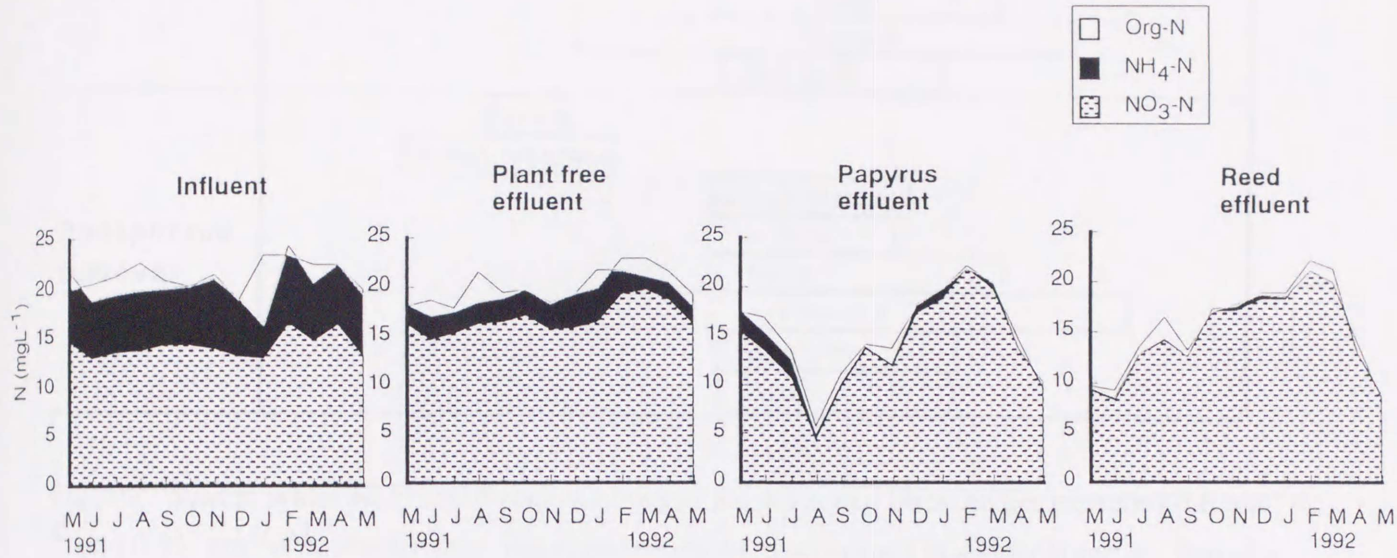


Fig. 4-8. Changes in nitrogen compound concentrations of the influents to and the effluents from the ditch (monthly average value).

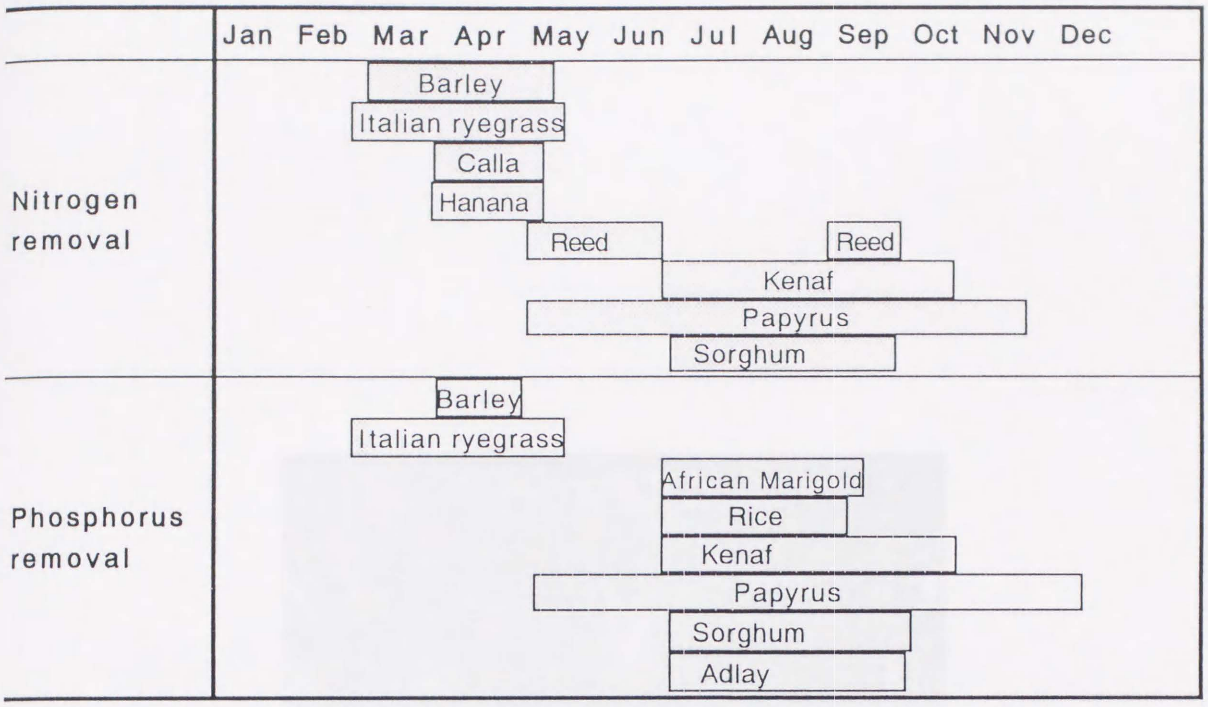


Fig.4-9. Season when the N and P removal rates of the plant bed filter ditches exceeded 0.8 $gm^{-2}d^{-1}$ and 0.15 $gm^{-2}d^{-1}$, respectively. The experiments were performed in a greenhouse in Tsukuba, Japan.

Plate 4-3. Papyrus (Cyperus papyrus L.)

Plate 4-4. Papyrus root mat.

Plate 4-5. Kenaf (*Hibiscus cannabinus* L.)

Plate 4-6. African marigold (*Tages electa* L.)

Plate 4-7. Italian ryegrass (*Lolium multiflorum* Lam.)

Plate 4-8. Hanana (*Brassica campestris* L. var.)

Plate 4-9. Calla (*Zantedeschia aethiopica* Spreng)

Chapter 5

Evaluation of Useful Plants for the treatment of Wastewater with low N and P Concentrations

Eutrophication associated with ponds for agricultural use has begun to adversely affect rice production and the residential living environment in Japan. Generally, N and P concentrations of eutrophic pond water are low, about one tenth of those of domestic wastewater. In this study, I evaluated and compared the ability of useful plants, which had already been found to be effective in the domestic wastewater treatment, to remove nitrogen and phosphorus from wastewater with low N & P concentrations such as eutrophic pond water.

Materials and Methods

(1) Plant-bed filter ditch design

Plant-bed filter ditches where both terrestrial and aquatic plants were cultivated contained baskets filled with the bed filter material zeolite (Fig.5-1) which is characterized by a high NH_4-N adsorption efficiency, suitability for bench-scale plant culture experiments (Chapter 3) and recycling in agriculture as a soil conditioner. The depth of the zeolite baskets varied depending on the saturation tolerance of the plant species . The bed filter surface was about 0.1m higher than the water level for the terrestrial species and the same as the water level for the aquatic species.

The experimental ditch was 0.5 m wide, 0.4 m deep, 1m long. Baskets, 0.4 m wide, 0.4 m deep, and 0.3 m long, were filled with zeolite (particle size 3 - 10 mm). Two baskets were placed in the ditches. Water depth was 0.3 m. The height of zeolite packed in the basket was 0.3 m for the aquatic species and 0.4 m for the terrestrial species. The weight of zeolite in each basket for the terrestrial species was 29 kg and that for the aquatic species, 22 kg. Generally 6 seedlings were planted in one basket.

(2)Operational conditions

Seven terrestrial and two aquatic plant species (Table 5-1) which had also been found to be effective in the treatment of domestic wastewater or aesthetically appealing were tested to evaluate their efficiency in removing N and P from polluted pond water. Each ditch was planted with one species. Seedlings of Italian ryegrass (*Lolium multiflorum* Lam.) and hanana (*Brassica campestris* L. var.) were planted on December 5, 1995 and harvested on May 7, 1996. Seedlings of African marigold (*Tages erecta* L.), Impatiens (*Impatiens sulutani* Hook. f.), sorghum (*Sorghum vulgare* Pers.), kenaf (*Hibiscus cannabinus* L.), and rhizome cuttings of papyrus (*Cyperus papyrus* L.) and reed (*Phragmites communis* Trin.) were planted on May 30 and harvested on October 29, 1996. Rhizome cuttings of peppermint (*Menta piperita* L.) were planted in July, 1995, established during half a year and the experiment was started on December 5, 1995. One ditch was left plant-free as a control. Experiments were conducted in a glass house whose windows were open from April to November in Tsukuba, Japan.

To ensure constant N and P concentrations and loading rates, artificial wastewater simulating an eutrophic pond water was continuously added from one end of the ditch and flowed out from the opposite end. The undiluted solution for artificial wastewater was diluted with tap water to 1/1000 automatically and supplied to each ditch at a constant flow rate using Kaneki diluter (Taiyo-kogyo). The eutrophic concentration was determined based on my surveys of ponds conducted in Ibaraki Prefecture. Ponds with domestic wastewater contained 0.7 - 4.5 mg L^{-1} of N and 0.1 - 0.8 mg L^{-1} of P (data not shown). Based of these observations, artificial wastewater containing 2.5 mg L^{-1} of N and 0.5 mg L^{-1} of P was used in this experiment . The loading rate of N was 1.2 g m^{-2} d^{-1} and for P was 0.23 g m^{-2} d^{-1} (Table 5-2).

(3) Sampling and Analysis

The volume of wastewater inflow and outflow was measured and the water quality analyzed once a week. Total N concentration was measured using a Mitsubishikasei T-N analyzer, and total P concentration using the ascorbic acid method (APHA, AWWA, and WPFC, 1989) after persulfate digestion.

The removal rate was calculated as the difference between the rate of N & P in the wastewater

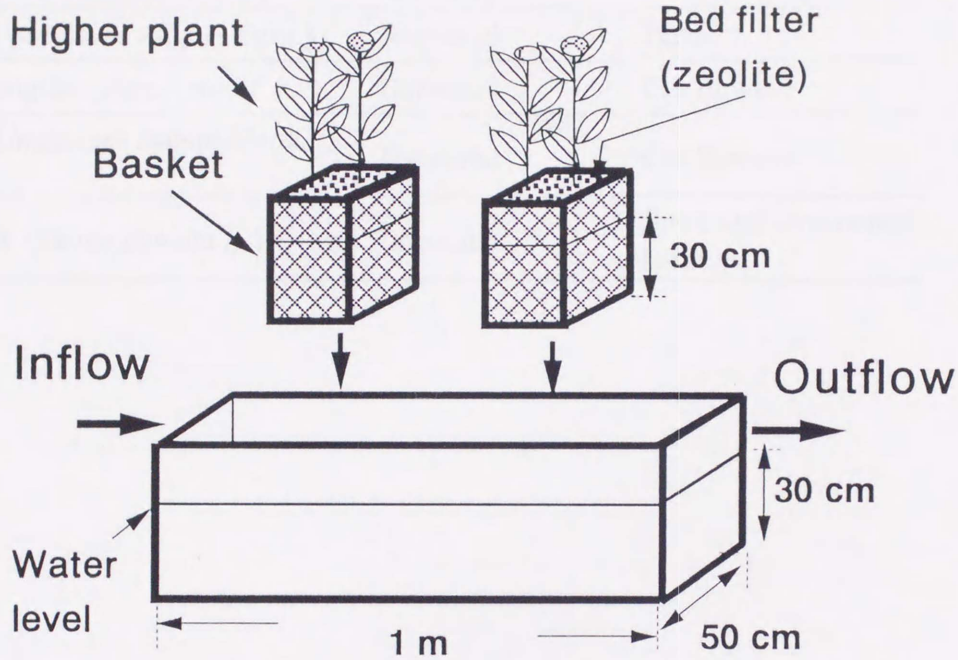


Fig.5-1. Plant bed filter ditch.

Table 5-1. Plants in bed filter ditches and possible uses.

Plant	Aquatic/Terrestrial	Use
Italian ryegrass (*Lolium multiflorum* Lam.)	Terrestrial	Feed
Hanana (*Brassica campestris* L. var.)	Terrestrial	Cut flowers
Papyrus (*Cyperus papyrus* L.)	Aquatic	Traditional paper and handicrafts
Reed (*Phragmites communis* Trin)	Aquatic	Handicrafts
Kenaf (*Hibiscus cannabinus* L.)	Terrestrial	Fiber and paper
Sorghum (*Sorghum vulgare* Pers.)	Terrestrial	Feed
African marigold (*Tages erecta* L.)	Terrestrial	Cut flowers
Impatiens (*Impatiens sultani Hook. f.*)	Terrestrial	Cut flowers
Peppermint (*Menta piperita L.*)	Terrestrial	Spice and ornamental plantings

Table 5-2. Concentration of components in artificial wastewater used to simulate the eutrofication of pond water and loading rate.

Component	Concentration (mg L-1)	Loading rate ($gm^{-2}d^{-1}$)
T-N	2.5	1.0-1.2
NH_4-N	0.6	
NO_3-N	1.9	
T-P	0.5	0.20-0.25
TOC	2-4	

Loading rate of wastewater was 400-500$Lm^{-2}d^{-1}$.

entering and leaving the ditches divided by the area of the ditches. (N & P entering rate: N & P concentration x rate of influent water volume . N & P leaving rate: N & P concentration x rate of effluent water volume.)

N and P plant contents were measured using a Technicon Traacs 800 after digestion with salicylate acid-thiosulfate as a modification of the Kjeldahl method (Bremner and Mulvaney 1982).

Results and Discussion

Monthly average T-N and T-P concentrations of the ditch influents and effluents are shown in Fig.5-2. Plant-free ditch was not effective in N and P removal from the wastewater. Addition of higher plants to the ditches enhanced N and P removal. The plants examined (Italian ryegrass , hanana, African marigold, impatiens, peppermint, sorghum, kenaf, papyrus, and reed) could grow in wastewater containing a concentration of about 1/10 N & P of that of domestic wastewater (about 1/100 N & P concentration of that of standard hydroponics solution) . As the plants grew, the N and P concentrations of the effluents decreased. Based on the data of effluent concentration determined once a week, the Italian ryegrass ditch decreased inflowing nitrogen concentrations to 0.3 - 0.6 mg L^{-1} during April and May, the papyrus ditch decreased them to 0.2 - 0.4 mg L^{-1} from August to October, and the kenaf ditch to 0.2 - 0.6 mg L^{-1} from August to October. Italian ryegrass ditch decreased inflowing P concentrations to 0.08 - 0.23 mg L^{-1} during April and May, papyrus decreased them to 0.02 - 0.1 mg L^{-1} from August to October, and kenaf to 0.08 - 0.14 mg L^{-1} in September and October.

Nitrogen and phosphorus balance calculated during the experiments (the period when each plant was cultivated in the ditch) showed that 43% (African marigold) - 87% (reed) of N and 49% (hanana) - 98% (reed) of P removed from wastewater were absorbed by the plants (Table5-3, Fig.5-3), indicating that the ditch removal efficiency was significantly affected by the plant N and P absorption rates.

The ratio of N and P absorbed by the underground parts of the plants was considerably higher in the case of aquatic papyrus and reed than in the case of the terrestrial species (Table5-3, Fig.5-3) because the aquatic plants extended roots and rhizomes deep in water, while the roots of the terrestrial species were concentrated near the water surface rich in oxygen.

The ditches planted with species producing a large biomass showed high N and P removal rates. Ditches containing Italian ryegrass, papyrus, and kenaf removed N and P more efficiently than the other seven ditches (Table 5-3). The average removal rate of Italian ryegrass was 0.62 $gm^{-2}d^{-1}$ for N and 0.10 $g\ m^{-2}\ d^{-1}$ for P, that of papyrus 0.73 $g\ m^{-2}\ d^{-1}$ for N and 0.15 $g\ m^{-2}\ d^{-1}$ for P, and that of kenaf 0.81 $g\ m^{-2}\ d^{-1}$ for N and 0.11 $g\ m^{-2}\ d^{-1}$ for P during the experiment. The peppermint was also efficient for removing N and P secondly to Italian ryegrass, papyrus, and kenaf (Figs. 5-2, 3, Table 5-3). The ditch planted with peppermint showed relatively high N and P removal rate all the year round.

In chapter 4, it was found that the average removal rates of kenaf, papyrus, and Italian ryegrass ditches were 0.8 - 1.0 $g\ m^{-2}\ d^{-1}$ for N and 0.13 - 0.17 $g\ m^{-2}\ d^{-1}$ for P when artificial domestic wastewater, which contained N and P concentrations about 10 times higher (N: 20 $mg\ L^{-1}$; P: 3.3 $mg\ L^{-1}$), was supplied at almost the same loading rates (N: 1.41 - 2.08 $g\ m^{-2}\ d^{-1}$; P: 0.20- 0.33 $g\ m^{-2}\ d^{-1}$) as those in the current experiment . These findings suggested that the N and P removal rates were hardly influenced by the N and P concentrations of wastewater when the wastewater concentrations were in the range of 2.5 - 20 $mg\ L^{-1}$ for N and 0.5 - 3.3 $mg\ L^{-1}$ for P.

I considered that plant-bed filter ditches could be used in the same way as the gardens utilized by communities or ornamental plantings around the pond to reduce the N and P load to the pond. I recommend that papyrus and kenaf be used mainly in summer and autumn, and that Italian ryegrass be used in winter and spring to treat polluted pond water. Peppermint which is effective for removing N and P all the year round and flowering species such as African marigold (summer and autumn) and hanana (winter and spring) are recommended for supplementary use with papyrus, kenaf, and Italian ryegrass to make ditches more aesthetically pleasing.

Conclusions

(1) Ditches cultivated with the plants, which had already been found to be effective for the treatment of domestic wastewater, were also effective for the removal of N and P from wastewater with low N & P concentrations about one tenth of the N and P concentrations of domestic wastewater.

(2) The ditches containing Italian ryegrass, papyrus, and kenaf removed N and P most efficiently. The average removal rate of Italian ryegrass was $0.62\ g\ m^{-2}\ d^{-1}$ for N and $0.10\ g\ m^{-2}\ d^{-1}$ for P, that of papyrus $0.81\ g\ m^{-2}\ d^{-1}$ for N and $0.15\ g\ m^{-2}\ d^{-1}$ for P, and that of kenaf $0.73\ g\ m^{-2}\ d^{-1}$ for N and $0.11 g\ m^{-2}\ d^{-1}$ for P during the experiment.

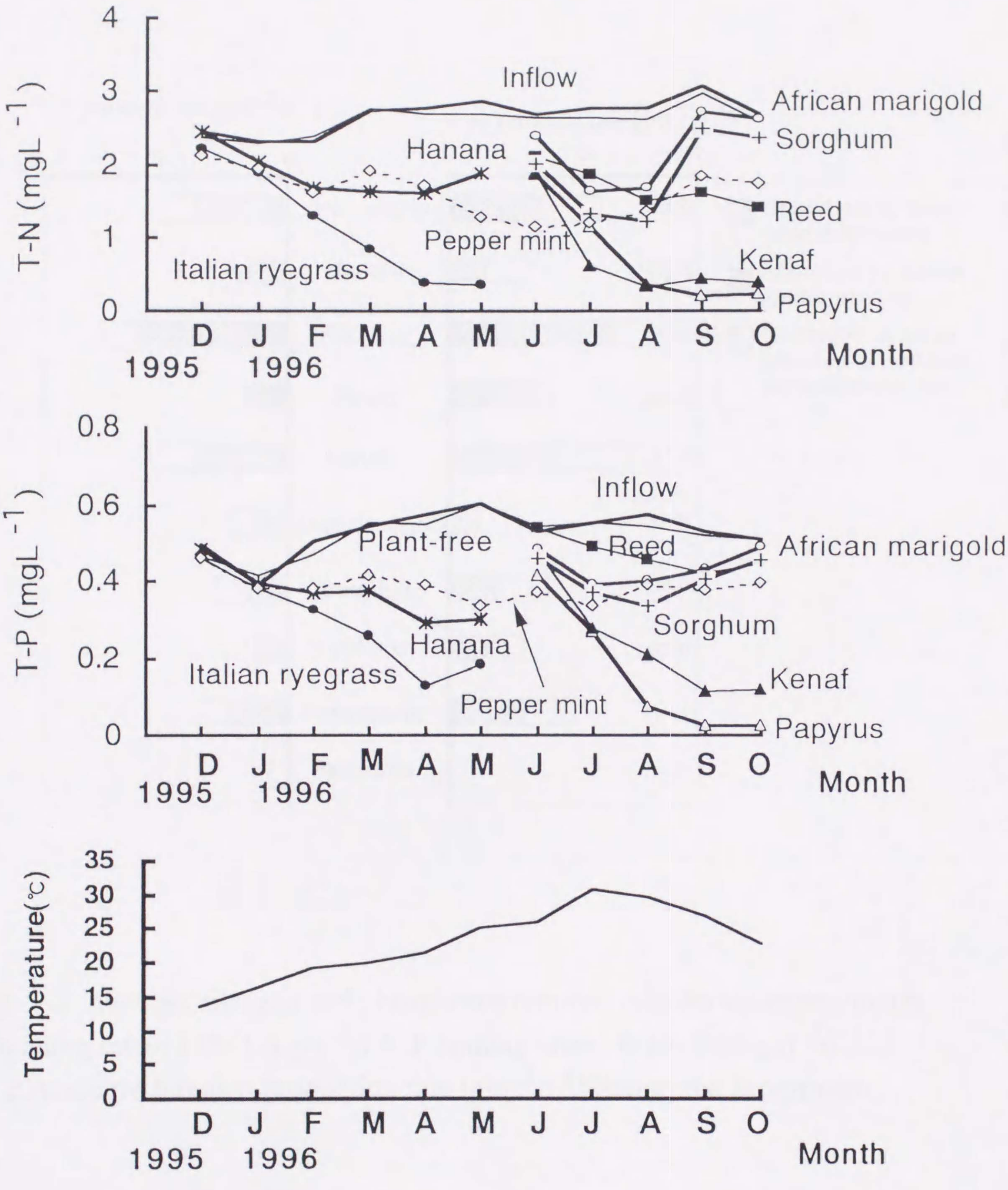


Fig. 5-2. Changes in T-N and T-P concentrations of ditch influent and effluents and atmospheric temperature at 11:00 AM in the glass house (monthly average value).

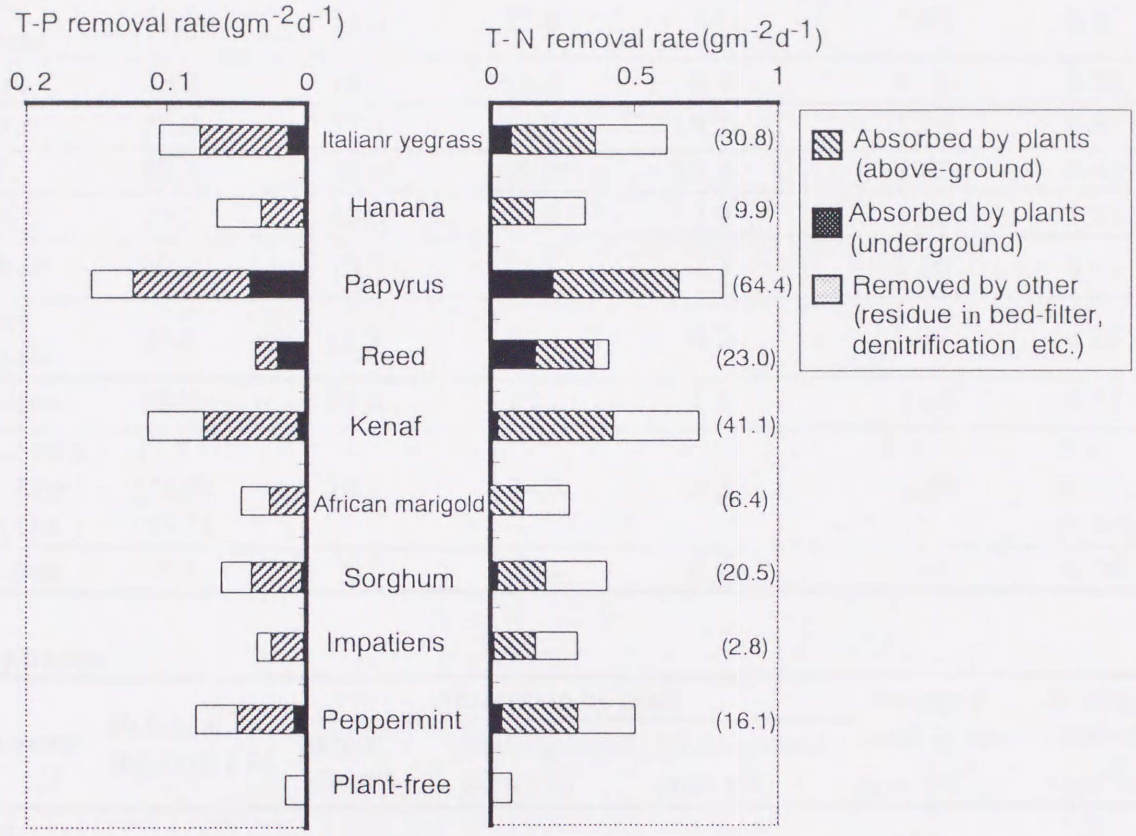


Fig. 5-3. Average nitrogen and phosphorus removal rate during experiments.
N loading rates: 1.00-1.2 $gm^{-2}d^{-1}$; P loading rates: 0.20- 0.25 $gm^{-2}d^{-1}$.
( ): Averagre biomass production rate ($gm^{-2}d^{-1}$) during the experiment.

Table 5-3. Nitrogen and phosphorus balance and average loading and removal rates during the experiment.

Nitrogen

Ditch name	Removal by the ditch (%)	Absorption by the plant			Average N loading rate ($gm^{-2}d^{-1}$)	Average N removal rate ($gm^{-2}d^{-1}$)
		Whole plant(%)	Aboveground parts (%)	Underground parts (%)		
Italian ryegrass	57.7	34.8	27.8	7.0	1.07	0.62
Hanana	30.2	14.2	13.8	0.4	1.10	0.33
Papyrus	70.8	57.4	38.2	19.2	1.15	0.81
Reed	40.1	35.0	19.2	15.7	1.03	0.42
Kenaf	73.1	43.0	40.0	2.9	1.00	0.73
Sorghum	39.2	18.7	16.3	2.3	1.05	0.41
African marigold	26.1	11.3	11.1	0.2	1.05	0.28
Impatiens	28.9	15.2	13.7	1.5	1.06	0.31
Pepper mint (Dec.-May) (May-Oct.)	43.2 (52.9) (35.2)	28.1	24.3	3.8	1.08	0.47 (0.52) (0.42)
Plant free	7.6	0.0	0.0	0.0	1.04	0.08

Phosphorus

Ditch name	Removal by the ditch (%)	Absorption by plant			Average P loading rate ($gm^{-2}d^{-1}$)	Average P removal rate ($gm^{-2}d^{-1}$)
		Whole plant(%)	Aboveground parts (%)	Underground parts (%)		
Italian ryegrass	49.0	35.8	29.9	5.9	0.21	0.10
Hanana	28.9	14.1	13.7	0.4	0.22	0.06
Papyrus	67.6	54.0	36.6	17.4	0.23	0.15
Reed	17.6	17.3	7.5	9.8	0.20	0.04
Kenaf	57.1	37.1	34.5	2.5	0.20	0.11
African marigold	23.1	13.2	13.1	0.1	0.20	0.05
Sorghum	29.2	18.6	17.2	1.4	0.21	0.06
Impatiens	17.5	12.4	11.5	0.9	0.20	0.03
Pepper mint (Dec.-May) (May-Oct.)	33.1 (38.7) (28.6)	22.8	19.2	3.7	0.21	0.07 (0.08) (0.07)
Plant free	7.1	0.0	0.0	0.0	0.21	0.01

Dry weight of Italian ryegrass was 4.77, hanana 1.53, papyrus 9.90, reed 3.54, kenaf 6.29, sorghum 3.15, African marigold 0.98, Impatiens 0.422, pepper mint 4.95 kgm^{-2} at harvest time.

Chapter 6

Effect of N and P Concentrations on Plant N and P Removal Rates

Plant bed filter ditches containing Italian ryegrass, papyrus, and kenaf removed N and P most efficiently from the artificial wastewater imitating the effluents from secondary treatment systems (with high N and P concentrations) and eutrophic pond water (with low N and P concentrations). It was also found that the N and P removal rates of these plants were the same for both high and low concentrations of wastewater. However some plant species were more effective for treating the high concentration wastewater. In order to determine the N & P concentration range in which these plants can be efficiently used for wastewater treatment, the author studied the influence of N & P wastewater concentrations on N & P removal rates of the plants.

Materials and methods

(1) Plants

Seedlings of Italian ryegrass (*Lolium multiflorum* Lam.), kenaf (*Hibiscus cannabinus* L.), sorghum (*Sorghum vulgare* Pers.), and African marigold (*Tages erecta* L.) and rhizome cuttings of papyrus (*Cyperus papyrus* L.) and peppermint (*Menta piperita* L.) were planted in small baskets. Italian ryegrass was precultured for 12 weeks, kenaf for 8 weeks, sorghum for 6 weeks, African marigold for 8 weeks, papyrus for 6 weeks, and pepper mint for 4 weeks in a ditch with a continuous artificial wastewater flow in a greenhouse. Wastewater contained 10 mg L^{-1} of nitrogen (NO_3-N: 7.6 mg L^{-1}) and 2 mg L^{-1} of phosphorus (PO_4-P: 2 mg L^{-1}).

(2) Measurement

The baskets with the plants were transferred to test containers containing 110 L of solution in the growth chamber under natural light. Artificial wastewater was added at one end of the container under a continuous flow and drained out at the opposite end. To make the concentration in the containers uniform, the container solution was mixed continuously by circulation (Fig. 6-1).

Undiluted wastewater containing 90 mg

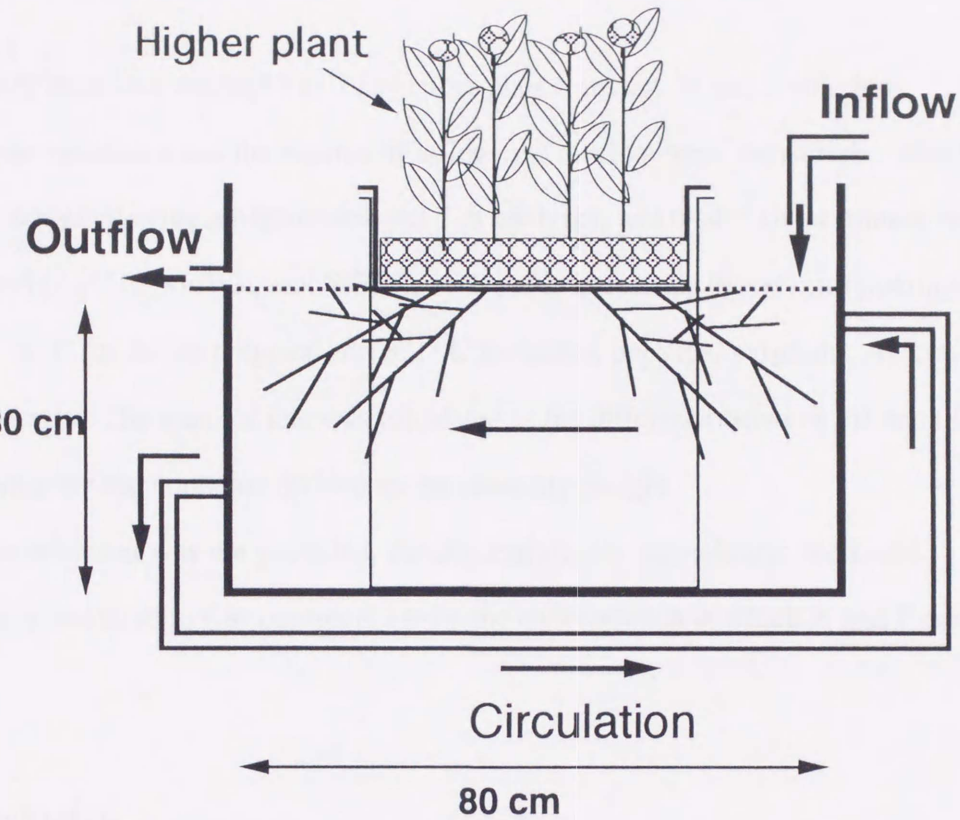


Fig. 6-1. Test container with continuous flow and circulation.

L^{-1} of nitrogen (NO_3-N: 85 mg L^{-1}) and 18 mg L^{-1} of phosphorus (PO_4-P: 18 mg L^{-1}) was diluted with tap water to 1/100 - 1/8 and supplied to the six test containers. The wastewater flow was measured.

After a steady-state was reached 3 to 7 days after plant transfer, N and P solution concentrations in the containers and the volume of inflow and outflow were measured. Total N concentration was measured using a Mitsubishikasei T-N analyzer, and total P concentration using the ascorbic acid method (APHA, AWWA, and WPFC, 1989) after persulfate digestion. Experiments were conducted at 20 C for Italian ryegrass and at 25 C for kenaf, papyrus, sorghum, African marigold and peppermint. The removal rate was calculated as the difference between the rate of N & P entering and leaving the test container divided by the plant dry weight.

When the wastewater was not provided, the concentration in the solution decreased. Observed minimum concentration was considered to be the concentration at which N and P removal was zero.

Results and Discussion

The relationship between N and P concentrations in the solution in the container and the removal rates of plants is shown in Figs. 6-2 and 6-3.

Concentrations at a removal rate of zero were 0.19 mg L^{-1}(papyrus)- 0.50 mg L^{-1}(sorghum) for N and 0.01 mg L^{-1}(papyrus, Italian ryegrass) - 0.06 mg L^{-1}(sorghum) for P. This suggests that these plants can treat pond water with N concentrations exceeding 0.19 - 0.5 mg L^{-1} and P concentrations exceeding 0.01 - 0.06 mg L^{-1}. The minimum nutrient concentration for water bloom formation has been reported to be 0.3 mgL^{-1} for N or 0.02 mgL^{-1} for P (Kojima et al. 1977). It was found that papyrus, kenaf, African marigold, and peppermint can purify water to the low concentrations at which water bloom does not occur .

At low concentrations, the N and P removal rates increased sharply with the increase of the solution concentrations. At high N and P concentrations, the removal rates were high and less affected by the concentrations (Fig. 6-2 and 6-3). In the experimental systems, N and P removal rates were considered to be equal to N and P uptake rate by plants. The uptake kinetics of many nutrients have been described using a Michaelis-Menten equation. I used a modified Michaelis-Menten equation (Nielsen and Barber, 1978) to fit the data.

$$V = \frac{Vmax\ (C - Cmin)}{Km + (C - Cmin)}$$

where V is net influx of nutrients (N and P removal rate), Vmax is maximum influx (maximum N and P removal rate), Km is the Michaelis constant, and Cmin is the concentration where net influx is zero

In the case of papyrus, the N and P concentrations at which the removal rate was half of the maximum removal rate (Km + Cmin) were 0.57 mg L^{-1} and 0.45 mg L^{-1}, respectively (Fig. 6-2 and 6-3). When the N concentrations did not exceed 0.57 mg L^{-1} and the P concentrations did not exceed 0.45 mg L^{-1}, N and P removal rates were low and significantly affected by the N and P concentrations in wastewater. In our previous experiments (Chapter 4), N removal rate of the plant bed filter ditch planted with papyrus was 0.85 - 1.48 $gm^{-2}d^{-1}$ from May to November when wastewater containing 20 mg L^{-1} was supplied to the ditch. However, the N removal rates of the papyrus ditch appeared to be much smaller than those recorded in the previous experiments when low N concentration wastewater (less than 0.57 mg L^{-1}) was fed. Therefore, it was difficult to estimate the ditch size based on the N and P removal rates recorded in the previous experiments (Chapter 4) if the wastewater concentration was quite low.

At higher N and P concentrations, the N and P removal rates could be considered to be constant independently of N and P concentrations and N and P removal functions appeared to resemble zero order kinetics. Thus the ditch size at the site could be estimated roughly based on the N and P removal rates of the plant-bed filter ditch recorded in the previous experiments (Chapters 4) using high N and P concentration wastewater. The concentrations at which the removal rate was half of the maximum removal rate (Km + Cmin) varied slightly depending on plant species : 0.24 mg L^{-}

^{1}(African marigold)- 0.86 mg L^{-1} (sorghum) for N and 0.09 (Italian ryegrass) mg L^{-1} - 0.46 mg L^{-1} (sorghum) for P (Fig. 6-2 and 3). I regarded the concentration range from 1.0 to 20 mgL^{-1} for N and from 0.5 to 4 mgL^{-1} for P as the range in which the removal rates are sufficiently high and unrestricted. I believe that these plant species can be most efficiently used at N and P concentrations at which the removal rates are unrestricted.

Conclusions

(1) The lowest concentrations at which Italian ryegrass, papyrus, kenaf, sorghum, African marigold and peppermint could remove N and P from the wastewater were 0.19 mg L^{-1}(papyrus)- 0.50 mg L^{-1}(sorghum) for N and 0.01 mg L^{-1}(papyrus, Italian ryegrass) - 0.06 mg L^{-1}(sorghum) for P.

(2) When the N concentrations were less than 0.2 mg L^{-1}(African marigold)- 0.9 mg L^{-1} (sorghum) for N removal and 0.09 (Italian ryegrass) mg L^{-1} - 0.46 mg L^{-1} (sorghum) for P removal, the removal rates were low and strongly affected by the concentration. It was difficult to estimate the ditch size based on the N and P removal rates in the plant-bed filter ditch recorded in the previous experiments using artificial domestic wastewater (Chapter 4) .

(3) At high N and P concentrations (1.0 - 20 mg L^{-1} for N, 0.5 - 4 mg L^{-1} for P) the removal rates were high and hardly affected by the concentration. Thus the ditch size at the site could be estimated roughly based on the N and P removal rates recorded in the previous experiments using artificial domestic wastewater (Chapter 4).

(4) These observations led us to recommend that plants be used to improve wastewater at N and P concentrations at which the removal rates are not adversely restricted.

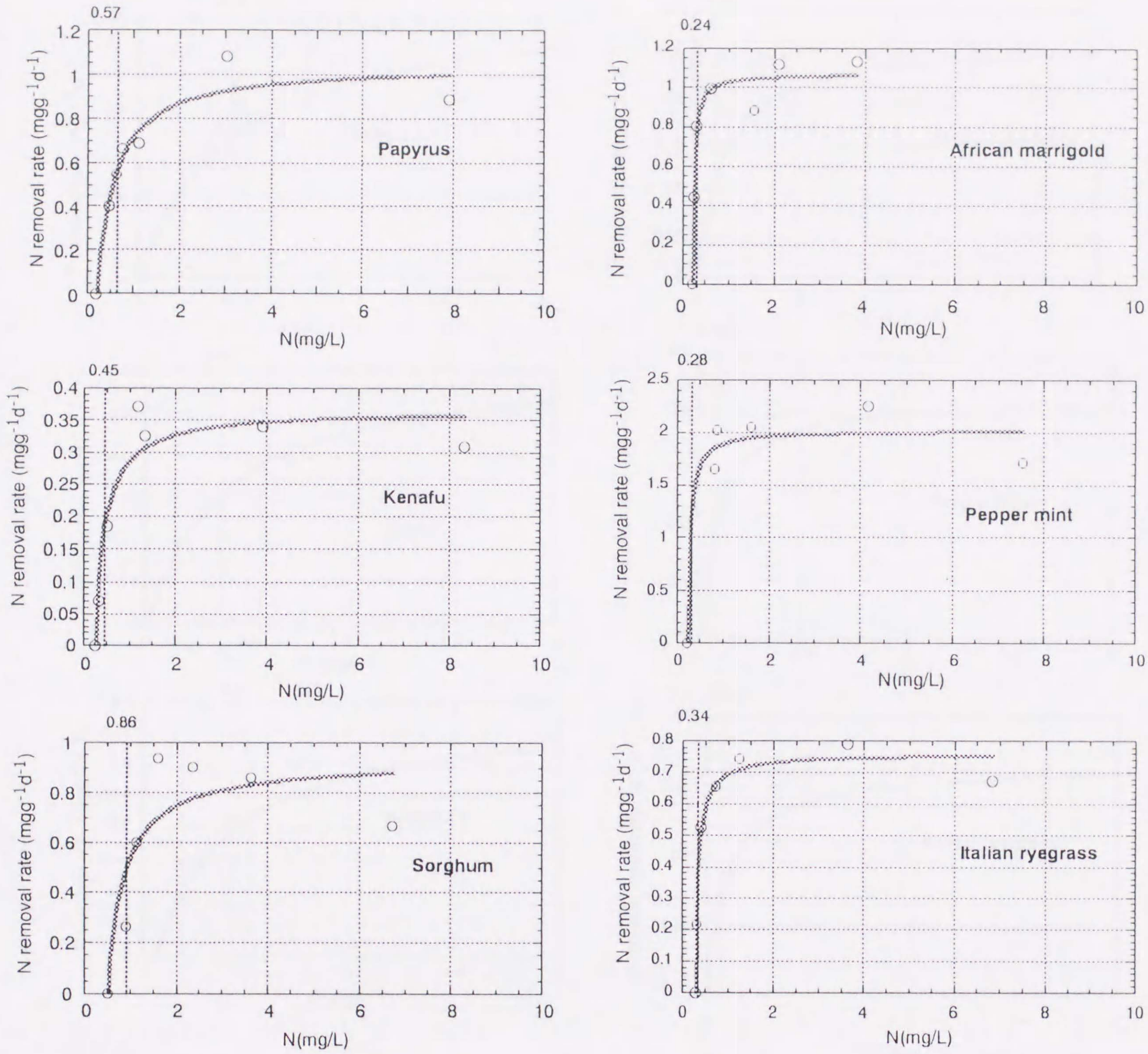


Fig.6-2 Nitrogen removal rates related to nitrogen concentrations in papyrus, kenaf, sorghum, African marigold, peppermint and Italian ryegrass.
N removal rate : removed N per plant dry weight per day.

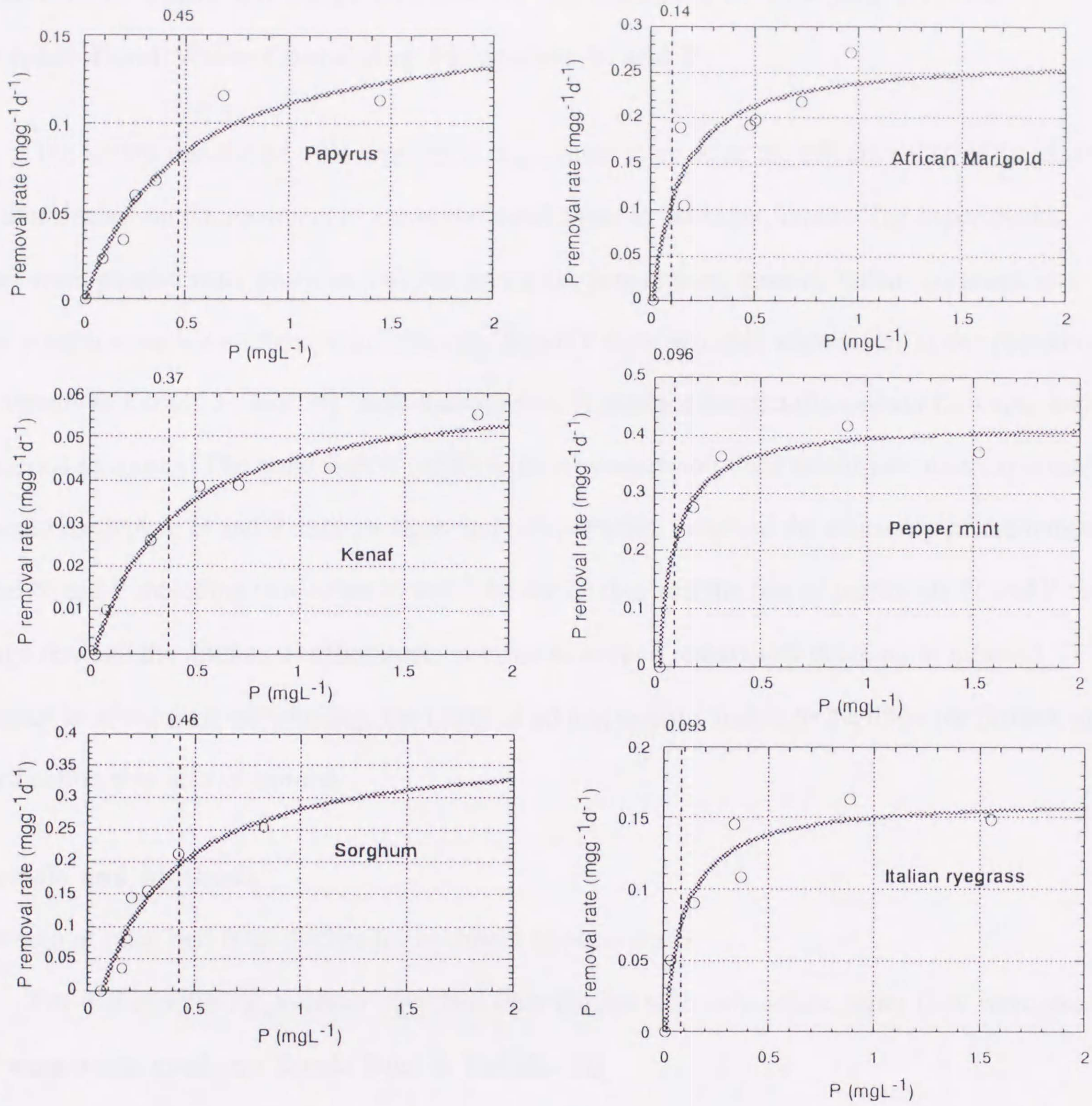


Fig.6-3 Phosphorus removal rates related to phosphorus concentrations in papyrus, kenaf, sorghum, African marigold, peppermint and Italian ryegrass.
P removal rate : removed P per plant dry weight per day.

Chapter 7

Evaluation of Plant bed Filter Ditches for the Removal of T-N and T-P from Eutrophic Pond Water Containing Particulate N and P

The author conducted a more practical experiment to evaluate the effectiveness of the plant bed filter ditches on the treatment of eutrophic pond water in Tsukuba, Japan. The experimental ditches were planted with papyrus, African marigold, peppermint, hanana, Italian ryegrass, etc. These plant species were effective in removing N and P from artificial wastewater in our previous experiments and could be used by rural communities to produce handicrafts and cut flowers, and for ornamental purposes. The pond water, unlike artificial wastewater used in our previous experiments, contained particulate N and P such as algae and soil particles. I studied the efficiency of the removal of total N and P including particulate N and P by the ditches and the fate of particulate N and P during passage through the ditches. Furthermore, in order to avoid a remarkable decrease in removal efficiency in winter and early spring, the effect of adding organic matter to the ditch for promoting denitrification was also examined.

Materials and Methods

(1) Design of plant bed filter ditches for treatment of pond water

For this experiment, outdoor plant bed filter ditches with subsurface water flow were used. They were constructed near Konda Pond in Tsukuba City.

A plant bed filter ditch filled with zeolite as bed filter material (particle size: 6-8 mm) enables the cultivation of both terrestrial and aquatic plants when the depth of zeolite is adjusted to the saturation tolerance of the plant species. The bed filter surface was about 0.1 m higher than the water level for terrestrial species and the same as the water level for aquatic species.

The experimental ditch was 0.4 m wide, 0.3 m deep, and 11.2 m long (Fig.7-1). Water depth was 0.2 m. The first 1.2 m section from the ditch inlet was 0.8 m deep (water depth 0.7 m) for precipitating suspended solids (SS). To prevent shortcut flow in the ditch, correction flow boards were placed at 1.2 m intervals. The ditch was filled with zeolite as bed filter material except for the first 1.2 m section. Sampling spaces not filled with zeolite were set up at 1.2 m intervals. The height of the zeolite filter was 0.2 m for aquatic species and 0.3 m for terrestrial species (Fig.7-1).

(2) Operational conditions

Three types of ditches examined are shown in Fig.7-2.

The planted ditch was planted with impatiens (*Impatiens sultani* Hook. f.), peppermint (*Menta piperita* L.), African marigold (*Tages erecta* L.), papyrus (*Cyperus papyrus* L.), and kenaf (*Hibiscus cannabinus* L.) in summer and autumn (Plates 7-1 and 7-2) and English daisy (*Bellis perennis* L), peppermint, hanana (*Brassica campestris* L. var.), and Italian ryegrass (*Lolium multiflorum* Lam.) in winter and spring (Plate 7-2). Seedlings of impatiens, African marigold, English daisy, hanana, and Italian ryegrass and rhizome cuttings of peppermint and papyrus were transplanted to the ditches. A total of 21 seedlings were planted per square meter of ditch surface area. The plants (above ground parts and under ground parts) cultivated in the ditch were harvested October, 1997 and 1998, and May, 1998. The zeolite filter was 0.3 m high for terrestrial species (impatiens, peppermint, African marigold, peppermint, English daisy, hanana, and Italian ryegrass) and 0.2 m for aquatic papyrus.

The planted/organic matter ditch was contained the same plants as those listed previously as well as organic matter within the bed filter in the midstream. Nets packed with 1.5 kg of dried rice straw and 1.0 kg of papyrus stems (cut into about 2 cm fragments) were buried in mid of October, 1997 and removed at the end of May, 1998 (Fig.7-2).

The control ditch did not contain plants (plant-free ditch) .

Pond water was pumped and supplied continuously to the ditches at a loading rate of about 200 Lm^{-2} (ditch area) d^{-1}. Retention time was about 20 hours.

(3) Sampling and analysis

The volume of wastewater inflow and outflow was measured. The influent and effluent of the ditch were collected once a week and the water quality was analyzed. On September 2, 1997, and April 17, 1998, the water in the ditch was collected at 2.4 m intervals (10 cm depth) from the inlet to the outlet .

Total N concentration (T-N) of water containing suspended solids was measured using a Technicon Traacs 800 after persulfate-NaOH digestion (Tsuzuki and Uchino, 1994). Total P

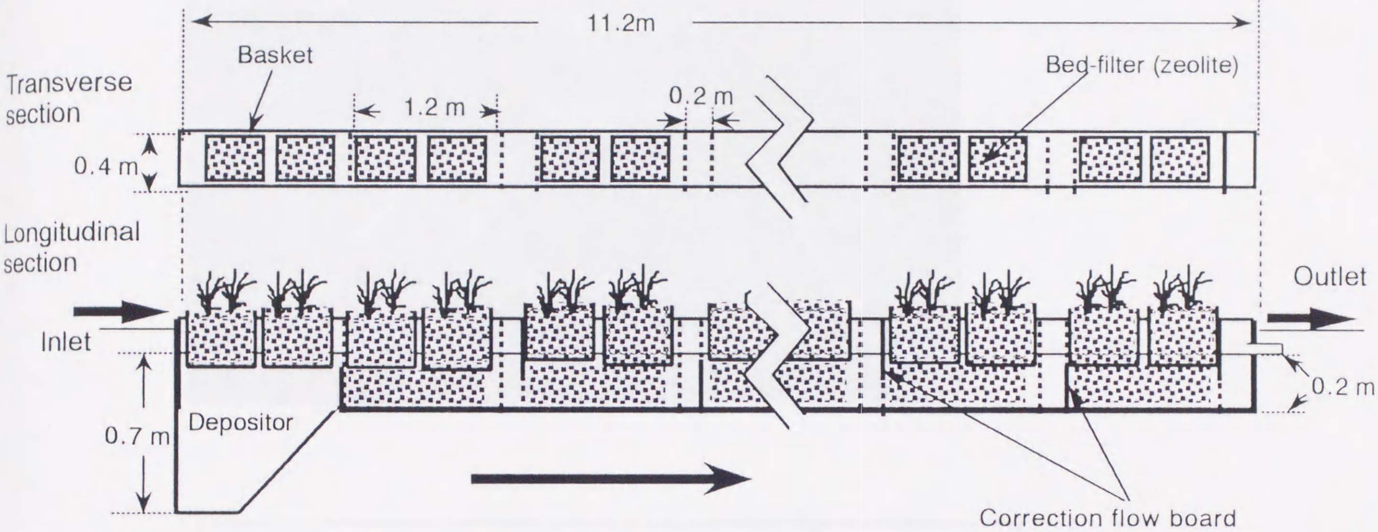


Fig.7- 1. Plant bed filter ditches for the treatment of polluted pond water.

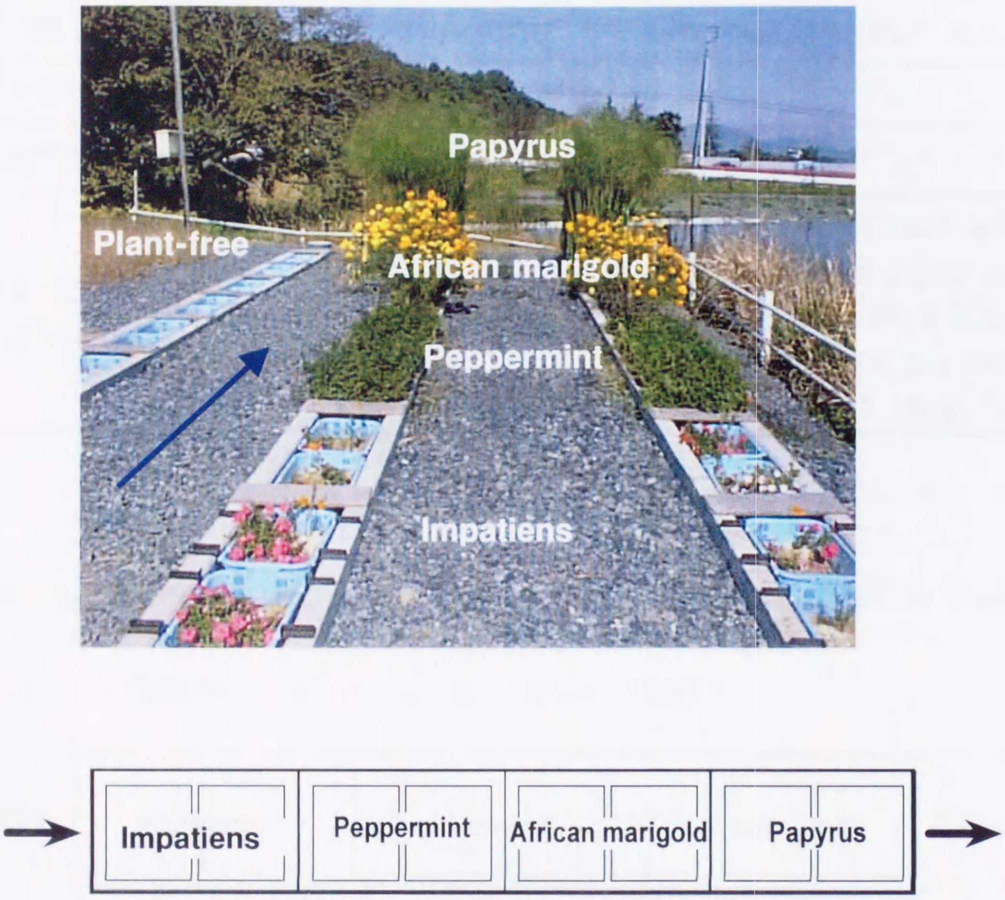


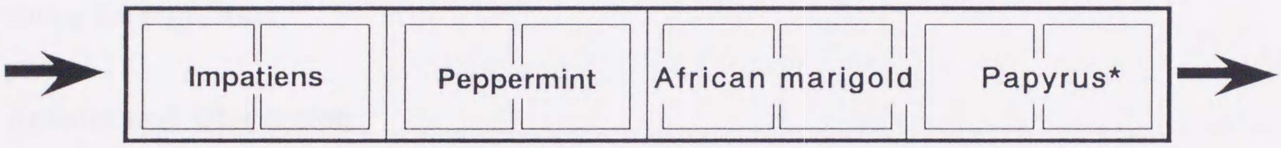
Plate 7-1　Plant bed filter ditch constructed near Konda Pond in Tsukuba City.

Experimental design

Ditch name	Planting	Organic matter addition
Plant-free ditch	-	-
Planted ditch	Planting	-
Planted/organic matter ditch	Planting	Rice straw 1.5kg and dried papyrus stems 1.0kg (cut into 2 cm fragments) were placed within the bed in the mid stream during the period from October, 1997 to May, 1998.

Planting in the planted ditch and the planted /organic matter ditch

August ~ October 1997 and June~October 1998



October 1997~May1998

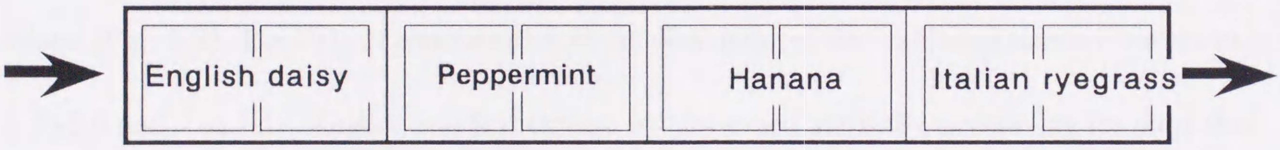


Fig. 7-2 . Experimental design.

* Instead of papyrus, kenaf was planted in the planted/organic matter ditch during the period from June to October, 1998.

concentration (T-P) of water containing suspended solids was measured using the ascorbic acid method after persulfate digestion (APHA, AWWA, and WPFC, 1989). Total dissolved N (TDN) and total dissolved P (TDP) concentrations were measured after filtration using a 0.45 μ m membrane filter. The concentrations of NO_3-N, NH_4-N, and PO_4-P were determined using a Technicon Traacs 800. Total organic carbon (TOC) concentration was measured by using Shimadzu TOC 500.

The removal rate was calculated as the difference between the rates of N & P entering and leaving the ditches divided by the ditch surface area.

The contents of N and P in the plants and the bed filter materials were measured by using Technicon Traacs 800 after digestion by salicylate acid-thiosulfate (modification of the Kjeldahl method (Bremner and Mulvaner 1982)).

In the calculation of the N and P balance, the amounts of N and P removed by the ditch were calculated as the difference between the amounts of N and P entering the ditch and leaving the ditch during the experiment .

Results and Discussion

N and P concentrations in the pond water

The T-N concentration of the ditch influent (pond water) was low in summer and high in winter (Fig. 7-3). The NO_3-N concentration of the ditch influent also exhibited seasonal variations - 1.5 -3.0 mgL^{-1} in July, August, and September, and increased markedly, accounting for more than 90% of total N in January and February when the temperature decreased (Fig. 7-3). This was probably because that the amount of algae in the pond water decreased and the proportion of NO_3-N absorbed by algae also decreased. The NH_4-N concentration of the ditch influent (pond water) was less than 0.5 mgL^{-1}. The total P concentration of the ditch influent (pond water) was 0.1-0.2 mgL^{-1} and the PO_4-P concentration was very low, less than 0.03 mgL^{-1} (Fig. 7-4). Most P was not dissolved because of the high pH value of the pond water (8-9) due to algal photosynthesis or absorption by algae. Ditch influent (pond water), unlike artificial wastewater used in our previous study, contained large amounts of particulate N and P (Figs.7-5 to 7-8) Ratio of P to N was 1:20 (in summer) to 1:70 (in winter). Amount of nitrogen seemed to be excessive compared with the ratio of P absorption to N absorption by plants.

Effect of adding plants to the ditches on effluent concentrations

The T-N and T-P concentrations of the effluent from the ditches containing plants decreased to less than the values recorded in the plant-free ditch during the experimental period. The concentration of the planted ditch effluent decreased less than 0.3 mgL^{-1} for N in summer and 0.02 mgL^{-1} for P after September 1997 (Figs. 7-3 and 7-4). The minimum nutrient concentration for water bloom formation has been reported to be 0.3 mgL^{-1} for N or 0.02 mgL^{-1} for P (Kojima et al. 1977). These findings indicate that the plant bed filter ditches effectively purified water and prevented water bloom.

The T-N concentration of the planted ditch effluent rose with the increase of the NO_3-N concentration of the influent (Fig. 7-3). The increase in the NO_3-N load and the restriction of plant growth in winter resulted in the decrease of the T-N removal efficiency.

The NH_4-N concentration of the ditch effluent was less tnan 0.05 mgL^{-1} in the three ditches during the experiment.

N and P removal functions in the ditches

The concentrations of the N and P compounds in the ditch from the inlet to the outlet determined on September 2, 1997, and April 17, 1998 are shown in Figs.7-5 to 7-8. Most of the particulate N (T-N minus TDN) and particulate P (T-P minus TDP) was removed by filtration in the first 5 m part of the zeolite bed filter in all the ditches. In the plant-free ditch, particulate N and P were effectively removed, unlike dissolved N and P. The concentrations of TDP and PO_4-P increased from the inlet to the outlet considerably in the plant -free ditch, suggesting that particulate P was dissolved in the bed filter under reduced conditions or by microbial decomposition. The planted ditch and the planted/organic matter ditch removed NO_3-N, PO_4-P and particulate N and P quite well in summer (Figs. 7-5, 7-6). NO_3-N that had not beed removed by filtration through the zeolite bed filter and PO_4-P dissolved from particulate P were absorbed by the plants in the ditch.

NO_3-N concentration decreased from 4.5 mgL^{-1} to 2.0 mgL^{-1} in the first 5 m part of the plant-free ditch on April 17, 1998 when almost all of the N in the influent was consisted of NO_3-N (Fig. 7-8). This suggests that denitrification was promoted by the use of organic compounds in the particles (suspended solids) accumulating in the bed filter as hydrogen donors. The NO_3-N concentration in the latter half of the planted/organic matter ditch was lower than that in the planted ditch, because organic compounds in rice straw and papyrus stems buried in the midstream of the ditch flowed downstream and accelerated denitrification and immobilization of nitrogen by microbial organisms there.

Effect of adding plants and organic matter to the ditches on N and P removal efficiency

Nitrogen removal rates in the planted ditch and the planted/organic matter ditch were generally exceeded 0.6 $gm^{-2}d^{-1}$ in summer (May to September), but decreased in winter and spring (Figs. 7-9). This was probably because filtration through the zeolite bed did not contribute to N removal owing to the decrease of particulate N concentration in pond water and plant growth was restricted in winter. During the period when the organic matter was buried in the planted/organic matter ditch (October, 1998 to May, 1999), the N removal rate there was greater than that in the planted ditch by 0.1 - 0.2 $gm^{-2}d^{-1}$.

Though TOC concentration in the planted/organic matter ditch effluents increased to 10.1 mgL^{-1} right after (one day) the organic matter was buried in the ditch, it decreased to the same level (0.5 - 2.0 mgL^{-1}) as that in the plant-free ditch and planted ditch soon afterward the next day. The addition of the organic matter to the ditch caused almost no TOC pollution of the ditch effluents (Fig.7-10). Thus, I recommend that the papyrus stems growing in the ditches during summer be buried within the bed filter and utilized to improve N removal during winter and early spring.

Fig. 7-11 shows the N removal efficiency for three periods. The removal efficiency of the plant free ditch dropped in winter and spring (from October, 1997 to May, 1998) when particulate N like algae decreased and the ratio of NO_3-N concentration to T-N increased markedly. The addition of plants to the ditch improved N removal efficiency by 30% in summer and autumn (August to

October, 1997 and June to October, 1998) and by 15% in winter and spring. Furthermore, burying the organic matter in the ditch improved N removal efficiency by 10% in winter and spring.

N load was 20 (summer) - 70 (winter) times as high as P (Figs. 7-9, 7-12). Average N uptake rates by the plants in the ditches were 10 - 20 times as large as P uptake rates. Thus almost all of the influent P was removed in plant-containing ditches (Figs. 7-12, 7-13), though excess N was absorbed only partially and remained in the ditch effluent, especially in winter. P removal efficiency of the plant-free ditch started to decline 9 months after the beginning of the experiment (Fig. 12). This was because the particulate P that had accumulated in the ditch continued to dissolve during this period.

N and P balance

Nitrogen and phosphorus balance during the experiment is shown in Tables 7-1, 7-2, and Figs. 7-14 and 7-15. In the plant-free ditch, 62 g of N remained in the bed filter and depositor of the ditch (corresponding to only 12.8% of N removed from pond water). In contrast, 12.5g of P, which corresponds to 90% of P removed from pond water, remained in the plant-free ditch. These data indicated that P was removed mainly by filtration and precipitation in the plant-free ditch, while N was assumed to be removed mainly by denitrification using organic compounds in particles (suspended solids) accumulating in the bed filter as hydrogen donors.

In the planted ditch and the planted/organic matter ditch, 756- 903 g of loaded N was removed, and 174 -224 g of N was absorbed by plants. It was found that 23% - 25% of N removed by the ditch was absorbed by plants and 6% - 7% of N removed was accumulated in the bed. In contrast, 26.9 - 29.3 g of loaded P was removed, 12.0 - 14.7 g of P was absorbed by plants and 6.5 - 8.6 g of P was accumulated in the bed. The amount of P absorbed by plants corresponded to 45% - 50% of P removed by the ditch and P accumulated in the bed corresponded to 24% - 29% of P removed. These data indicate that P was removed mainly by filtration and plant absorption, and N was removed mainly by denitrification and plant absorption.

Fig.7 -16, 7-17 show the details of the N and P absorption by plants. Papyrus, which was planted in summer and autumn, contributed the most to N and P removal. Peppermint which was planted throughout the experiment, also played an important role.

Plants growth

The plants in the ditches grew well through the supply of eutrophic pond water without the addition of other nutrients in the bed filter where suspended solids accumulated (Plate 7-1,7-2).

However, the dry weight of African marigold, papyrus, hanana, and Italian ryegrass which were cultivated in the latter half (downstream) of the ditch was much lower than that recorded in our previous experiment (Chapter 5) performed by using artificial wastewater in a greenhouse (Table 7-3). Since the P loading rate in this experiment was low (0.01 - 0.03 $gm^{-2}d^{-1}$, about 1/10 the P loading rate of that in the experiment mentioned in Chapter 5) (Fig. 7-12). Thus, probably, P was short in the downstream and plant growth in the down stream was limited.

Papyrus, kenaf, and Italian ryegrass biomass downstream, 10.5-11.2 m from the ditch inlet, were 46-75% of their upstream biomass, 8.4 -9.1 m from the ditch inlet. These plant species did not remove N or P from artificial wastewater where the N concentration was below 0.2- 0.3mgL^{-1} and the P concentration was below 0.01-0.02 mgL^{-1}. In addition the removal rate was markedly restricted when the P concentration was below 0.09 -0.45mgL^{-1} and N concentration below 0.34-0.57mgL^{-1}, based on an experiment using artificial wastewater containing N mainly as NO_3-N and P as PO_4-P (Chapter 6). This suggests that the biomass production downstream was restricted by the low N and P concentrations.

Recommended use of plant bed filter ditches

Calculations of the volume and T-N and T-P concentrations of wastewater entering the pond once a week showed that about 1.3 kg N and 26 g P entered Konda Pond daily. Based on the average removal rate of the planted ditches, 30% of N and 70% of P entering the pond from the catchment area were removed by the plant bed filter ditches with an area of about 600m^2 (about one sixth of the pond area) in summer and autumn.

Some ponds used for agriculture in Japan have been transformed into parks. I believe that the plant bed filter ditches could be used as flower beds or for ornamental purposes in pond parks to reduce the N and P load to the ponds. I found that the plant bed filter ditches purified the pond water, resulting in a decrease of the N and P concentrations below the minimum concentrations required for water bloom formation. The plant-bed filter ditches could also supply clear water for ornamental streams in parks, where children could play in the water.

Conclusions

(1) Plant bed filter ditches planted with plant species which effectively remove N and P from artificial wastewater were able to treat pond water more efficiently than a plant-free ditch.

(2) The plant free ditch (depositor and bed filter) was effective for removing particulate P, but PO_4-P was dissolved from particulate P accumulated in the bed filter. The addition of plants to the ditches removed PO_4-P successfully. Plant uptake and filtration by bed filters played important roles in P removal in the ditches containing plants.

(3) The plant-free ditch removed particulate N completely and NO_3-N to some extent. The ditch containing plants removed NO_3-N and particulate N well. The N balance indicated that N was removed mainly by denitrification and plant absorption. This suggests that denitrification was promoted by using suspended solids accumulated in bed filter as hydrogen donor.

(4) The planted ditches purified eutrophic pond water resulting in a T-N concentration below 0.3 mgL^{-1} and T-P below 0.02 mgL^{-1}, the minimum N and P concentrations required for water bloom formation.

(5) The average N removal rate in the ditches containing plants was generally exceeded 0.6 $gm^{-2}d^{-1}$ in summer (May to September), but decreased in winter. Almost all of the influent P was removed in the plant-containing ditches during the experiment because the phosphorus load was much lower than the N load (1/20 to 1/70 of N load).

(6) The addition of organic matter to the ditch was effective in improving the N removal efficiency by 0.1 - 0.2 $gm^{-2}d^{-1}$ in winter and spring.

(7) I recommend that plant-bed filter ditches containing papyrus and flowers be used for ornamental purposes to remove T-N and T-P from the pond water and provide clear water that could be used as ornamental streams.

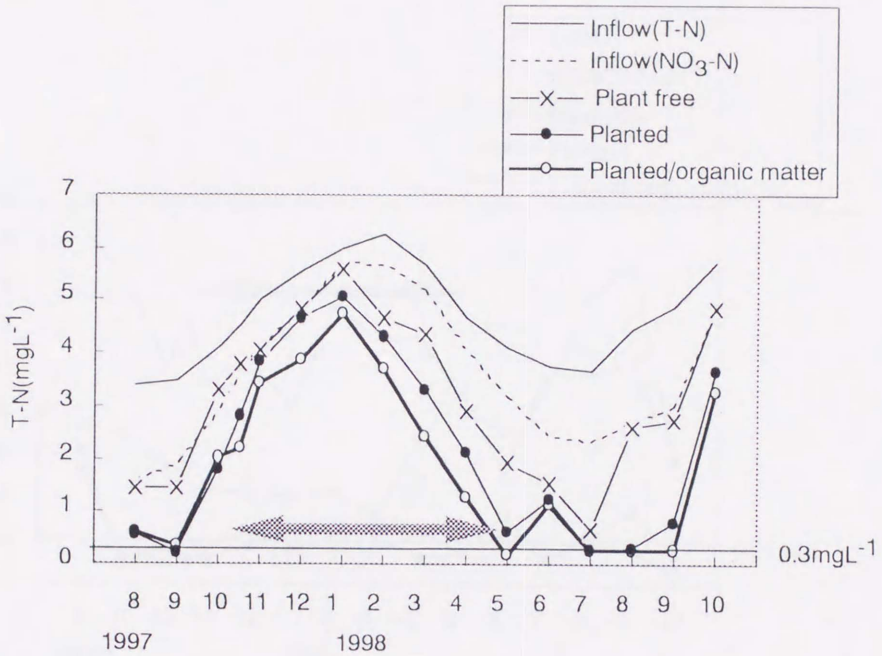


Fig. 7-3 Changes in T-N concentrations of ditch influents and effluents (monthly average value).
The arrow indicats the period when the organic matter was set in the planted/organic matter ditch.
Inflow : water of Konda Pond in Tsukuba City
0.3 mgL-1 : the minimum nutrient concentration for water bloom formation

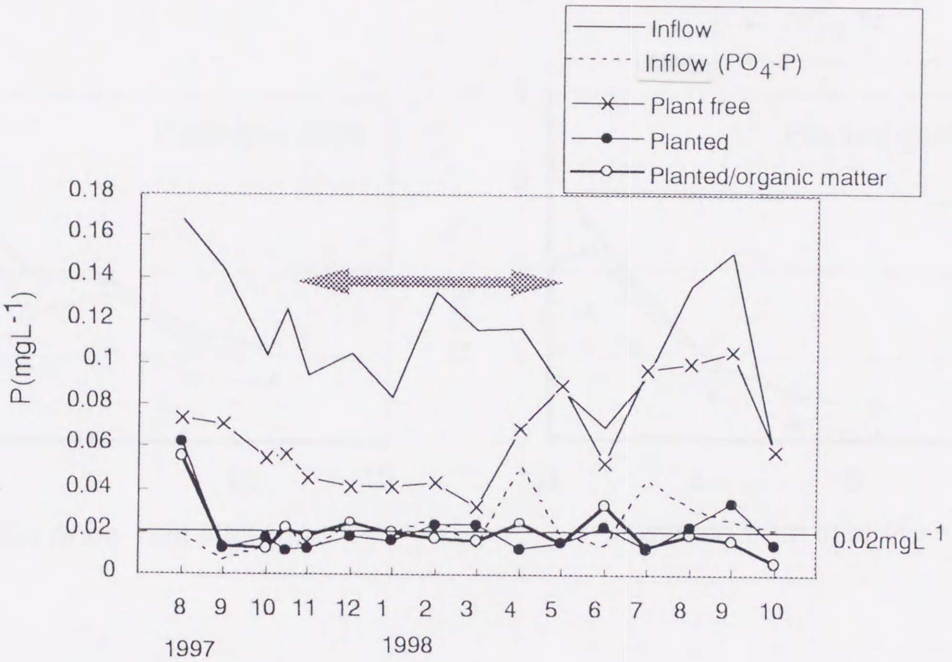


Fig. 7-4 Changes in T-P concentrations of ditch influents and effluents (monthly average values).
The arrow indicats the period when the organic matter was set in the planted/organic matter ditch.
Inflow : water of Konda Pond in Tsukuba City
0.02 mgL-1 : the minimum nutrient concentration for water bloom formation.

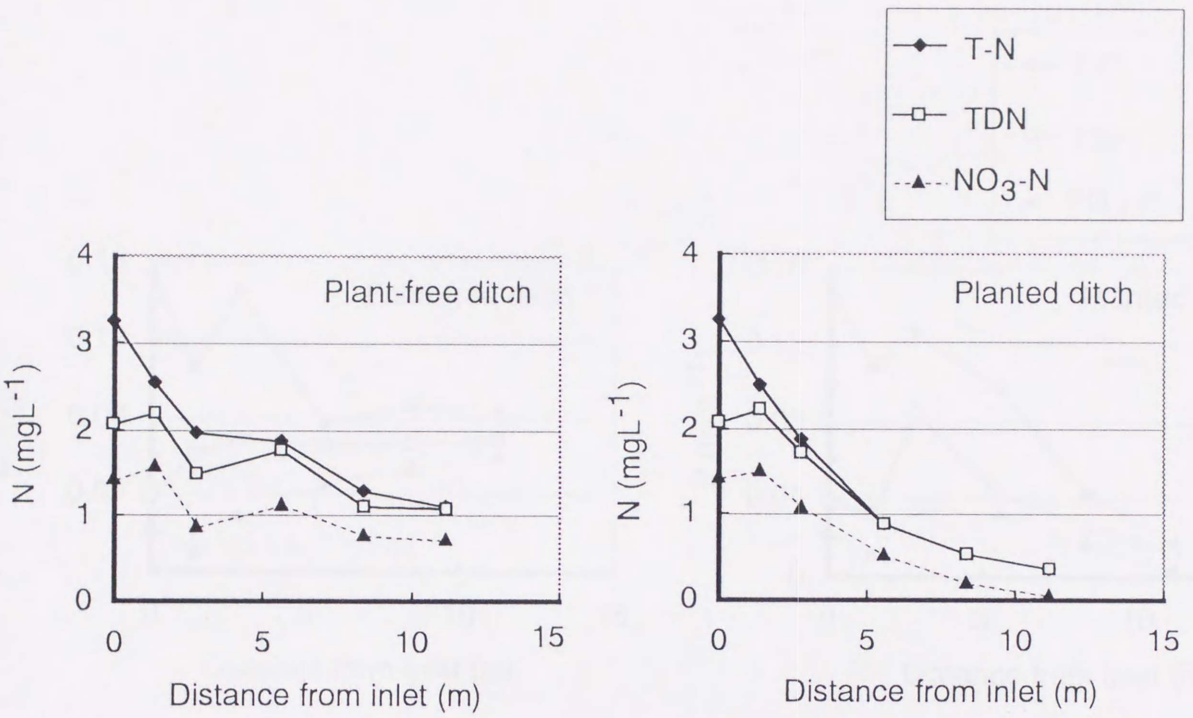


Fig.7-5. T-N, TDN, and NO_3-N concentrations in ditches from inlet to outlet on September 2, 1997.

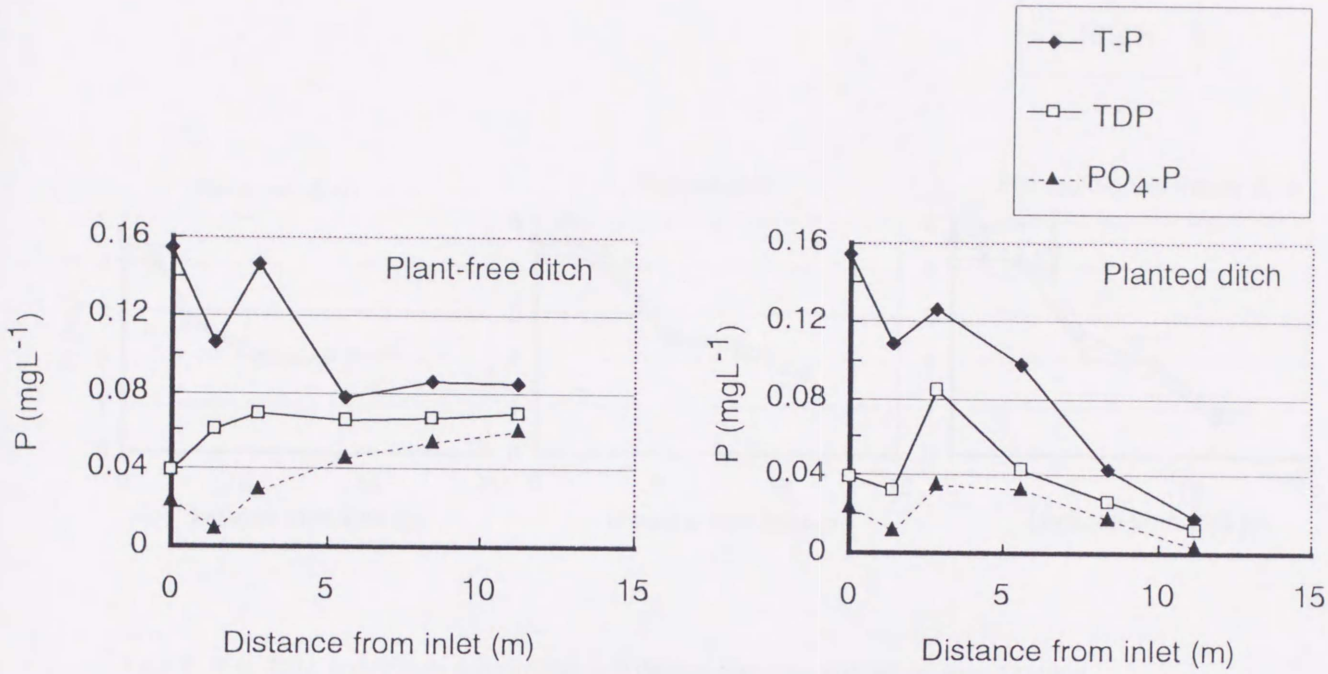


Fig. 7-6. T-P, TDP, and PO4-P concentrations in ditches from inlet to outlet on September 2, 1997.

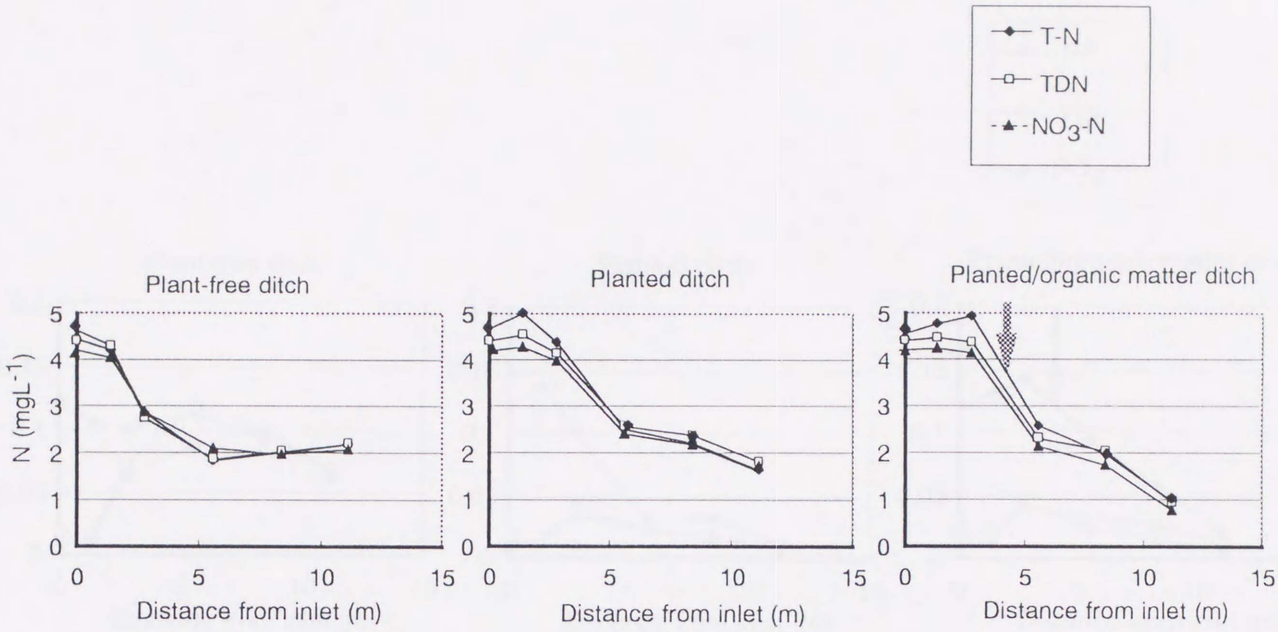


Fig.7-7. T-N, TDN, and NO_3-N concentrations in ditches from inlet to outlet on April 17, 1998.
The arrow indicats the place where organic matter was set.

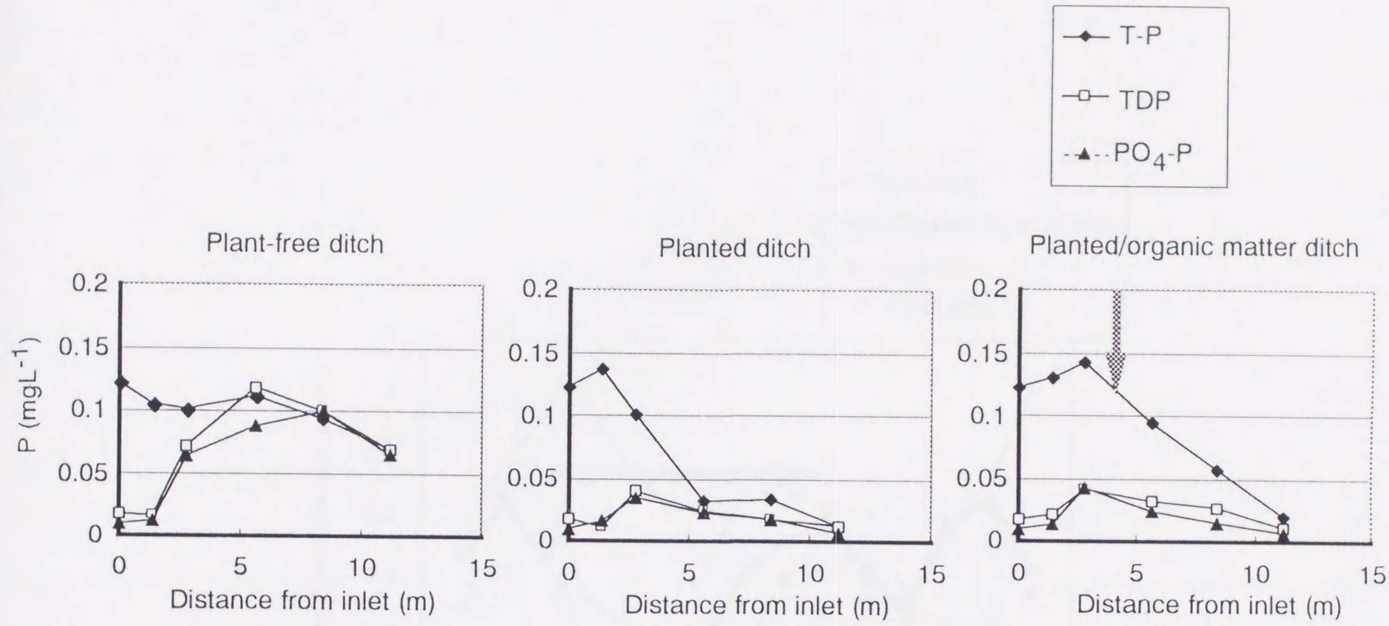


Fig. 7-8.. T-P, TDP, and PO4-P concentrations in ditches from inlet to outlet on April 17, 1998.
The arrow indicats the place where organic matter was set.

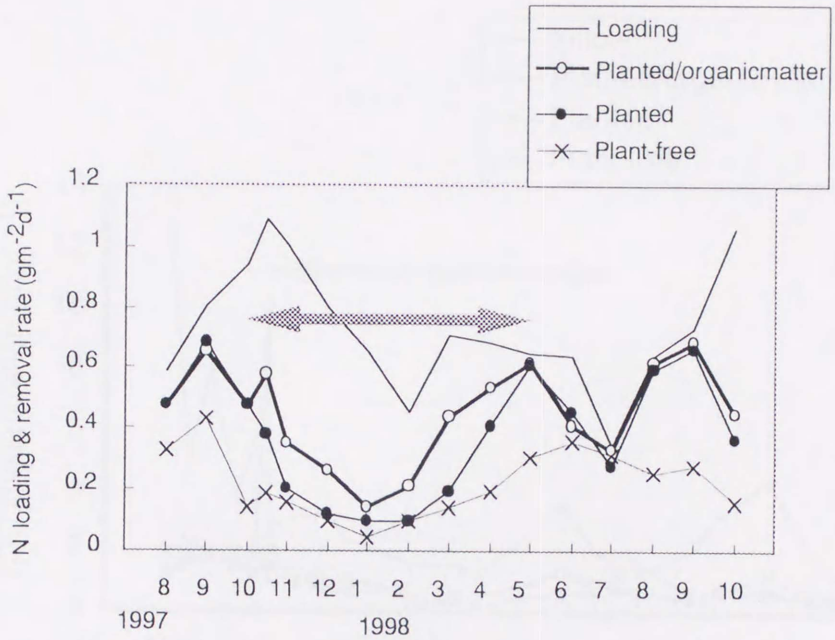


Fig. 7-9. Changes in T-N removal rates of the ditches (monthly average value).
The arrow indicats the period when the organic matter was set in the planted/organic matter ditch.

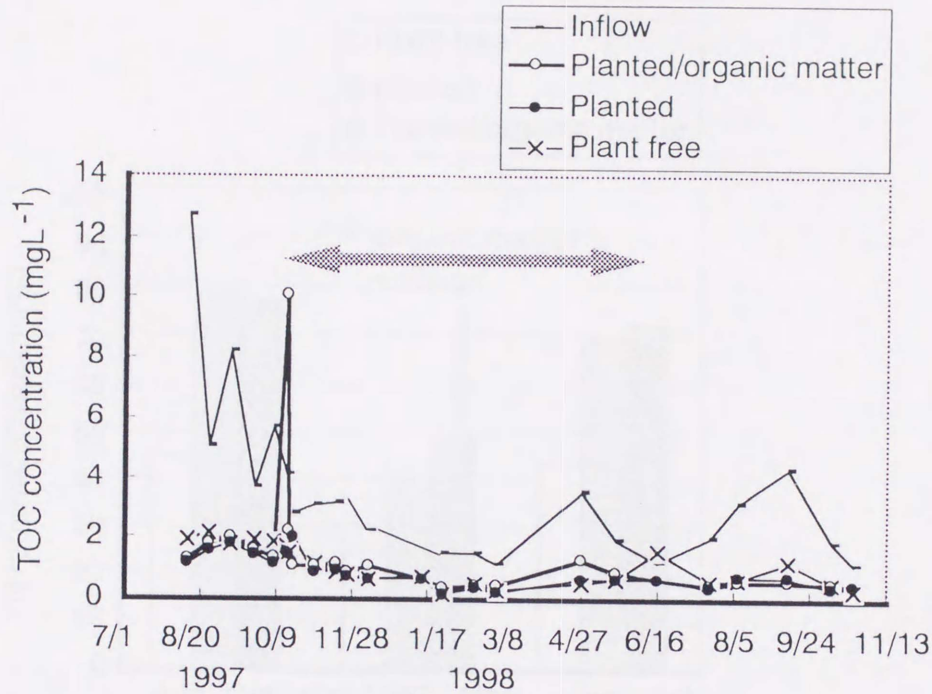


Fig.7-10 Changes in TOC concentrations of influents and effluents.
The arrow indicats the period when the organic matter was set in the planted/organic matter ditch.

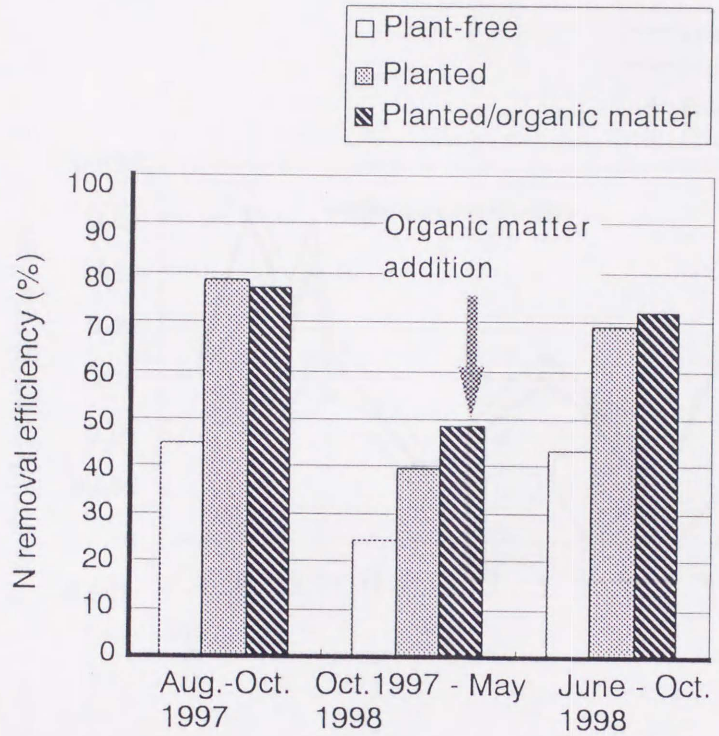


Fig.7-11. N removal efficiency
The arrow indicats the period when the organic matter was set in the planted/organic matter ditch.

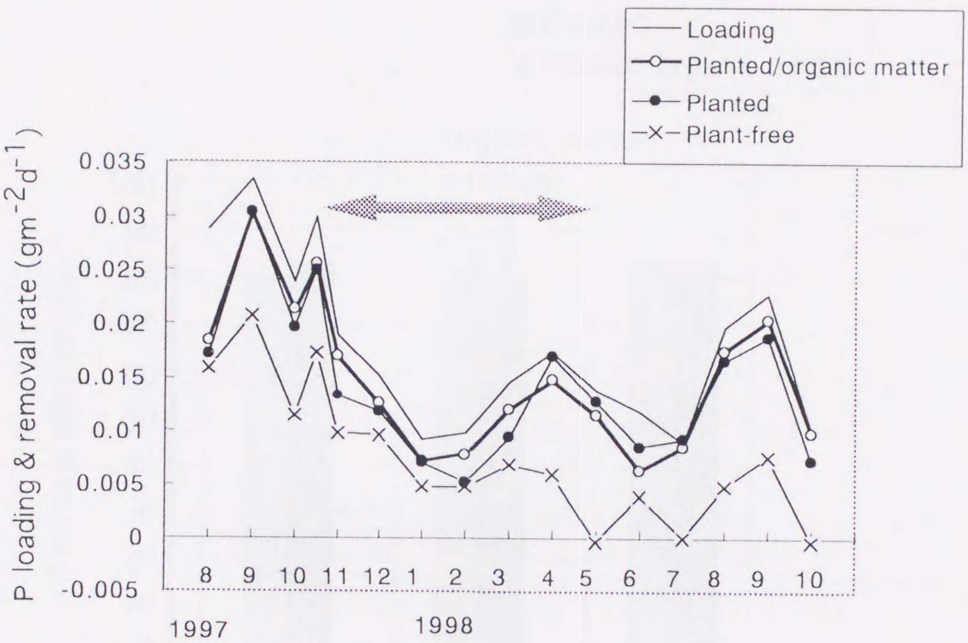
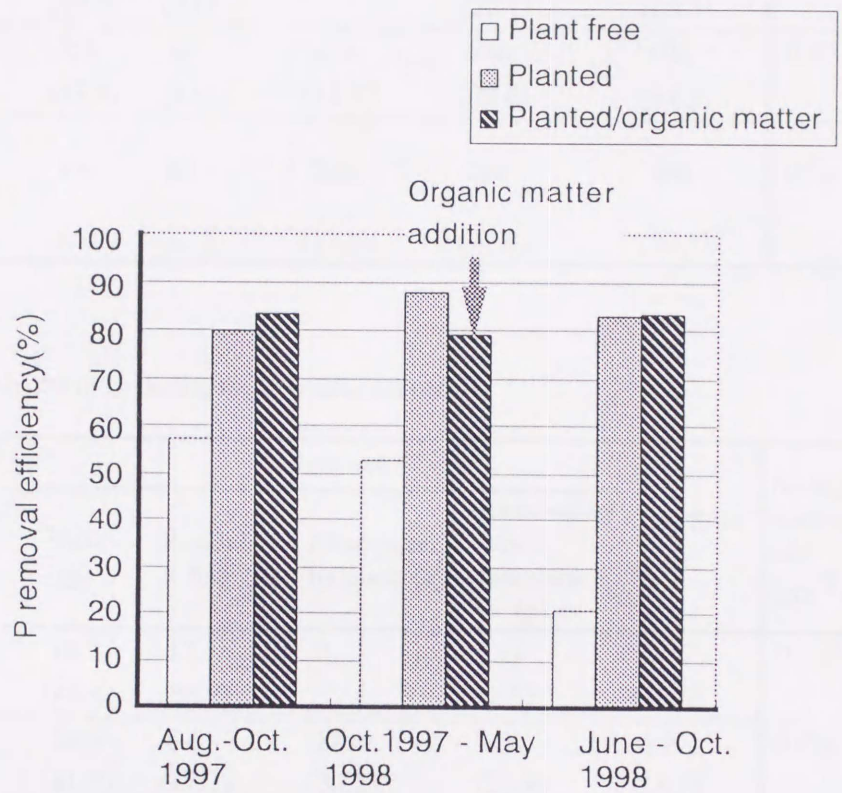


Fig. 7-12. Changes in T-P removal rate of the ditches (monthly average value).
The arrow indicats the peoriod when organic matter was set to the planted/organic matter ditch.



F1g.7-13. P removal efficiency of each ditch.
The arrow indicats the peorid when the organic matter was set in the planted/organic matter ditch.

Table 7-1. N balance in the ditch during the experimental period

	Inflow (g)	Removal				Outflow (g)	Average loading rate ($gm^{-2}d^{-1}$)	Average removal rate ($gm^{-2}d^{-1}$)
		Total (g)	Residues in bed (g)	Absorption by plant (g)	Removal by denitrification etc. (g)			
Plant-free	1340	451	62	0	390	889	0.67	0.22
(%)	(100)	(33.7)	(4.6)		(29.1)	(66.3)		
Planted	1356	756	45	174	536	600	0.67	0.38
(%)	(100)	(55.8)	(3.4)	(12.8)	(39.6)	(44.2)		
Planted /organic matter	1490	904	62	224	618	586	0.74	0.45
(%)	(100)	(60.7)	(4.1)	(15.0)	(41.5)	(39.3)		

Table 7-2. P balance in the ditch during the experimental period

	Inflow (g)	Removal				Out flow (g)	Average loading rate ($gm^{-2}d^{-1}$)	Average removal rate ($gm^{-2}d^{-1}$)
		Total (g)	Residues in bed (g)	Absorption by plant (g)	Removal by other functions (g)			
Plant-free	32.8	13.3	12.5	0	0.7	19.6	0.016	0.007
(%)	(100)	(40.4)	(38.2)		(2.3)	(59.6)		
Planted	33.1	26.9	6.5	12.0	8.4	6.2	0.016	0.013
(%)	(100)	(81.3)	(17.7)	(36.2)	(25.4)	(18.7)		
Planted /organic matter	35.8	29.3	8.6	14.7	5.6	6.5	0.018	0.015
(%)	(100)	(81.8)	(23.9)	(41.1)	(16.7)	(18.2)		

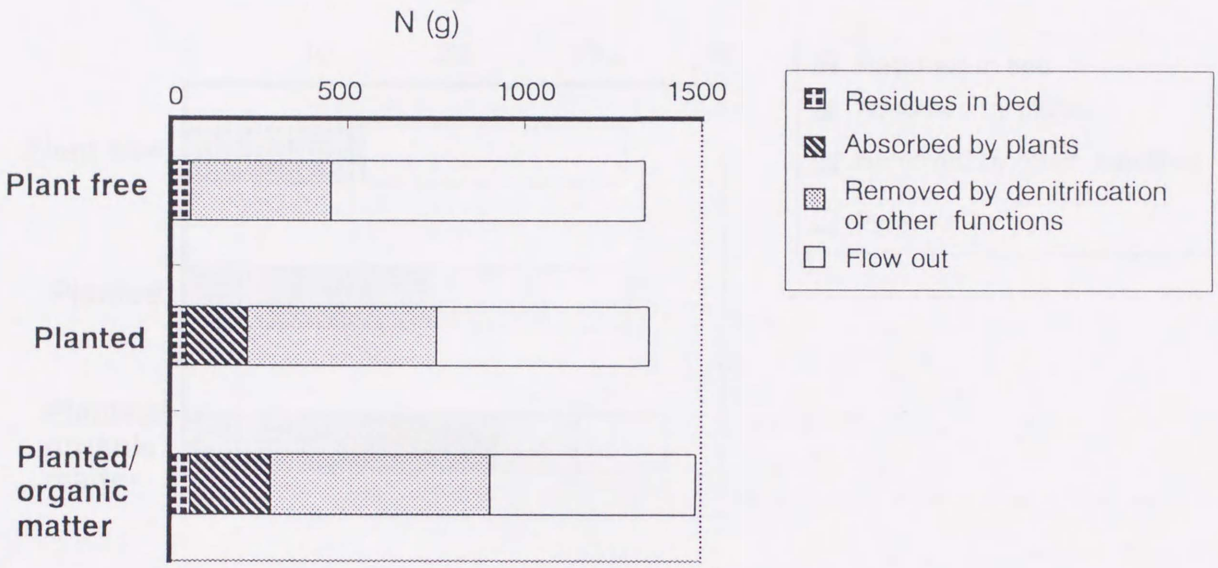


Fig.7-14 Nitrogen balance during the experiment.

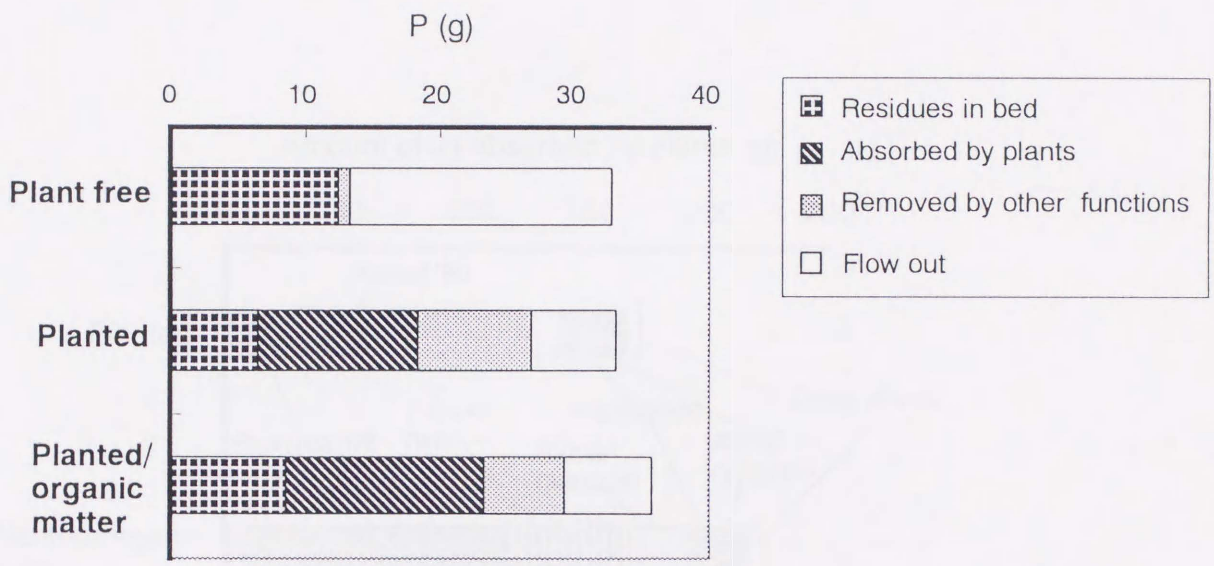


Fig.7-15 Phosphorus balance during the experiment.

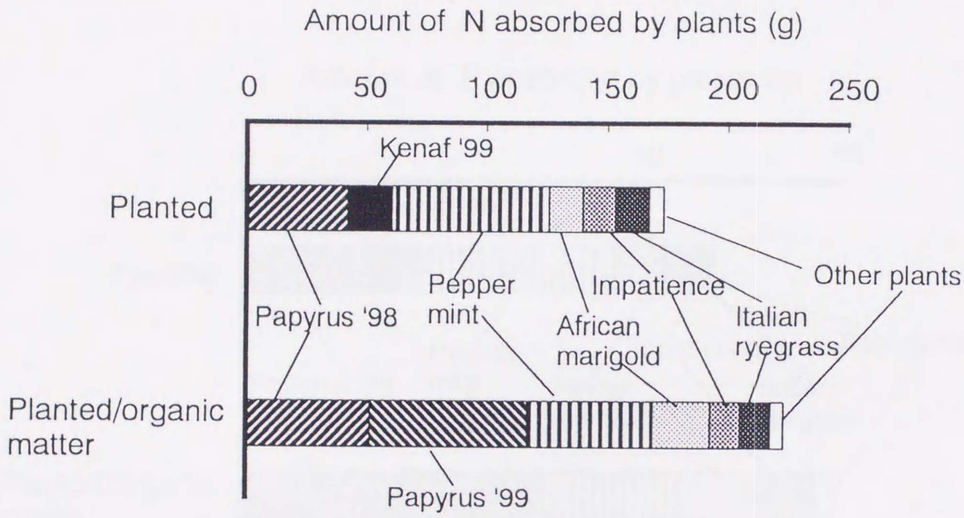


Fig.7-16 Contribution of plant species to N removal.

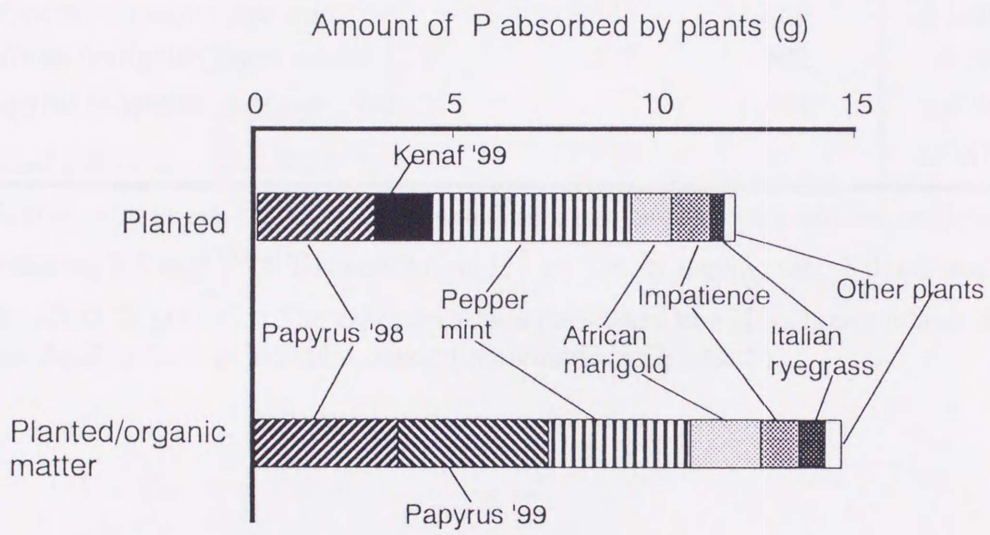


Fig.7-17 Contribution of plant species to P removal.

Table 7-3. Dry weight of plants in the plant bed filter ditch provided pond water and artificial wastewater.

(gm^{-2})

	Planted ditch	Planted/organic matter ditch	Experiment using artificial wastewater*
Winter and spring (Nov. 1997 - May 1998)			(Dec. 1995 - May 1996)
Pepper mint (*Menta piperita* L.)	1,192	719	2,204
Hanana (*Brassica campestris* L. var.)	160	179	1,531
Italian ryegrass (*Lolium multiflorum* Lam.)	1,042	1,256	4,772
Summer and autumn (June - Oct. 1998)			(June - Oct. 1996)
Impatiens (*Impatiencs sultani* Hook. f.)	370	307	421
Peppermint (*Menta piperita* L.)	1,683	1,869	2,740
African marigold (*Tages erecta* L.)	287	382	978
Papyrus (*Cyperus papyrus* L.)		4,404	9,858
Kenaf (*Hibiscus cannabinus* L.)	1,600		6,287

* In this experiment, the ditch was planted with one plant species and fed artificial wastewater containing 2.5 mgL^{-1} of T-N and 0.6 mgL^{-1} of T-P. N loading rate: 1.0-1.2 $gm^{-2}d^{-1}$, P loading rate: 0.2-0.25 $gm^{-2}d^{-1}$. The experiment was performed in a glass house whose windows were open from April to Nov. in Tsukuba, Japan (mentioned in Chapter 5).

Plate 7–2. Plant bed filter ditch near Konda Pond.
The top: October, 1997, the bottom: April, 1998.

Chapter 8

General Discussion and Conclusions

The increase of wastewater production coinciding with an increase in the human and livestock population in rural areas has led to the eutrophication of aquatic ecosystems. Most of the nitrogen and phosphorus load in rural areas derives from domestic wastewater and livestock wastewater. It is thus necessary to develop a low cost wastewater treatment system suited to rural areas. It is also desirable to add resource reuse and amenity to the wastewater treatment system in order to make the system attractive and acceptable. Livestock wastewater contains extremely high concentrations of N and P, 10 times higher than those of domestic wastewater and 100 times higher than those of eutrophic pond water.

So far I have examined a system consisting of a combination of aerobic soil column and anaerobic contact column for the livestock wastewater treatment, and a plant bed filter ditch that I developed for the treatment of domestic wastewater and eutrophic pond water. The optimum conditions and management, including selection of plant species, were discussed.

8-1 Management of the aerobic soil column and anaerobic column system

This system consists of two columns mounted in series, an aerobic soil column and an anaerobic column. The wastewater from which suspended solids (SS) is removed is fed into the aerobic column where organic matter is decomposed, phosphorus is sorbed onto clay minerals of soil in the column, and ammonium is oxidized to nitrate by nitrifying bacteria. The effluent from the aerobic column then flows into the anaerobic column (submerged condition) where nitrate in the influent is converted to nitrogen gas by denitrification bacteria.

The addition of 20% crushed limestone to the soil in the aerobic column was effective for preventing the acidification of the packed soil and promoting nitrification for a long period of time. Ammonium, phosphorus, and TOC in the wastewater were successfully treated by the aerobic column packed with 60% volcanic ash soil, 20% zeolite, and 20% crushed limestone. The NH_4-N treatment (nitrification) rate was 36.2 $gm^{-3}d^{-1}$.

In the anaerobic column, carbonized rice husks and charcoal chips were more suitable materials as packing media than volcanic ash soil in terms of permeability of the influent through the medium. The denitrification of 1 g of NO_3-N required about 3 g of methanol. In the anaerobic column packed with carbonized rice husks or charcoal chips with added methanol, NO_3-N treatment rate was 64 $gm^{-3} d^{-1}$. Though methanol is widely used as a hydrogen donor for denitrification in the wastewater treatment plants, methanol is poisonous and adding it constantly to the column is troublesome. It was found that mixing the straw with the column packing medium was effective for accelerating denitrification.

Average swine excretes urine containing 24 g of N and 1 g of P a day (Tabuch and Takamura 1985). If it is possible to enlarge the bench scale column to a practical scale with similar figures, 0.66 m^3 of the aerobic column and 0.38 m^3 of the anaerobic column is necessary to treat the urine of one swine. Reuse of N and P accumulated in the column packing medium is important for the nutrient recycle in rural areas. Further research on the evaluation of the packing medium as soil conditioner is needed.

8-2 Plant bed filter ditch system management

It is necessary for wastewater treatment plants to have some other attractive functions in order to be welcomed by local residents. Using crops and flowers for wastewater treatment helps to recycle N and P in rural areas and also to give amenity functions to the wastewater treatment system. I designed a plant bed filter ditch in which crops, and flowering and ornamental plants are used for removing N and P from wastewater.

(1) Plant bed filter ditch design

Since the majority of the plants used for human life are terrestrial species, I designed a wastewater treatment ditch in which terrestrial species can grow. The bed filter material was zeolite (particle size; 3 - 10 mm) due to its high NH_4-N adsorption efficiency, and its suitability for plant culture in bench scale experiments (Chapter 3), and its ability to be reused in agriculture as soil conditioners. The bed filter surface was about 0.05-0.1 m higher than the water level for terrestrial species and the same as the water level for aquatic species. Almost all of the plants studied in this experiment grew well and plant roots grew out of the baskets and formed root mats in the water.

(2) Evaluation of plant species ability to remove N and P from wastewater

The use of higher plants in the ditches enhanced the N and P removal rates from the wastewater. Plant species in the ditches considerably affected the N and P removal efficiency. The ditch removal efficiency was significantly affected by the plant N and P absorption rates. The plant bed-filter ditches with plants which exhibited high biomass production rates showed high N and P removal rates. The season and period when the ditches showed the highest N and P removal efficiency also depended on the plant species cultivated in the ditches. Kenaf, papyrus and Italian ryegrass were the most effective for maintaining high removal efficiency for a long period with both artificial domestic wastewater and artificial pond water. Among flowering and ornamental plant species, African marigold, peppermint, hanana, and calla were effective in enhancing the removal efficiency of the ditch. Kenaf and papyrus are recommended for use in plant bed filter ditches mainly in summer and autumn, while Italian ryegrass is recommended for winter and spring, because of both their excellent removal efficiency and resource recycling functions. African marigold (summer and autumn), hanana, calla (winter and spring) and peppermint (year round) are recommended for supplementary use in order to give amenity function to the ditches.

It also appears that adding plants to the ditches accelerated microbial activity such as nitrification and denitrification. Nitrification proceeded more actively in the papyrus and reed ditches than in the plant-free ditch even in the winter. It is likely that O_2 which was supplied from roots through the lacunae of papyrus and reeds accelerated the nitrification process in the ditch. N and P balance data of the plant bed filter ditches (in Chapters 4 and 5) indicated that denitrification contributed somewhat to N removal in addition to absorption by the plants. Dead plant roots and exudate from roots were probably used as hydrogen donors for denitrification.

(3) Effect of wastewater concentration and composition on N and P removal rates

When the relationship between N and P removal rates of plants and N and P concentrations was expressed by a Michaelis-Menten type equation, the concentrations at which the removal rate was half of the maximum removal rate varied slightly depending on plant species, 0.24 mg L^{-1}(African marigold)- 0.86 mg L^{-1} (sorghum) for N and 0.09 (Italian ryegrass) mg L^{-1} - 0.46 mg L^{-1} (sorghum) for P. When the N and P concentrations did not exceed the concentration at which the removal rate was half of the maximum removal rate, N and P removal rates were lower and significantly affected by the wastewater concentration. Thus the N and P removal rates of the plant-bed filter ditch when such low concentrations of wastewater were supplied were seemingly much smaller than those obtained from the experiments using higher concentration wastewater (20 mg L^{-1} for N, 3-4 mg L^{-1} for P) as in Chapter 4 . It is difficult to estimate the ditch size based on the N and P removal rates in the plant-bed filter ditch recorded in the experiments in Chapter 4.

At high N and P concentrations, the removal rates were high, hardly affected by the concentration, and N and P removal function could be considered to resemble zero order kinetics. I regarded the concentration range from 1.0 to 20 mgL^{-1} for N and from 0.5 to 4 mgL^{-1} for P as the range in which the removal rates are sufficiently high and unrestricted. It was found that N and P were removed from artificial wastewater (N: 20 mgL^{-1}, P: 3-4 mgL^{-1}) at the rate of 0.8 $gm^{-2}d^{-1}$ for N and 0.15 $gm^{-2}d^{-1}$ for P consistently except in the winter, when recommended plant species were cultivated in the ditches. This indicates that we can roughly estimate the ditch size at an actual site based on the N removal rates of 0.8 $gm^{-2}d^{-1}$ and P removal rate of 0.15 $gm^{-2}d^{-1}$, when the N concentration of the wastewater is from 1.0 to 20 mgL^{-1} and P concentration was from 0.5 to 4 mgL^{-1}.

The relationship between the ratio of N to P concentration in the influent and the ratio of N to P absorption rates by plants is summarized in Fig. 8-1. The ratios of N to P concentration in the influent were 1.6 :1 to 48:1, while the ratios of N to P absorption rates by plants were 3:1 to 20:1. This indicates that the excess component, N or P, was not absorbed by plants when the ratio of N to P concentration in the influent was extremely high (like pond water in Chapter 7) or low. (As pond water contains N excessively, N removal efficiency was much lower than P removal.) In such cases, bed filters with functions of N or P adsorption and promotion of denitrification process are necessary to remove the excess component.

The contribution of plant absorption to N and P removal depended on wastewater quality. When water contains organic compounds, nitrogen is removed by both denitrification and plant uptake. When water contains suspended solids (particulate-P and N), filtration by bed filter supplements in addition to plant absorption and denitrification on N and P removal, as noted in Chapter 7. In Chapter 3, the addition of plants to bed filter systems did not have good results on organic compounds treatment, compared with N and P removal. I believe that the plant bed filter system is more effective for removing N and P from water that contains relatively few organic compounds, such as secondary treated water.

(4) Recommended planting, ditch size and management of the plant bed filter ditch

The plant bed filter ditches work effectively in the treatment of wastewater whose N and P concentrations exceed 1.0 and 0.5, respectively. I suggests that such ditches should be constructed as flower and crop gardens around a community's wastewater treatment plants or eutrophic pond in rural areas. Fig.8-2 shows the recommended plantings of the plant bed filter ditch. Kenaf and papyrus are recommended for use in summer and autumn, and Italian ryegrass is recommended for in winter and spring, because of their excellent removal efficiency and their uses for handicrafts, and as paper sources and feed. African marigold (summer and autumn), hanana, calla (winter and spring) and peppermint (year round) are preferable for supplementary use because of their amenity function and relatively high removal efficiency. Flowering and ornamental plants should be planted more upstream than kenaf, papyrus and Italian ryegrass on the ditch. If not, the flowering and ornamental plants might not grow well due to the lack of nutrients and the ditch will become unsightly. In order to avoid remarkable decrease of N removal efficiency in winter and early spring, I recommend burying the plants growing in summer and autumn (i.g. papyrus stem) in the bed and utilizing them as hydrogen donors for denitrification.

The average person produces 12 g of N and 1.8 g of P as domestic wastewater everyday (Tabuchi and Takamura 1985) . The N and P treatment efficiency of a sewage treatment plant is said to be less than 50% (10-50%). Assuming the N and P treatment efficiency of a sewage treatment plant is 40%, the plant bed filter ditch should cover an area of approximately 1000-1300 m^2 in order to treat about 70% of N and P in the secondary effluent from a community treatment plant for 200 people (Fig. 8-3). In areas where sewerage is not constructed, most of the domestic wastewater, excluding urine and excrement, is discharged into water bodies without prior treatment. One person discharges 3 g of N and 0.9 g of P as domestic wastewater, excluding urine and excrement, every day . In order to eliminate 70% of the N and P entering a pond from the community including 50 persons, a plant bed filter ditch with an area of about 130-200m^2 is needed based on rough estimates.

On the other hand, it was found that the ditches planted with papyrus, African marigold, peppermint, or Italian ryegrass purified eutrophic pond water resulting in a T-N concentration below 0.3 mgL^{-1} and T-P below 0.02 mgL^{-1}, i.e., the minimum N and P concentrations required for water bloom formation. The plant-bed filter ditches could be used to supply clear water for ornamental streams for parks, where children could play in the water.

(5) Problems with and improvements in the application of the plant bed filter ditch to different sites

Problems and improvement when the plant bed filter ditch is applied to several kinds of wastewater are summarized in Table 8-1.

In the treatment of domestic wastewater which contains much SS, removal of SS prior to the treatment by the plant bed filter ditch or removing SS accumulated in the bed filter periodically is necessary to prevent ditch clogging. In the treatment of secondary treated wastewater (domestic or livestock wastewater) , the removal of excessive P (e.g. using bed filter having high P adsorption capacity) is necessary if the treatment plant has a denitrification process. In the treatment of eutrophic pond water which contains much SS and more excessive N than P, the addition of SS and N removal technique to the ditch is necessary. Adding a hydrogen donor for denitrification like straw etc. to the bed is one way. Looking for nitrate adsorption material is another way. Cultivated land underdrainage, ground water and springs polluted with nitrates usually have quite low concentrations of P. Promoting nitrogen removal from wastewater besides plant uptake is also important. Hydroponic culture wastewater contains high concentrations of N and P (10 times as high as that of secondary treated sewage). It is thus necessary to decrease N and P concentrations by using another mechanical treatment system prior to the treatment by the plant bed filter ditch.

As the plant bed filter ditch has some demerits shown in Table 8-1, it is desirable that the ditch is used in combination with an other suitable treatment system depending on the condition of the site which needs wastewater treatment.

The plant bed filter ditch provides for resource reuse and amenity function in addition to wastewater treatment. Many local governments are interested in and want to introduce our system to improve aquatic ecosystems now. At such time, the ditch needs a large area and some volunteers to look after plants such as harvesting and transplanting. In rural areas, as a flower garden or space for ornamental plantings, about 3-6 m^2 ditch area per person in a farmer family yard (15-30 m^2 per family) or in the common space of communities around the wastewater treatment plants (1000-1200 m^2 per 200 people) can be acquired. Recently, there are many activities organized by residents to improve aquatic ecosystems close to their homes. Thus it may be possible for residents to manage local plant bed filter ditches. It is desirable that the residents enjoy taking care of the plants and utilize them, and even to earn some money by selling plants growing in the ditches. In order to popularize the plant bed filter ditches and operate them for a long time, local governments need to help construct both the ditches and the infrastructure needed to manage them.

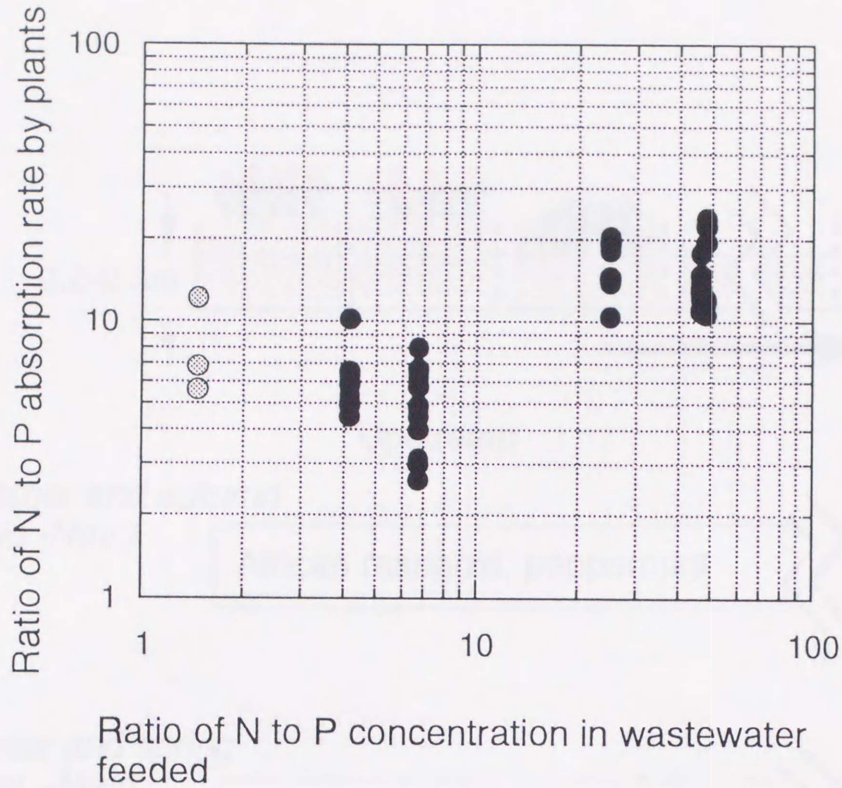


Fig. 8-1. Relationship between the ratios of N to P absorption rate by plants and the ratios of N to P concentration in wastewater feeded.

● the value calculated from the experiments in Chapter 4 - 7.

◎ the value cited from Osada, 1997.

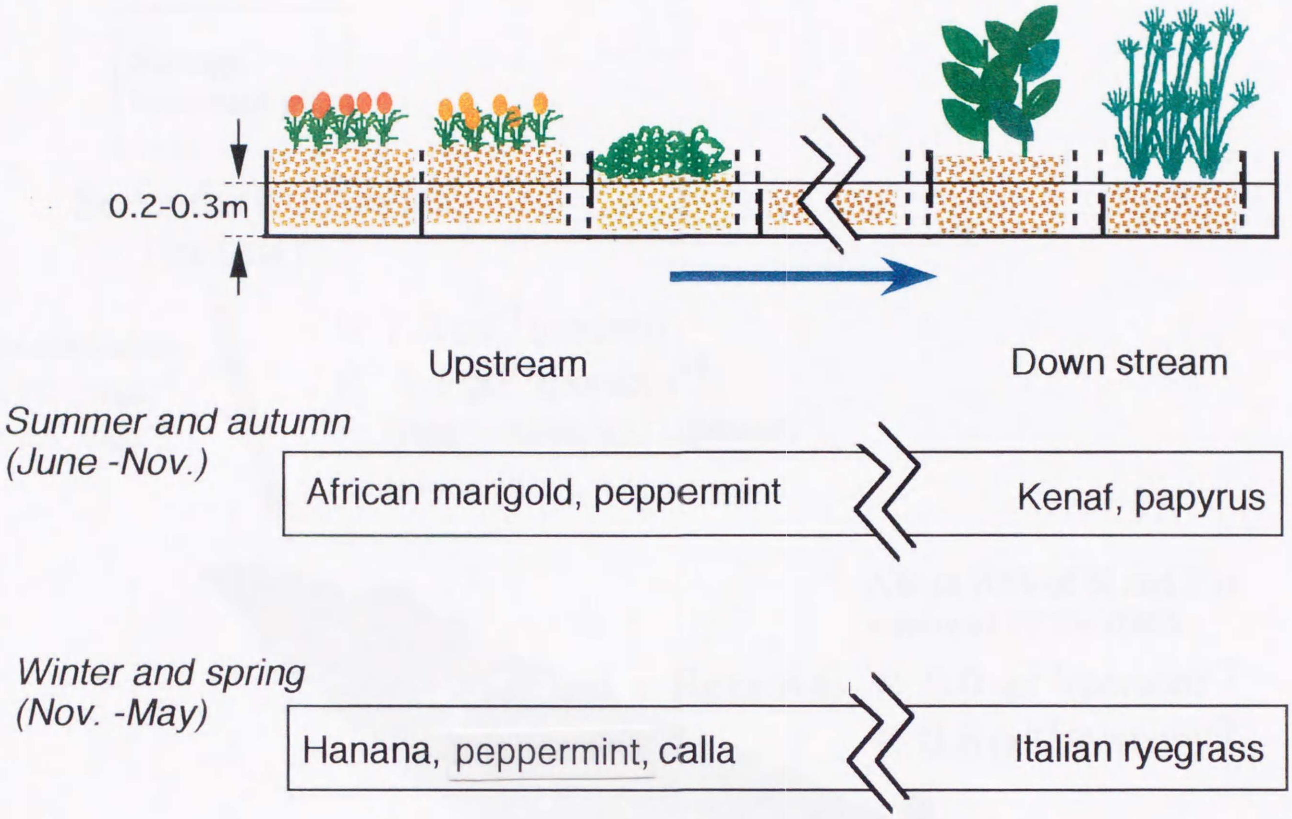


Fig.8-2 Plantings recommended for the plant bed filter ditch as crop or flower gardens.

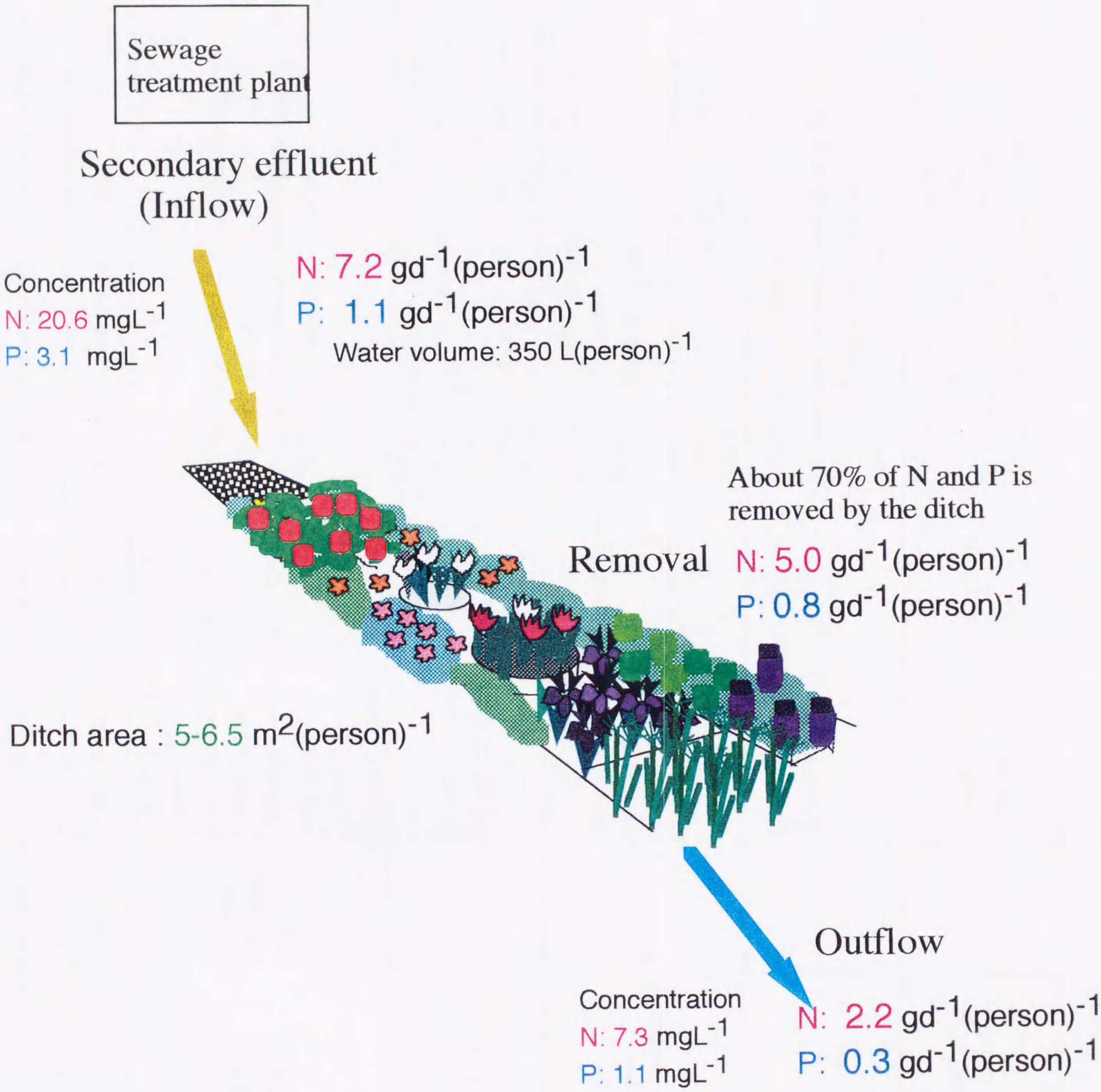


Fig. 8-3. Roughly estimation of the size of the plant bed filter ditch in rural areas.
Evapotranspiration is assumed 9 Lm^{-2}d^{-1}.

Table 8-1 Problems and improvement in introducing the plant bed filter ditch for the treatment of typical wastewater found in rural areas

Kinds of wastewater	N	P	Others	Major removal functions	Problems and improvements
Domestic wastewater not containing urine and excrete	High Org-N	High Org-P	Organic compounds and SS	Filtration of particulate N,P(=SS) by bed filter. Decomposition of organic compounds. Adsorption of NH_4-N by zeolite bed filter. N and P absorption by plants Denitrification	The addition of SS removal technique to the ditch is necessary. Organic compounds treatment before the plant bed filter treatment is necessary.
Secondary treated domestic wastewater	High NO_3-N (NH_4-N)	High PO_4-P		N and P absorption by plants (Denitrification)	P is tended to be excessive when sewage treatment plant contains denitrification process. The addition of P removal technique to the ditch is necessary. For example, using bed filter material with high P adsorption capacity.
Eutrophic pond or lake water	Low NO_3-N Particulate-N	Low Particulate-P	SS	Filtration of particulate N,P(=SS) by bed filter N and P absorption by plants Denitrification	The addition of SS removal technique to the ditch is necessary. N(NO_3-N) is excessive. Acceleration of removing N is necessary (e.g. adding hydrogen donor for denitrification to the bed).
Cultivated land underdrainage, ground water, spring polluted with nitrate	High NO_3-N	Low		N and P absorption by plants (Denitrification)	N(NO_3-N) is excessive. Acceleration of removing N is necessary. (e.g. adding hydrogen donor for denitrification to the bed).
Hydroponic culture wastewater	Quite high NO_3-N (NH_4-N)	Quite high PO_4-P		N and P absorption by plants (Denitrification)	N and P concentration is quite high (10 times as high as domestic wastewater). Decrease N and P concentration by using other mechanical treatment system prior to the treatment by the plant bed filter ditch.

Acknowledgments

I wish to thank Dr. Masayuki Seto, Professor at Tokyo University of Agriculture and Technology for his kind supervision, continuous guidance, and fruitful discussions. I also expresses my thanks to Dr. Masatsugu Kubota, Professor at Ibaraki University, Dr. Hidemasa Kato, Professor at Utsmoniya University, Dr. Yoko Katayama, Associate Professor at Tokyo University of Agriculture and Technology, and Dr. Takeshi Izuta, Associate Professor at Tokyo University of Agriculture and Technology for their useful suggestions.

I am sincerely grateful to Dr. Yasuo Ozaki, Chief of Water Quality Control Laboratory, National Agriculture Research Center, for his worthwhile advice, discussions and encouragement. I also thankful to Dr. Minoru Morooka, Association for Advancement of Agriculture Science and Dr. Nobuharu Kihou, National Institute of Agro-Environmental Science, for their valuable suggestions; to Mrs. Kazue Mizuta, Fukuoka Agriculture Research Center, for her worthwhile discussions and assistance; and to Mr. Morihiro Maeda, National Agriculture Research Center, for his helpful advice and suggestions.

I would like to expresses my thanks to the Tsukuba City government and the Konda West Self-Governing Council for providing experimental ditch space; to Mr. Kazuo Mikami and Mr. Manabu Nihei of National Agriculture Research Center for their assistance in the field works; and to Mrs. Kumiko Nakano of National Agriculture Research Center for her exallent assistance in laboratory and field works.

Finally, I extended my thanks to the stuffs of Department of Soils and Fertilizers, National Agriculture Research Center for their warmhearted support.

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要旨

資材、植物等を用いた資源循環及びアメニティ機能を持つ水質浄化法に関する研究

阿部　薫

近年、農村地域でも、湖沼等の富栄養化が進行しており、水産業、取水、生活環境上の被害に加え、農業生産への被害も問題となっている。畜舎排水や都市化・混住化に伴う生活系排水の増大が、その重要な要因の一つと考えられ、公共用水域に排出される前に発生源の近傍で処理することが望まれる。しかし、農村地域では、これら負荷源が、分散して存在するので、都市型の大規模集中方式の汚水処理施設をそのまま適用することには問題が多く、農村地域に適した、生態系と調和した浄化技術の開発が求められている。一方、汚水処理施設は、近隣の居住者にとっては迷惑施設となることも多いため、汚水処理以外の好ましい付加価値を持たせることが必要である。本研究では、土壌、天然鉱物（ゼオライトなど）など農地で再利用可能な資材の化学物質吸着能や、資材表面で生育する微生物の有機物分解・硝化・脱窒機能、並びに、作物・花卉などの有用植物の窒素リン吸収機能を活用し、汚水中の窒素・リンを資源として再利用でき、景観形成等のアメニティ機能を持つ簡易な汚水浄化手法の開発、及びその浄化特性の解明、運転管理手法の検討等を行った。

1．家畜尿汚水の高度処理のための好気・嫌気カラム充填資材の検索と管理法の検討

家畜尿汚水は、窒素、リンを高濃度に含んでいるが、これらは、従来の活性汚泥法等では十分処理できず、小規模の畜産農家でも設置できる、簡易で、窒素、リンの処理効率の高い新たな処理方法が望まれている。近年、汚水中の有機物の分解、リンの収着除去、NH_4-Nの硝化を目的とした好気土壌カラムと、脱窒によるNO_3-Nの除去を目的とした嫌気土壌カラムから成る処理法が有効であることが報告されている。筆者らは、浄化効率を上げるため、新たに農耕地等で再利用可能な適切なカラム充填資材を検索すると共に、脱窒に必要な水素供与体添加量を明らかにした。

好気カラムについては、黒ボク土にゼオライトと粗砕石灰石を20％混和した資材を用いると処理能力が高まり、その長期的維持が可能と成ることを明らかにした。

嫌気カラム充填材としては、土壌よりもみがらくん炭や炭の方が透水性の面で優れており、また充填材にわらを添加するとNO_3-Nの除去率が向上することを明らかにした。嫌気カラムにおいて、NO_3-N　1gを除去するのにメタノール約3ｇの添加が必要であり、これは、理論値の1.5-1.6倍であることを解明した。

2．生活雑排水の窒素・リン浄化に適した濾材・植物等の比較

現在、下水道や農村集落排水処理施設の未整備地域においては、生活雑排水（生活排水から屎尿を除いた排水）は、未処理のまま放流されている場合が多く、窒素リンの環境負荷源の1つとなっている、また、下水処理場等でも、窒素・リンの浄化は不十分な場合が多く、簡易な処理技術が求められている。一方、作物、花卉等有用植物を水質浄化に利用し、迷惑施設となりがちな汚水処理施設に、汚水中の窒素・リンの再利用、景観形成等の機能を付加することも必要である。

そこで、有用植物を用いた水質浄化手法の開発に当たって、まず、水質浄化に向く濾材と植物の調査をベンチスケールで行った。濾材は、ゼオライト、ゼオライト+貝化石、炭の3種類、植物は、イネ（多用途米）、エンサイ、クレソン、（野菜）、ジニア、ストック（花卉）の5種類について比較検討した。

植物を濾材上に栽植すると、窒素、リン浄化能は高まり、また、植物種がこれに影響をあたえることが判った。夏 秋（6-12月）においては、エンサイやイネがジニアより優れ、冬 春(1-5月)においては、クレソンがストックより優れていた。しかし、全有機炭素除去に対する植物栽植の

効果は、明らかで無く、本システムは、有機物が分解・除去された二次処理水の高度処理により適していると考えられた。　濾材に関しては、ゼオライト、ゼオライト+貝化石が炭にくらべ窒素、リン除去に効果的であることがわかった。

3. 植物-濾材系水路の試作

農村集落排水処理施設の周囲の植え込みや花壇、家庭菜園等として利用でき、近隣の住民が利用可能な作物・花卉等を栽培できる浄化システムを目指し、多くの有用植物が陸生植物であることから、水生植物と陸生植物の両者を一緒に利用できる浄化水路を考案した。

水質浄化水路は、濾材（ゼオライト：粒径　3～10mm）を詰めた網篭に植物を植えて並べた水路で、汚水中の窒素・リンは、水路を流下する過程で、植物根、濾材、微生物等の作用を受け除去される。濾材の高さを植物の耐湿性に応じて変え、陸生植物については濾材面を水面より約10cm高くし、水生植物は水面と同じにすることで、陸生と水生の植物を同一水路内で栽培可能とした。資源作物や修景効果の高い花卉・観葉植物を、水質浄化に利用できる点が本水路一つの特長である。ゼオライトを濾材として用いているのは、ベンチスケールの試験の結果、植物の栽培床として適しており、また、アンモニア態窒素吸着能が高く、使用後土壌改良資材として農耕地への還元が可能なこと等による。濾材には、植物の支持体としての役割もあり、大型の植物も栽培できるよう、濾材の充填高さは30～40cmとしている。

4. 植物-濾材系水路による生活系排水の窒素・リン浄化に適した植物の検索と評価

前述のベンチスケールの試験より、植物の種類が窒素・リンの浄化に大きく影響することが判ったため、陸生植物13種類を含む資源作物、飼料作物、花き等20種類の植物について、浄化水路に栽植し、生活系排水の2次処理水の浄化に対する有効性を調査・検討した。人工汚水(窒素濃度：$20 mgL^{-1}$、リン濃度：$3\ mgL^{-1}$）を、水路面積当たりの窒素負荷速度：$1.4 \sim 2.1\ gm^{-2}d^{-1}$ 、リン負荷速度：$0.2 \sim 0.33\ gm^{-2}d^{-1}$で流入させて実験を行い、水路は窓のあるガラス室内に設置し、4～11月の間窓を開放した。

バイオマス生産速度の高い植物を栽植した水路ほど窒素･リンの除去速度は高く、植物による吸収が大きな割合を占めていた。パピルス栽植水路では晩春から秋に、ケナフ水路及びソルガム水路では夏から秋に、また、イタリアンライグラス水路とオオムギ水路では春先に、窒素・リン除去速度はN：$0.8 gm^{-2}d^{-1}$、P：$0.15 gm^{-2}d^{-1}$を上回る高い値となった。また、修景効果を持つ花卉のなかでは、アフリカンマリーゴールドやカラー、ハナナなどにも高い浄化効果が認められた。パピルス、ケナフ、ソルガム、イタリアンライグラス、オオムギ、アフリカンマリーゴールド、カラー、ハナナなどの植物を適切に組み合わせて栽培すれば、真冬期間を除き、水路面積当たりN除去速度：$0.8\ gm^{-2}d^{-1}$、P除去速度：$0.15\ gm^{-2}d^{-1}$で、汚水処理が安定して行える事が判明した。

一方、パピルスやアシを植えた水路では、冬期に硝化の促進が認められ、これらは、水生植物の根の曝気効果によるものと考えられた。また、窒素収支より、栽植水路で脱窒が窒素の除去浄化に一定の寄与をしていることが示唆された。

5. 富栄養化した湖沼水等の比較的低濃度汚濁水の浄化に適した植物

農業用水源となる湖沼・溜池等の富栄養化は、農業生産上の被害をもたらすとともに、近隣の住民の生活環境の悪化にも繋がり、水辺環境の改善への要望は高まっている。富栄養化した湖沼水の窒素・リン濃度は、一般に生活系排水に比べ1オーダー低い濃度であるため生活系排水の浄化に効果の高かった作物・花卉等について、低濃度域での水質浄化特性の解明が必要とされた。

富栄養化した溜池の水質調査結果をもとに、低濃度人工汚水(窒素濃度：$2.5\ mgL^{-1}$、リン濃度：$0.5\ mgL^{-1}$)を作成し、生活系排水浄化試験と同程度の窒素・リン負荷速度となるように、水路面積窒素負荷速度：$1.2\ \ gm^{-2}d^{-1}$、リン負荷速度：$0.23\ gm^{-2}d^{-1}$で供給した。試験に供試した植物を栽植した水路はいずれも、人工汚水の窒素・リン濃度を更に低濃度に浄化した。特に、パピルス、ケナフ、イタリアンライグラスの浄化効果が高く、また、アフリカンマリーゴールド、インパチエンス、ハナナなどの花卉やペパーミント（ハーブ）などにも一定の浄化効果が認められた。

除去された窒素の4割以上及びリンの6割以上が植物体に吸収されており、植物の吸収が浄化に大きな割合を果たしていることが判かった。

窒素・リン浄化機能の高いパピルス、ケナフ（夏期）やイタリアンライグラス（冬期）等を浄化の主体として用い、水路の修景効果を高めるためアフリカンマリーゴールド等の花卉やペパーミントを合わせて栽植するのが望ましいと考えている。

6. 汚水の窒素・リン濃度と植物の窒素・リン除去速度の関係

環境中の汚濁水（生活排水から富栄養化した湖沼水）の窒素・リン濃度は、1から2オーダーの幅があり、植物を浄化に用いる際、それぞれの植物に適した浄化域を把握しておくことが必要である。

窒素としてNO_3-N、リンとしてPO_4-Pを主に含む人工汚水を用い、濃度レベルを数段階変えて、汚水濃度と植物（ケナフ、パピルス、イタリアンライグラス、ソルガム、アフリカンマリーゴールド、ペパーミント）の窒素・リン除去速度の関係について調査を行った。各植物の除去速度0となる濃度は、窒素: 0.19（パピルス）～0.5 mgL^{-1}（ソルガム）、リン: 0.01（パピルス、イタリアンライグラス）～0.06 mgL^{-1}（ソルガム）であった。高濃度域では、除去速度は濃度に殆ど影響されないが、低濃度域では濃度依存して低くなる関係が認められ、Michaelis-Menten式をあてはめると、パピルスの場合Michaelis定数は　N:0.57mgL^{-1}、P:0.45 mgL^{-1}となり、これ以下の濃度では窒素・リン除去速度は、低く、濃度に強く依存した。除去速度が､濃度に制約されない窒素・リン濃度域で、植物をを浄化に用いるのがより効率的と考えられる。供試植物全てについて、N:1.0 mgL^{-1}、P:0.5 mgL^{-1}以上であれば、除去速度は高くほぼ一定となった。窒素1 mgL^{-1}～20 mgL^{-1}、リン0.5 mgL^{-1}～4 mgL^{-1}の汚水からの、植物の窒素・リン除去はほぼ0次反応（濃度に依存しない）になるとみなし、また、水路における浄化の主体は植物の窒素・リン吸収であったことから、水路の設計に当たっては、前述の生活系排水と池水を模した人工汚水の浄化試験で得られた水路面積当たりの除去速度（N：0.8 $gm^{-2}d^{-1}$、P：0.15 $gm^{-2}d^{-1}$）をもとに概算できるものと考える。

7. 富栄養化した溜池水の浄化現地試験

これまでの成果を踏まえ、つくば市内の富栄養化した溜池に、流入部に沈殿槽を有する花壇状の植物-濾材系水路を設置し、浄化効率の優れたパピルス等や一定の浄化効果が認められた花卉やハーブを栽植して池水を流入させ、浄化試験を行った。植物-濾材系水路が、懸濁物等を含む実際のため池水の浄化に有効であるかどうか、懸濁態を含む全窒素・全リンの挙動に注目して、その浄化特性を調査するとともに、浄化機能の低下する冬期には、脱窒の水素供与体となる有機資材（イナワラ・パピルスの茎）を水路内に埋設し、窒素浄化機能の向上効果を調べた。

無栽植水路は、懸濁物の除去には効果があったが、NO_3-N、PO_4-Pは除去できず、水路内で懸濁態のリンが可溶化しPO_4-Pの流出が認められた。同水路では、リンの浄化機能は、経時的に低下しており、水路内に蓄積した懸濁物からのリンの可溶化の進行が認められた。

これに対し、植物を栽植した水路（栽植水路、栽植・有機資材水路）では、懸濁態の窒素・リンの除去に加え、NO_3-N、PO_4-Pが除去され、また、リンについて無栽植水路のような浄化機能の低下も認められず、植物による吸収効果が明示された。また、本水路により富栄養化（水の華発生）の限界濃度と言われている窒素：0.3 mgL^{-1}、リン：0.02 mgL^{-1}以下の処理水を得られることを実証した。

窒素の除去速度・除去率は、冬期に大きく低下したが、冬期に、有機資材（パピルス茎、イナワラ）を水路内に埋設すると、脱窒または有機化によるものと考えられる0.1～0.2 $gm^{-2}d^{-1}$の窒素除去速度の向上（除去率10％上昇）が認められ、夏期に水路で栽培したパピルス等の一部を冬期に水路内に埋設して利用することで、冬期の水質改善を図れることを明らかにした。

除去されたリンの46%－50%が植物に吸収されており、24～29％が水路内(沈殿槽や濾材部分)に残存したことから、リンの除去は主に植物の吸収と濾過によるものであることが判った。一方、

除去された窒素の23%～25%が植物に吸収されていたが、水路内に残存していたのは6～7%であったことより、窒素の除去は植物の吸収と脱窒が主体で在ることが示唆された。また、濾材間に蓄積した懸濁物からPO_4-Pが溶出して植物に吸収されていること、懸濁物中の有機物が脱窒の水素供与体として利用されていることが推定された。

8. 植物-濾材系水路の現地への適用の際の指針と問題点

浄化水路の植物としては、パピルス、ケナフ（夏～秋）やイタリアンライグラス（冬～春）等を浄化の主体として用い、水路の修景効果を高めるためアフリカンマリーゴールド（夏～秋）、ハナナ、カラー（冬～春）等の花卉やペパーミント（通年）を合わせて栽植するのが望ましい。農村集落排水の処理水の高度処理のため農村集落排水処理施設のまわりに本水路を設置し、7割程度（冬期を除く）の除去率を得るには、一人当たり5～6.5 m^2程度の水路面積が必要と試算される。一方、本水路は、富栄養化（水の華発生）の限界濃度と言われる窒素：0.3 mgL^{-1}、リン：0.02 mgL^{-1}以下の極めて低濃度に汚水を処理できるので、この特長を生かし、子供たちが水遊びできるような公園内の修景用水を得る目的で、小規模に利用するのも一つであろう。

植物-濾材系水路を現地に適用する際は、汚水の濃度や性状によりそれに合わせた水路の設計や濾材・植物の選定等の改変が必要である。植物の窒素とリンの吸収速度の比と実験に用いた汚水等の窒素とリンの濃度比を比較すると前者が、3：1から20：1であるのに対し、後者は、1.6：1から48：1であり、植物の吸収にとって過剰にある成分は、吸収されず流出する。植物の吸収から見て窒素・リンの濃度比が著しくアンバランスな汚水については、過剰にある成分を除去するため濾材等に除去能（窒素・リンを吸着する資材や、脱窒等の微生物活動を促進するイナワラ・パピルス乾燥茎等の埋設）を持たせる等の改良が必要である。また、懸濁物を多く含む汚水については、水路流入部への沈澱槽やストレーナーの設置等により濾材の目詰まり防止を図ることも大切である。

植物-濾材系水路に興味を示し、導入を希望している地方公共団体や市民団体も多い。本水路は、花壇や植え込み等としての修景機能や作物の生産等の付加価値をもつ水質浄化技術であるが、植物の栽培等の日常の管理がある程度必要となる。近年、自然との共生・循環型社会構築への人々の関心は高く、地域住民が積極的に身近な水環境の保全に取り組む事例が各地で見受けられており、水路の管理等も、地域住民の参画により進められることが望ましい。そのためには、行政が経済的支援や水路管理のための社会的な組織作りに積極的に取り組むことも必要と考える。