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Full Length Research Paper

Rice field for the treatment of pond aquaculture effluents

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We conducted an experiment to evaluate the efficiency of rice fields in treating pond aquaculture effluent and its responses to different fertilizer treatments. Four treatments was considered in the experiment: no rice planted as the control (CT); rice planted and no fertilizer input (RE); rice planted and a rate of approximately 1.0 g m^{-1} d^{-1} potassium chloride application (RK) and rice planted and mineral fertilizer (N: P_2O_5: K_2O = 0.6: 0.5: 0.8) applied before the experiment (RF). Inflow and effluent water from the treatments were monitored weekly. The water quality parameters monitored in this study included: total phosphorus (TP), dissolved phosphorus (PO_4^{3-}-P), total nitrogen (TN), ammonia-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N) and chemical oxygen demand (COD). Rice plant height and yield were evaluated at the end of the experiment. Under different fertilizer treatments, high average removal rates of TN, TP and COD were obtained (over 56, 68 and 53%, respectively). They showed no significant differences ($p > 0.05$), indicating that the rice field could remove the pollutants effectively and the different fertilizer treatments had no impact on the removal efficiencies. However, the different fertilizer treatments showed significant differences in rice yield ($p < 0.05$). The RF treatment resulted in the highest production of 649.53 ± 94.2 g m^{-2}, followed by RK at 523.83 ± 71.5 g m^{-2}; the fertilizers increased yield by 42.93 and 15.27%, respectively over the RE trial. Rice fields can purify pond effluents efficiently without reducing production when appropriate mineral fertilizers are applied.

Key words: Rice field, pond effluent, nutrient removal.

INTRODUCTION

Freshwater pond aquaculture has grown significantly in China from a yield of 4.17 megatons in 1990 to 20.08 megatons in 2006 (CAFM, 2006). This is a 381% increase. However, wastewater produced in pond aquaculture has also increased greatly and has become a serious environmental problem. Untreated wastewater discharged from pond aquaculture operations into natural water bodies can result in eutrophication in aquatic ecosystems (Naylor et al., 2002), which has raised increasing concerns in China.

Various approaches have been developed to treat the pond effluent before it is discharged into the receiving water bodies to remove or reduce the contaminants to environmentally safe levels (Li et al., 2007). These approaches include wetland construction (Lin et al., 2002; Schulz et al., 2004; Lin et al., 2005; Li et al., 2007; Sindilariu et al., 2007), water discharge reduction (Lin et al., 2001), particle removal via sedimentation and bivalves (Wang, 1990; Jones et al., 2001) and improved aquaculture feeds and feeding practices (Diana et al., 1994; Cho and Bureau, 1997). These measures can reduce the load of organic matter in the discharge water. However, these treatments may not be suitable for most fish farms because of the high cost of facilities or failure to provide additional economic returns (Brown et al., 1999a, 1999b; Kouka and Engle, 1996; Mcintosh and Fitzsimmons, 2003).

The integration of aquaculture with agriculture appears to be a potential solution. Crop plants can remove a significant fraction of nutrients from the effluent and provide additional economic returns. Additionally, this

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approach actually reduces effluent water volume through plant evapotranspiration (Brown et al., 1999a, 1999b). It has been used successfully for the disposal of freshwater aquaculture effluent with several crops, such as cherry tomatos (*Solanum lycopersicum var. cerasiforme*) (Castro et al., 2006), wheat (*Triticum* spp.) (Hussain, 1993) and cowpeas (*Vigna unguiculata*) (Azevedo et al., 2002).

SRAC (1994) and Kouka and Engle (1996) concluded that, irrigation of rice was the most cost-effective way of treating channel catfish (*Ictalurus punctatus*) pond effluents, compared with recycling water through constructed wetlands and through a pond stocked with filter-feeding fish (bighead carp). Rice, with a cultivated area of 2.8 to 3.2 billion ha, is the major crop in China. The water needed for rice production ranges from approximately 8,000 to 12,000 m^3 per ha (Frei and Becker, 2005). Lin and Yang (2003) and Yang et al. (2006) demonstrated that, the effluents from hybrid catfish ponds can completely replace mineral fertilizers as a nutrient source for rice crops.

Rice fields have been used for aquaculture effluent treatment by farmers in China and elsewhere in the world. Most studies have focused on the impacts on pond water quality but did not specifically measure the efficiency of effluent removal. Few studies dealt with continuous irrigation of rice fields for aquaculture effluent treatment. This raised several questions such as whether fertilizer application and potassium (K) supplements can improve the treatment efficiency and whether rice fields can purify pond effluents without reducing rice production. To answer these questions, we conducted a field study to evaluate the performance of a rice field in treating pond effluent and the connection in removal efficiency and rice yield with different fertilizer treatments.

MATERIALS AND METHODS

Experimental design

The experiment was conducted in a set of concrete tanks (4.1 × 6.7 m), located in Honghu City, Hubei province of China from June to September of 2008. Before the experiment, each tank was filled to a depth of 20 cm with topsoil from an adjacent rice field except the control tank. The collected topsoil was homogenized by mixing before been added to the tanks.

Four treatments arranged in a randomized complete block design with three replicates were included: no rice planted and no fertilizer input as the control (CT); rice planted with no fertilizer input (RE); rice planted with potassium fertilizer input at a rate of 1.0 g m^{-1} d^{-1} ($K_2O \geq 60\%$) (RK); rice planted with ammonium bicarbonate (17% N, 80 g m^{-2}), calcium biphosphate (16.7% P_2O_5, 70 g m^{-2}) and potassium chloride ($K_2O \geq 60\%$, 30 g m^{-2}) applied before the experiment (RF) at a rate recommended by Tan et al. (2007) (Table 1).

The rice (*Indica* hybrid rice Yangliangyou 6; cropping duration 130 to 140 days) was transplanted according to local practice (two to three seedlings per hill, spacing between hills 25 × 20 cm). Before the transplantation, the soil was homogenized by flooding the soil surface with 3 to 5 cm water. 20 days after transplanting, pond effluents from the drainage canal were pumped into the tanks. Every tank received water from the same source. Each tank had a water inlet and an outlet placed at a level of 15.0 cm above the soil surface and a flow rate of approximately 600 liters (L) per day controlled by a flow meter. Thus, all treatments experienced the same inflow nutrient concentrations and hydraulic retention time for approximately seven days.

Inflow and effluent water samples from the treatments were collected and analyzed weekly to determine the rice treatment efficiency. The water quality parameters that were monitored included: total phosphorus (TP), dissolved phosphorus (PO_4^{3-}-P), total nitrogen (TN), ammonia-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N) and chemical oxygen demand (COD). All analyses were conducted in accordance with the standard methods recommended by State Environmental Protection Administration of China (1997). Evaluations of plant height and grain yield were performed at the end of the experiment. They were determined by placing a 2 m^2 frame at four randomly selected sites in each tank. Rice plants inside the frame were cut at soil level and the dry matter of plant, grain, TN and TP content in plant were determined. The physico-chemical water parameters, namely pH, dissolved oxygen (DO) and temperature (T), were monitored with a multimeter sensor (Hydras, America).

Statistics

The data were assessed using one-way analysis of variance (ANOVA) with the fertilizer treatment as the factor. When the ANOVA indicated that, there were significant differences among treatments pairwise comparisons were carried out to determine how each mean differed from other means. Differences of means were evaluated for significance by least-significant difference (LSD) ($p \leq 0.05$) for homogeneous variances (Levene test) and by Dunnett's T3 ($p \leq 0.05$) for inhomogeneous variances. Calculations were performed with the SPSS software package (SPSS 13.0 for windows, 2006). Differences were considered significant at alpha of 0.05.

RESULTS AND DISCUSSION

Effluent treatment efficiency

Removal rate of phosphorus

High removal rates of TP were obtained in both the rice-plant systems and the control (38.65 to 70.21%). According to the results (Table 2), initial TP levels in pond effluent were 0.43 ± 0.13 mg l^{-1} with the contents of 15.6% soluble phosphorus, indicating a maximum of 84.4% particle bound phosphorus. This agrees with the result reported by Bergheim and Brinker (2003) that 30 to 84% of TP in aquaculture effluent is bound in particles. TP removal was governed mainly by sedimentation and adsorption (Schulz et al., 2003). TP concentration in the outflow of the rice-plant treatments (0.13 to 0.14 mg l^{-1}) showed no significant differences (P = 0.6493 to 0.8636), but were significantly lower than for the control (0.27 mg l^{-1}) (P = 0.0010). This suggests that the presence of rice played an important role in TP removal, probably via

Table 1. Illustration of all scenarios and their code names.

Code name	Illustration of scenario
CT	No rice planted and no fertilizer input as the control
RE	Rice planted with no fertilizer input
RK	Rice planted with potassium fertilizer input at a rate of 1.0 g m^{-1} d^{-1} (K_2O ≥ 60%)
RF	Rice planted with ammonium bicarbonate (17% N, 80 g m^{-2}), calcium biphosphate (16.7% P_2O_5, 70 g m^{-2}) and potassium chloride (K_2O ≥ 60%, 30 g m^{-2}) applied before the experiment

Table 2. Water quality parameters by rice field under different treatments.

Parameter		Pond effluent	CT	RE	RK	RF
TP	Concentration (mg/l)	0.43 ± 0.13 [a]	0.27 ± 0.06 [b]	0.14 ± 0.03[c]	0.13 ± 0.05[c]	0.13 ± 0.04[c]
	Removal efficiency (%)	-	38.65±10.15[b]	68.98±6.34[a]	70.11 ± 6.89[a]	70.21 ± 8.51[a]
PO_4^{3-}-P	Concentration (mg/l)	0.067 [b] ± 0.029	0.095 ± 0.052[a]	0.038 ± 0.014[c]	0.030 ± 0.021[c]	0.049 ± 0.029[b]
	Removal efficiency (%)	-	-43.04 ± 66.84[c]	42.64 ± 21.88[a]	55.66 ± 18.69[a]	26.67 ± 20.84[b]
TN	Concentration (mg/l)	1.97 ± 0.47 [a]	1.49 ± 0.65[b]	0.86 ± 0.23[c]	0.76 ± 0.23[c]	0.82 ± 0.24[c]
	Removal efficiency (%)	-	24.13 ± 10.63[b]	56.43 ± 5.30[a]	61.32 ± 7.05[a]	58.15 ± 4.45[a]
NH_4^+-N	Concentration (mg/l)	0.43 ± 0.22 [a]	0.47 ± 0.22[a]	0.18 ± 0.11[b]	0.17 ± 0.13[b]	0.19 ± 0.15[b]
	Removal efficiency (%)	-	-8.48 ± 15.36[b]	58.41 ± 18.90[a]	59.78 ± 17.81[a]	53.59 ± 16.84[a]
NO_3^--N	Concentration (mg/l)	0.13 ± 0.02 [a]	0.15 ± 0.05[a]	0.10 ± 0.03[b]	0.10 ± 0.03[b]	0.10 ± 0.02[b]
	Removal efficiency (%)	-	-12.76 ± 22.84[b]	24.85 ± 8.51[a]	24.77±11.26[a]	28.01 ± 14.89[a]
NO_2^--N	Concentration (mg/l)	0.022 ± 0.017 [a]	0.032 ± 0.012[a]	0.006 ± 0.004[b]	0.007 ± 0.003[b]	0.009 ± 0.002[b]
	Removal efficiency (%)	—	-44.76 ± 51.03[b]	70.38 ± 13.31[a]	66.67 ± 20.90[a]	58.04 ± 22.80[a]
COD	Concentration (mg/l)	9.78 ± 2.27 [a]	4.87 ± 0.92[b]	4.52 ± 0.74[b]	4.42 ± 0.66[b]	4.57 ± 0.76[b]
	Removal efficiency (%)	-	48.70 ± 12.18	53.78 ± 9.88	54.81 ± 9.74	53.27 ± 10.58
T(℃)		26.3 ± 4.32 [a]	26.5 ± 4.66[a]	25.5 ± 4.32[b]	25.2 ± 4.68[b]	24.8 ± 3.86[b]
pH		7.73 ± 0.62	7.78 ± 0.55	7.41 ± 0.56	7.46 ± 0.64	7.39 ± 0.82
DO (mg/l)		4.21 ± 0.87 [a]	4.36 ± 0.62[a]	2.58 ± 0.72[b]	2.62 ± 0.73[b]	2.35 ± 0.54[b]

Data are presented as means ± SD (n=30) and values in the same line with different letters are significantly different ($p < 0.05$).

assimilating directly, providing surface area for the attachment of epiphytic algae and micro-organisms and reducing re-suspension of settled material (Brix, 1997; James et al., 2004). According to Richardson (1985), the most important process for inorganic phosphate was the adsorption of iron and aluminum compounds of the soil. The phosphate-binding capacity varied with the pH and the oxidation-reduction in the soil by influencing the protonation of iron and aluminum surfaces or the reactive velocity (Bergheiser et al., 1980; Gumbricht, 1993). We concluded that, fertilizer treatments did not influence TP removal processes and could improve PO_4^{3-}-P removal slightly.

Removal rate of nitrogen

As with phosphorus, removal of nitrogen in the rice-plant treatments was effective (56.43 to 61.32%) and no statistical differences were found (P = 0.3163 to 0.7259), indicating that fertilizer treatments had little impact on nitrogen removal. Nitrogen removal was dependent on a combination of the settlement of particulate matter, its uptake into plants and bacterial biomass and bacterial nitrification and denitrification (Ciria et al., 2005). According to Schulz et al. (2003; 2004), nitrogen elimination begins with microbial ammonification of orga-nic nitrogen, which can convert organic N into ammonium (NH_4^+) in either aerobic or anaerobic state (Hiley, 1995). Then, bacteria convert ammonium to nitrate (NO_3^-) through the process of nitrification. *Nitrosomonas* bacteria mediate the conversion of nitrate to nitrite (NO_2^-), which is then quickly converted to nitrate by *Nitrobacter* bacteria (Hagopian and Riley, 1998). The primary importance of nitrification is in the production of nitrate, which is a basilic participant in denitrification reactions. Denitrification is the bacterial conversion of nitrate to elemental nitrogen (N_2) or nitrous oxide (N_2O) gasses lost to the atmosphere and certain conditions are required, such as oxygen content and available organic carbon. Finally, organic nitrogen is recruited from ammonium and nitrate, through plant and microorganism uptake.

In contrast to Bergheim and Brinker (2003), where the total nitrogen content of rainbow trout effluents was mainly characterized by soluble inorganic NH_4^+-N and NO_3^--N contents, the TN in the pond effluents in this study was characterized by high (70%) organic nitrogen. TN elimination in the rice-plant treatments in this study (56.43 to 61.32%) was comparable to the 5 to 49% in common treatment technologies, such as microscreens or settling tanks (Schulz et al., 2003), but lower than natural surface-flow wetlands, which have an estimated average nitrogen removal rate of 110 mg N m^{-2} day^{-1} (Knight et al., 1993) due to lower areal loading.

Significantly, higher NH_4^+-N and NO_2^--N removals observed in the rice-plant treatments (53.59 to 59.78 and 58.04 to 70.38%, respectively) indicated that high microbial nitrification took place within the treatments. Many reports have indicated that rice plants have aerenchyma in their shoots and roots. Atmospheric or photosynthetic oxygen diffused down into the rice roots (Armstrong, 1971; Justin and Armstrong, 1987; Blom and Voesenek, 1996) and partial oxygen was released into the soil (Frenzel et al., 1992). Thus, nitrification could occur immediately and the activity was maximal in rhizosphere soil, followed by those in the bulk soil and the root surface (Li et al., 2008). This hypothesis was supported by the decrease in pH levels (Table 2). Due to the release of H^+ during processes, reduction of pH was a typicality of nitrification (Hagopian and Riley, 1998; Eding et al., 2006); this pH decrease was also detected in other studies with high NH_4^+-N reduction rates (Schulz et al., 2003; Lin et al., 2005; Sindilariu et al., 2007). Additionally, some studies (Wang et al*.,* 1993; Arth et al*.,* 1998; Kronzucker et al*.,* 1998) have suggested that NH_4^+ was the main form of N available to the rice and that plant uptake was a factor responsible for the NH_4^+-N removal (Jin et al., 2002). Another reason for the high removal efficiency of the NH_4^+-N is the charge. The ammonium ions (NH_4^+) were positively charged and thus, held by negatively charged clay particles and organic matter, which prevented the NH_4^+ from releasing to the water.

In relation to NO_3^--N, significantly lower mean concentrations obtained in the rice-plant treatments (0.10 mg l^{-1}) could be explained by the NO_3^--N removal by the plants. Nitrate was readily taken up and was a major form of N utilized by the rice crop (Kronzucker et al., 1999; Zhang et al., 2004; Li et al., 2007). Kirk and Kronzucker (2005) established a model to estimate the potential for nitrification, denitrification and nitrate uptake of rice. The model calculation showed that, NO_3^--N uptake accounted for 34% of the total N uptake and the rate of NO_3^--N uptake was comparable with those of NH_4^+-N. Moreover, the denitrification process was rapid and some authors (Reddy et al., 1989; Reilly, 2000; Bachand and Horne, 2000a; 2000b) have pointed out that it was an important nitrogen removal process. Several reports indicate that denitrification begins at a threshold level of 0.25 mg O_2 L^{-1}, with increasing activity as oxygen content declines (Chan and Cambell, 1980; Rönner and Sörensson, 1985). However, according to Bahlo and Wach (1993), denitrification could be found in effluents of constructed wetlands even with oxygen levels of more than 4.0 mg l^{-1}. Therefore, the medium level (between 0.25 mg O_2 L^{-1} and 4.0 mg l^{-1}) of dissolved oxygen (2 to 3 mg l^{-1}) in the system could not interdict the denitrification process.

The high mean nitrogen concentrations in the control treatment (TN: 1.49 ± 0.65 mg l^{-1}; NH_4^+-N: 0.47 ± 0.22 mg l^{-1}; NO_3^--N: 0.15 ± 0.05 mg l^{-1}; NO_2^--N: 0.03 ± 0.01 mg l^{-1}) suggests that, the presence of rice had positive impacts on the nitrogen removal. Apart from nutrient uptake and transfer of oxygen to facilitate microbial processes, the submerged roots and stems of rice could provide a large attachment area for both epiphytes and bacterial populations; thus, nutrient removal could be augmented through the processes of assimilation, nitrification and denitrification (Gumbricht, 1993; Weisner et al., 1994; Redding et al, 1997). On the other hand, the low removal rates obtained in the control treatment might result from less microbial processes and no uptake.

Removal rate of COD

All treatments had a high removal rate (48.70 to 54.81%) of COD and showed no significant difference ($p > 0.05$). This result was consistent with the studies of Manios et al. (2003) and Ciria et al. (2005), who found that the presence of a macrophyte did not lead to a reduction in COD. It meant that, the removal of this parameter was mainly due to physical processes (sedimentation and adsorption) rather than biological processes (Ciria et al., 2005).

Nutrient removal over the course of the experiment under each treatment is presented in Figures 1 to 7. We found that removal efficiencies were bound up with the nutrient loadings evidently. The result agreed with previous studies (Lin et al., 2002; Schulz et al., 2004; Lin et al., 2005; Li et al., 2007; Sindilariu et al, 2007) that areal removal rose with increasing areal loading. The reduction in growth and deterioration of the stems and leaves might have decreased removal rates during the later stages of the experiment. The rice tissue released most of its nitrogen and phosphorous to water during decomposition (Richardson, 1985; Graneli and Solander, 1988). However, nutrient removals were still taking place despite this impact of decomposition (Figures 1 to 7).

Compared with the results of other studies of untreated aquaculture effluents (Lin et al., 2002; Schulz et al., 2004; Lin et al., 2005; Li et al., 2007; Sindilariu et al., 2007), the

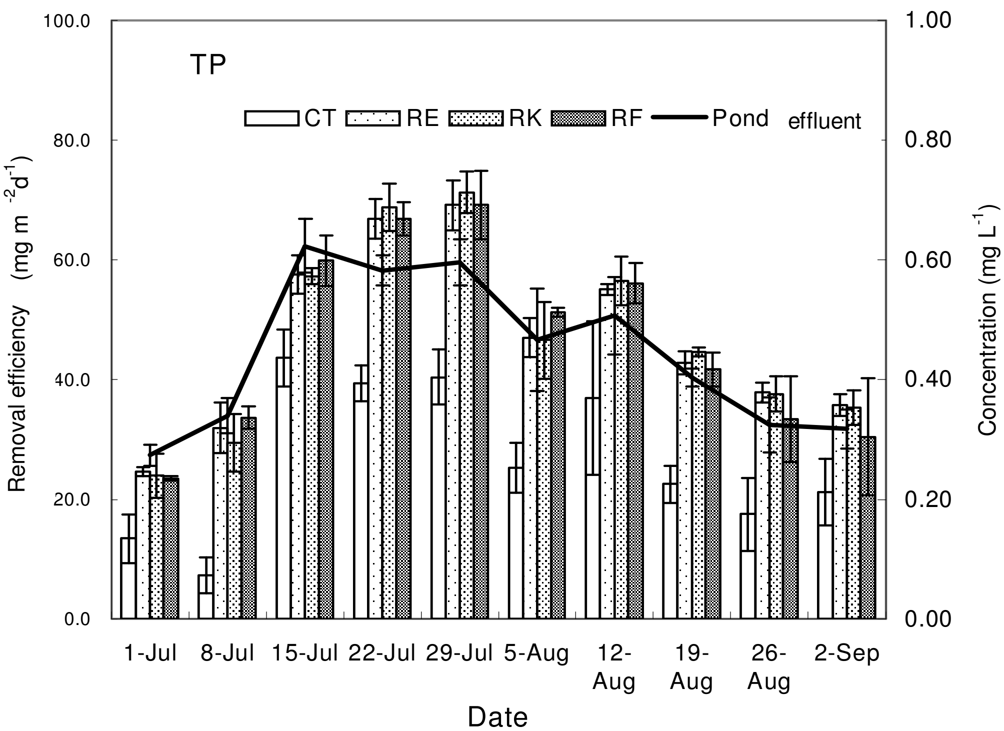

Figure 1. Temporal course of TP removal under different treatments in 2008. Mean values ± standard deviations are shown (n = 3).

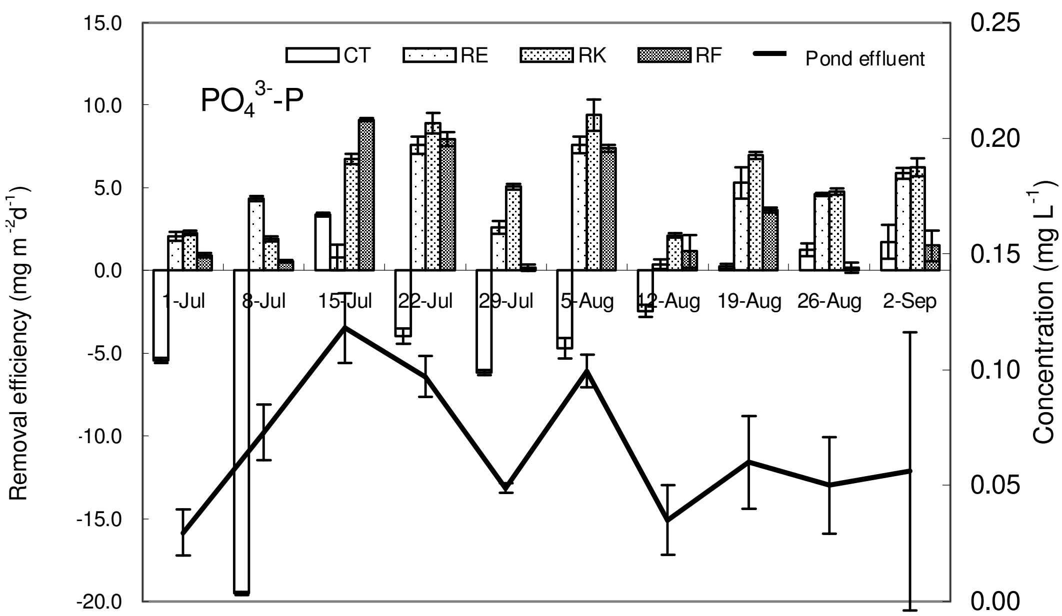

Figure 2. PO_4^{3-}-P removal over the course of the experiment under each treatment in 2008. Mean values ± standard deviations are shown (n = 3).

nutrient concentrations in this study were lower. This was however relevant to various factors concerning hydraulic management, oxygen and feeding management (Summerfelt et al., 1995; Cripps and Bergheim, 2000). A

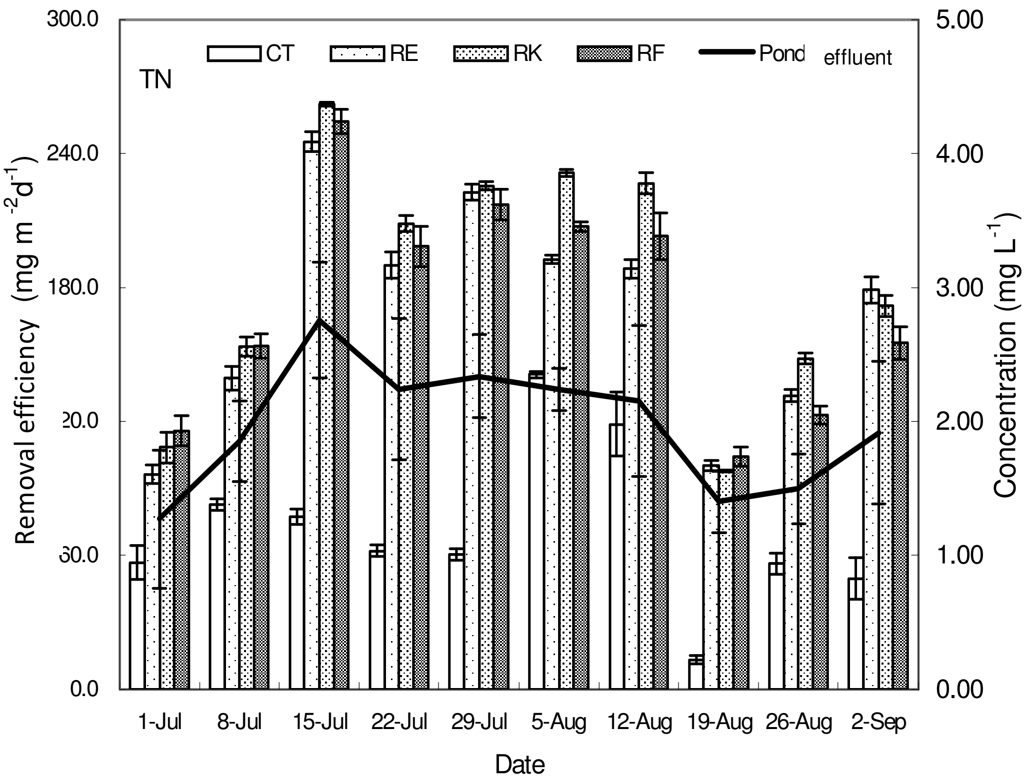

Figure 3. TN removal over the course of the experiment under each treatment in 2008. Mean values ± standard deviations are shown (n = 3).

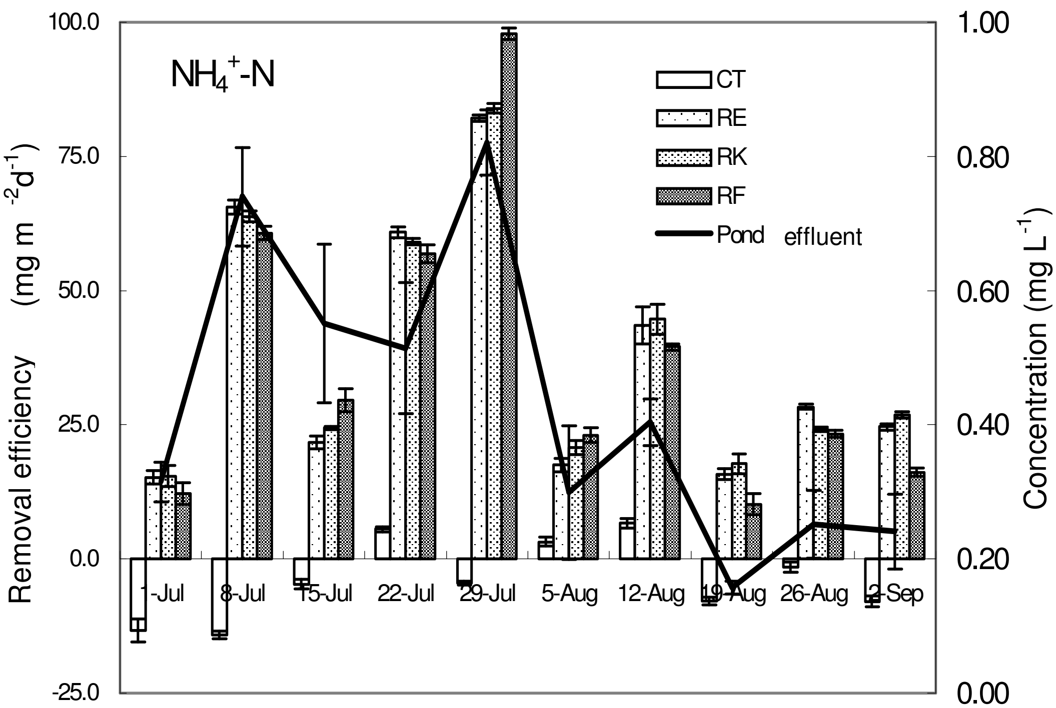

Figure 4. Temporal course of NH_4^+-N removal under different treatments in 2008. Mean values ± standard deviations are shown (n = 3).

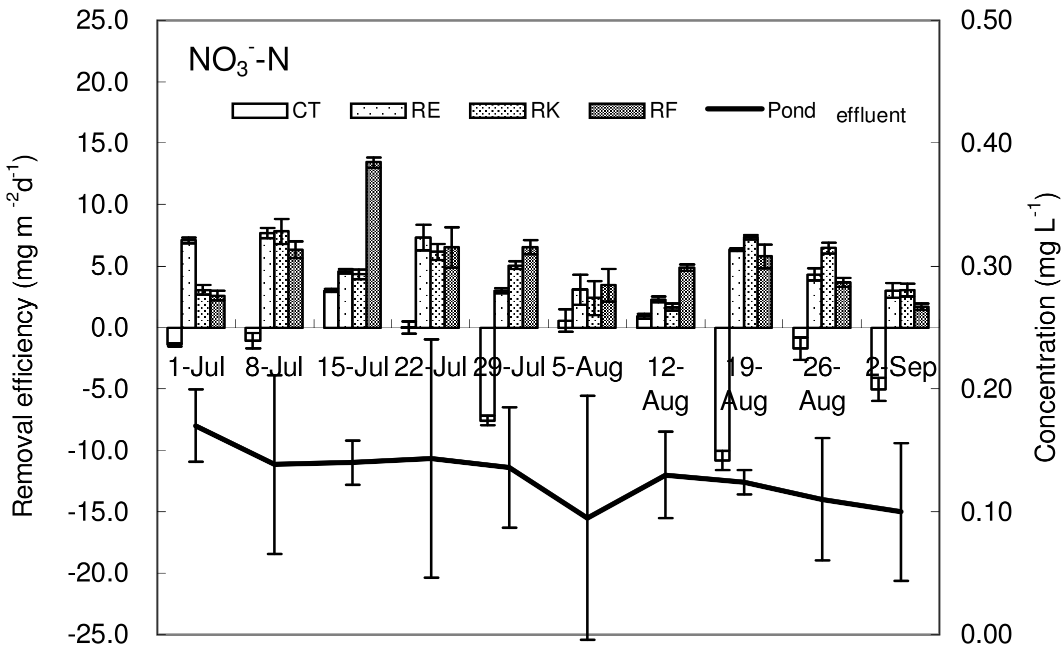

Figure 5. Temporal course of NO_3^--N removal under different treatments in 2008. Mean values ± standard deviations are shown (n = 3).

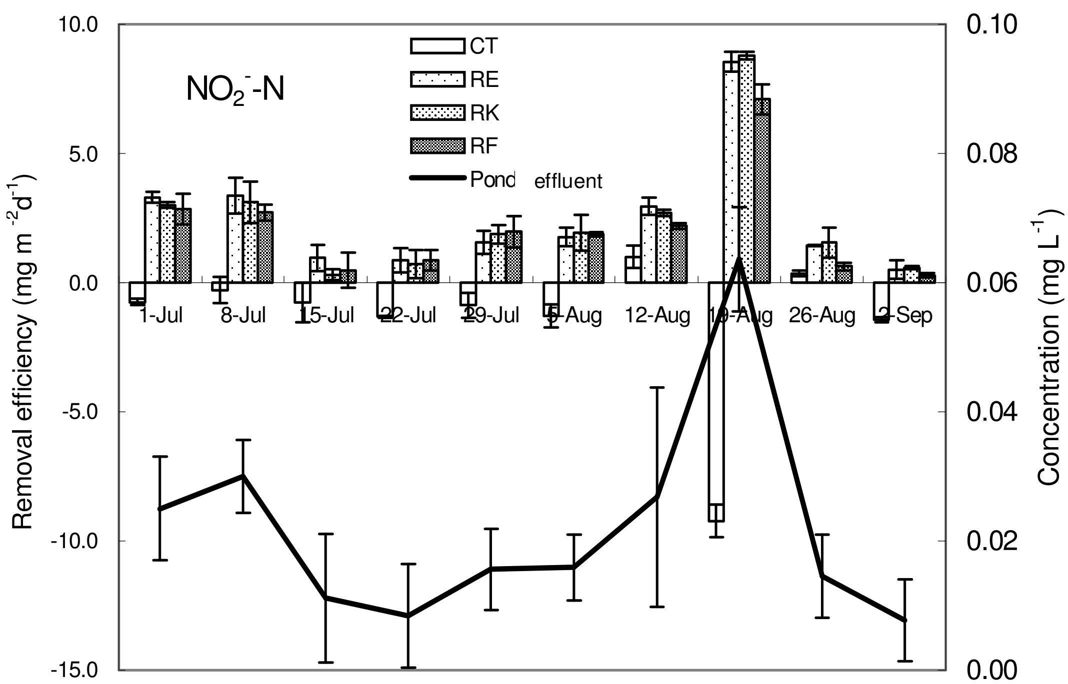

Figure 6. Temporal course of NO_2^--N removal under different treatments in 2008. Mean values ± standard deviations are shown (n = 3).

hydraulic loading rate of 0.6 m^3 per day was applied in this study in line with appropriate water levels for rice growth and farm practices. According to standards for China surface water environmental quality (2002), pond effluents in this study were considered seriously polluted, but could be reused for aquaculture after been treated with the rice

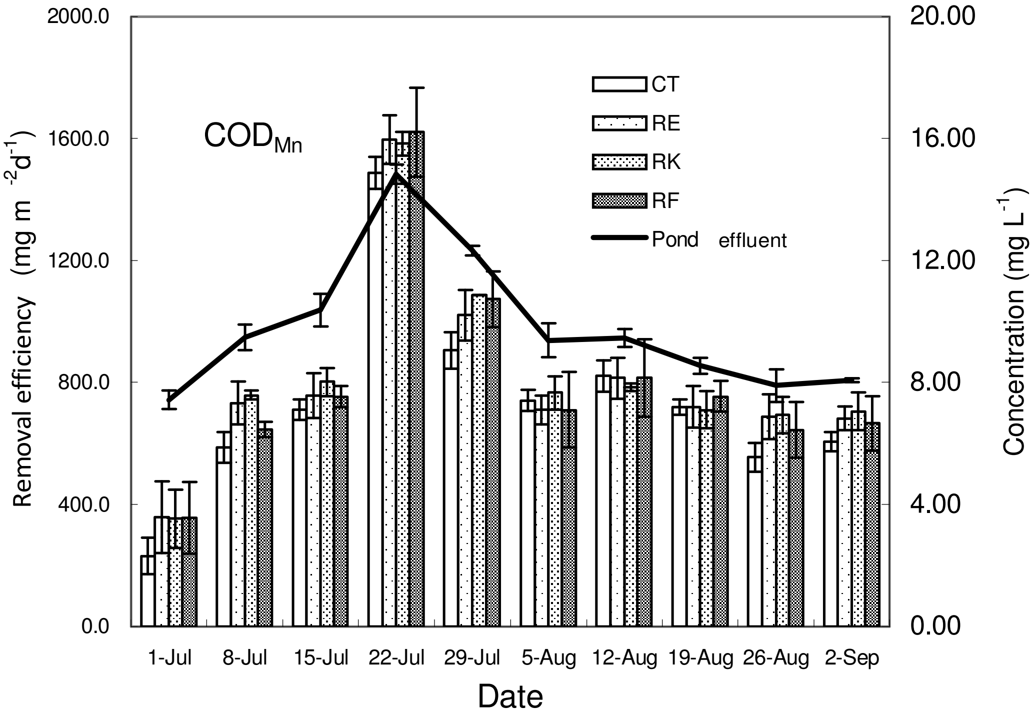

Figure 7. Temporal course of COD removal under different treatments in 2008. Mean values ± standard deviations are shown (n = 3).

fields described in this study.

Rice crop performance

The plant height in the RF treatment was highest (100.00 ± 10.10 cm). It was not significantly different from that in the RK treatment (94.10 ± 13.80 cm; $p > 0.05$), but was significantly higher than that in the RE treatment (91.90 ± 12.70 cm; $p < 0.05$). The RF treatment had the highest grain yield and dry matter (649.53 ± 94.20 and 1192.82 ± 205.60 g m^{-2} respectively), followed by RK (523.83 ± 71.50 and 980.24 ± 156.40 g m^{-2}, respectively). Significant differences were observed in the grain yield and dry matter across the three fertilizer treatments ($p < 0.05$; Table 3).

Yield in this experiment was inconsistent with the results obtained by Lin and Yang (2003) and Yang et al. (2006), who found no significant difference in grain yield between rice fertilized by effluent and rice fertilized by minimal fertilizers. It is well documented that, nitrogen and phosphorus play important roles in regulating plant growth and development (Wang et al., 2005; Yan et al., 2005). According to Hu and Wang (2004), potassium fertilizer could improve rice nutrient-absorbing capacity from soil and promote transfer of nitrogen form leaf and straw to panicle. As a physiological response to potassium, the number of filled spikelet and thousand-grain weight increased, so grain yield increased. However, the grain yield and dry matter in the RK treatment only increased by 15.27 and 16.27%, respectively, far lower than those in the RF treatment (42.93 and 41.58%, respectively) when compared with the RE treatment. It could be hypothesized that the deficiency of available nitrogen and phosphorus rather than potassium were the limiting factors for the rice crop. Additionally, among the macronutrients required by rice plants, nitrogen (N) required for the biosynthesis of amino acids and secondary metabolites was consumed in the greatest quantities (Li et al., 2008). N availability, as nitrate (NO_3^-) or ammonium (NH_4^+), usually limits plant growth and development (Crawford and Glass, 1998; Escobar et al., 2006). According to Tan et al. (2007), a rate of 225.0 kg ha^{-1} nitrogen and 100.0 kg ha^{-1} phosphorus fertilizers were required for optimum production of this rice cultivar. Overall, nitrogen and phosphorus provided by pond effluents were comparable to those assimilated by rice within all rice-plant treatments. Furthermore, nutrients absorbed by rice fluctuated and the rate of uptake was not constant. Typically, the important uptake peak is during the tillering stage, beginning about 10 days after transplanting (Ramanathan and Krishnamoorthy, 1973).

The grain yields in rice treatments were lower than the average yield of this rice variety obtained by normal local practice (774.56 ± 70.70 g m^{-2}). However, excepting the lower filled-grain percentage and thousand-grain weight

Table 3. Rice crop performance under different fertilizer treatments.

Treatment	Plant height (cm)	Grain yield (g m^{-2})	Dry matter (g m^{-2})	TN uptake (g m^{-2})	TP uptake (g m^{-2})
RE	91.9 ± 12.7 [b]	454.44 ± 43.8 [c]	842.53 ± 123.5 [c]	9.52 ± 1.25 [c]	1.94 ± 0.75 [c]
RK	94.1 ± 13.8 [a,b]	523.83 ± 71.5 [b]	980.24 ± 156.4 [b]	10.49 ± 1.38 [b]	2.35 ± 1.16 [b]
RF	100.0 ± 10.1[a]	649.53 ± 94.2 [a]	1192.82 ± 205.6 [a]	17.65 ± 1.51 [a]	2.62 ± 0.89 [a]

Data are presented as means ± SD (n = 4) and values in the same column with different letters are significantly different ($p < 0.05$).

that resulted from diseases and insect pests, all other yield compositions in the RF treatment were improved remarkably (unpublished data), thus, higher yield could be expected.

Conclusions

The main conclusions drawn from this study regarding using rice fields for pond effluent treatment were as follows: (1) The presence of rice had a positive impact on the removal of pollutants with the rice field removing the nutrients from pond effluents effectively and reducing TN, TP and COD by 56, 68 and 53%, respectively; (2) both basic mineral fertilizer application before the experiment and potassium application during the experiment had no impact on the treatment effectiveness and (3) nitrogen and phosphorus nutrients provided by pond effluents solely could not fully meet the demand of the rice crop. Basic mineral fertilizer application before the experiment and potassium application during the experiment can improve rice productivity significantly.

In summary, rice fields can purify pond effluents efficiently without a reduction in the production when appropriate mineral fertilizer is applied, which is an effective alternative for treating pond effluents.

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REFERENCES

Armstrong W (1971). Radial oxygen losses from intact rice roots as affected by distance from the apex, respiration and water-logging. Physiol. Plant, 25: 192-197.

Arth I, Frenzel P, Conrad R (1998). Denitrification coupled to nitrification in the rhizosphere of rice. Soil Biol. Biochem., 30: 509-515.

Azevedo CMSB, Barreto AKG, Filho JL, Maia CE (2002). Stimulating nodulation and growth in cowpea with fish effluent. World Aquact. Mag., 33: 49-64.

Bachand PAM, Horne AJ (2000a). Denitrification in constructed free-water surface wetlands: I. Very high nitrate removal rates in a macrocosm study. Ecol. Eng., 14: 9-15.

Bachand PAM, Horne AJ (2000b). Denitrification in constructed free-water surface wetlands: II. Effects of vegetation and temperature. Ecol. Eng., 14: 17-32.

Bahlo K, Wach G (1993). Naturnahe Abwasserreinigung, Planung und Bau von Pflanzenkla ranlagen. 2. Auflage, ökobuch Staufen bei Freiburg.

Bergheim A, Brinker A (2003). Effluent treatment for flow-through systems and European environmental regulations. Aquacult. Eng., 27: 61-77.

Bergheiser VE, Street JS, Rao PSC, Yuan TL (1980). Partitioning of inorganic orthophosphate in soil–water systems. CRC Crit. Rev. Environ. Control, 10: 179-211.

Blom CWPM, Voesenek LACJ (1996). Flooding: the survival strategies of plants. Tree, 11: 290-295.

Brix H (1997). Do macrophytes play a role in constructed treatment wetlands? Water Sci. Tech., 35: 11-17.

Brown JJ, Glenn EP (1999a). Reuse of highly saline aquaculture effluent to irrigate a potential forage halophyte, Suaeda esteroa. Aquacult. Eng., 20: 91-111.

Brown JJ, Glenn EP, Fitzsimmons KM, Smith SE (1999b). Halophytes for the treatment of saline aquaculture effluent. Aquaculture, 175: 255-268

CAFM (China Agriculture Fisheries Ministry) (2006). China Fisheries Yearbook. China Agriculture Press, China.

Castro RS, Azevedo CMSB, Bezerra-Neto F (2006). Increasing cherry tomato yield using fish effluent as irrigation water in Northeast Brazil. Sci. Hortic., 110: 44-50

Chan YK, Cambell NER (1980). Denitrification in lake 227 during summer stratification. Can. J. Fish. Aquat. Sci. 37: 506-512.

Cho CY, Bureau DP (1997). Reduction of waste output from salmonid aquaculture through feeds and feeding. Prog. Fish-Cult., 59: 155-160.

Ciria MP, Solano ML, Soriano P (2005). Role of Macrophyte Typha latifolia in a Constructed Wetland for Wastewater Treatment and Assessment of its Potential as a Biomass Fuel. Biosyst. Eng., 92: 535-544.

Crawford NM, Glass ADM (1998). Molecular and physiological aspects of nitrate uptake in plants. Trends Plant Sci., 3: 389-395.

Cripps SJ, Bergheim A (2000). Solids management and removal for intensive land-based aquaculture production systems. Aquacult. Eng., 22: 33-56.

Diana JS, Lin CK, Jaiyam K (1994). Supplemental feeding of tilapia in fertilized ponds. J. World Aquacult. Soc., 25: 497-506.

Eding EH, Kamstra A, Verreth JAJ, Huisman EA, Klapwijk A (2006). Design and operation of nitrifying trickling filters in recirculating aquaculture: a review. Aquacult. Eng., 34: 234-260.

Escobar MA, Geisler DA, Rasmusson AG (2006). Reorganization of the alternative pathways of the Arabidopsis respiratory chain by nitrogen supply: opposing effects of ammonium and nitrate. Plant J., 45: 775-788.

Frei M, Becker K (2005). Integrated rice-fish culture: Coupled production saves resources. Nat. Resour. Forum, 29: 135-143.

Frenzel P, Rothfuss F, Conrad R (1992). Oxygen profiles and methane turnover in a flooded rice microcosm. Biol. Fertil. Soils, 14: 84-89.

Graneli W, Solander D (1988). Influence of aquatic macrophytes on

Phosphorous cycling in lakes. Hydrobiology, 170: 245-266.
Gumbricht T (1993). Nutrient removal processes in freshwater submersed macrophyte systems. Ecol. Eng., 2: 1-30.
Hagopian DS, Riley JG (1998). A closer look at the bacteriology of nitrification. Aquacult. Eng., 18: 223-244.
Hiley PD (1995). The reality of sewage treatment using wetlands. Water Sci. Technol., 32(3): 329-338.
Hu H, Wang GH (2004). Nutrient Uptake and Use Efficiency of Irrigated Rice in Response to Potassium Application. Pedosphem, 14: 125-130.
Hussain G, Al Jaloud AA, Alsadon AA, Siddiqui AQY (1993). Use Aquaculture Effluent as a Supplemental Source of Nitrogen Fertilizer to Wheat Crop. Arid Soil Res. Rehab., 7: 233-241.
James WF, Barko JW, Butler MG (2004). Shear stress and sediment resuspension in relation to submersed macrophyte biomass. Hydrobiologia, 515: 181-191.
Jin G, Kelley T, Freeman M, Callahan M (2002). Removal of N, P, BOD_5, and coliform in pilot-scale constructed wetland systems. Int. J. Phytorem., 4: 127-141.
Jones AB, Dennison WC, Preston NP (2001). Integrated treatment of shrimp effluent by sedimentation, oyster filtration and macroalgal absorption: a laboratory scale study. Aquaculture, 193: 155-178.
Justin SHFW, Armstrong W (1987). The anatomical characteristics of roots and plant response to soil flooding. New Phytol., 106: 465-495.
Kirk GJ, Kronzucker HJ (2005). The potential for nitrification and nitrate uptake in the rhizosphere of wetland plants: a modeling study. Ann. Bot., 96: 639-646.
Knight RL, Ruble RW, Kadlec RH, Reed SC (1993). Wetlands for Wastewater Treatment: Performance Database, In G.A. Moshiri (ed.). Constructed wetlands for water quality improvement. Lewis Publishers, Boca Raton, FL.
Kouka PJ, Engle CR (1996). Economic Implications of treating Effluents From Catfish Production. Aquacult. Eng., 15: 273-290.
Kronzucker H J, Schjoerring JK, Erner Y, Kirk GJD, Siddiqi MY, Glass ADM (1998). Dynamic interactions between root NH_4^+ influx and long-distance N translocation in rice: insights into feedback processes. Plant Cell Physiol., 39: 1287-1293.
Kronzucker HJ, Siddiqi MY, Glass AD, Kirk GJ (1999). Nitrate-ammonium synergism in rice: a subcellular flux analysis. Plant Physiol., 119: 1041-1045.
Li G, Wu ZB, Cheng SP, Liang W, He F, Fu GP, Zhong F (2007). Application of Constructed Wetlands on Wastewater Treatment for Aquaculture Ponds. Wuhan Univ. J. Nat. Sci., 12: 1131-1135.
Li YL, Zhang YL, Hu J, Shen QR (2007). Contribution of nitrification happened in rhizospheric soil growing with different rice cultivars to N nutrition. Biol. Fertil. Soils, 43: 417-425.
Li, YL, Fan XR, Shen QR (2008). The relationship between rhizosphere nitrification and nitrogen-use efficiency in rice plants. Plant Cell Environ., 31: 73-85.
Lin CK, Shrestha MK, Yi Y, Diana JS (2001). Management to minimize the environmental impacts of pond effluent: harvest draining techniques and effluent quality. Aquacult. Eng., 25: 125-135.
Lin CK, Yang Y (2003). Minimizing environmental impacts of freshwater aquaculture and reuse of pond effluents and mud. Aquaculture, 226: 57-68.
Lin YF, Jing SR, Lee DY, Chang YF, Chen YM, Shih KC (2005). Performance of a constructed wetland treating intensive shrimp aquaculture wastewater under high hydraulic loading rate. Environ. Pollut., 134: 411-421.
Lin YF, Jing SR, Lee DY, Wang TW (2002). Nutrient removal from aquaculture wastewater using a constructed wetlands system. Aquaculture, 209: 169-184.
Manios T, Stentiford EI, Millner P (2003). The removal of chemical oxygen demand from primary-treated domestic wastewater in surface-flow reed beds using different substrates. Water Environ. Res., 75: 336-341.
Mcintosh D, Fitzsimmons K (2003). Characterization of effluent from an inland, lowsalinity shrimp farm: what contribution could this water make if used for irrigation. Aquacult. Eng., 27: 147-156.
Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MC, Clay J, Folke C, Lubchenco J, Mooney H (2002). Effect of Aquaculture on World Fish Supplies. Nature, 405: 1017-1024.
Ramanathan KM, Krishnamoorthy KK (1973). Nutrient uptake by paddy during the main three stages of growth. Plant. Soil, 39: 29-33.
Redding T, Todd S, Midlen A (1997). The Treatment of Aquaculture Wastewaters-A Botanical Approach. J. Environ. Manage. 50: 283-299.
Reddy KR, Patrick WH, Lindau CW (1989). Nitrification-denitrification at the plant root-sediment interface in wetlands. Limnol. Oceanogr., 34: 1004-1013.
Reilly JF, Horne AJ, Miller CD (2000). Nitrogen removal from a drinking water supply with a large-scale free-surface constructed wetlands prior to groundwater recharge. Ecol. Eng., 14: 33-47.
Richardson CJ (1985). Mechanisms controlling phosphorous retention capacity in freshwater wetlands. Science, 228: 1424-1427.
Rönner U, Sörensson F (1985). Denitrification rates in the low-oxygen waters of stratified Baltic proper. Appl. Environ. Microbiol., 50: 801-806.
Schulz C, Gelbrecht J, Rennert B (2003). Treatment of rainbow trout farm effluents in constructed wetland with emergent plants and subsurface horizontal water flow. Aquaculture, 217: 207-221.
Schulz C, Gelbrecht J, Rennert B (2004). Constructed wetlands with free water surface for treatment of aquaculture effluents. J. Appl. Ichthyol., 20: 64-70.
Sindilariu PD, Schulz C, Reiter R (2007). Treatment of flow-through trout aquaculture effluent in constructed wetland. Aquaculture, 270: 92-104.
Sindilariu PD, Wolter C, Reiter R (2008). Constructed wetlands as a treatment method for effluents from intensive trout farms. Aquaculture, 277: 179-184.
SRAC (Southern Regional Aquaculture Center) (1994). Seventh Annual Progress Report. Southern Regional Aquaculture Center, Stoneville, MS.
State Environmental Protection Administration of China (1997). Methods for Chemical Analysis of Water and Waste, 3rdEd. Beijing: China Environmental Science Press, pp. 32-220 (in Chinese).
State Environmental Protection Administration of China (2002). China surface water environmental quality standards. China Environmental Science Press, China (in Chinese).
Summerfelt ST, Adler PR, Glenn DM, Kretschmann RN (1995). Aquaculture sludge removal and stabilization within created wetlands. Aquact. Eng., 19: 81-92.
Tan CL, Zhang HX, Dai ZY, Zhao BH, Li AH, Wang BH (2007). Effect of Nitrogen Fertilizer Application on Yield and Nitrogen Utilization Rate of Two-line Indica Hybrid Rice Yangliangyou 6. Jiangsu J. Agric. Sci., 23: 178-183 (in Chinese).
Wang J (1990). Managing shrimp pond water to reduce discharge problems. Aquat. Eng., 9: 61-73.
Wang JH, Liu JS, Li YF (2005). The effect of nitrogenous and phosphorus fertilizers on accumulation and movement of nitrogen in shallow layer of dark soil. Chin. J. Soil Sci., 36: 341-344 (in Chinese with English abstract).
Wang MY, Siddiqi MY, Ruth TJ, Glass ADM (1993). Ammonium uptake by rice roots. I. Fluxes and subcellular distribution of $^{13}NH_4^+$. Plant Physiol., 103: 1249-1258.
Weisner S, Eriksson PG, Graneli W, Leonardson L (1994). Influence of macrophytes on nitrate removal in wetlands. Ambio, 23: 363-366.
Yan DZ, Wang DJ, Lin JH (2005). Effects of fertilizer-N application rate on soil N supply, rice N uptake and groundwater in taihu region. Acta Pedol. Sin., 42: 440-446 (in Chinese).
Yang Y, Lan LM, Lin CK (2006). Using effluents from an intensive catfish (*Clarias macrocephalus* × *C. gariepnus*) culture pond to irrigate rice crop. In: Ohgaki S, Fukushi K, Katayama H, Takizawa S, Polprasert C (eds.). Southeast Asian Water Environment I - Biodiversity and Water Environment. International Water Association, IWA Publishing, London, UK.
Zhang YL, Shen QR, Duan YH (2004). Physiological effects of different nitrogen forms on rice. Nanjing Agr. Univ. J. Nat. Sci., 27: 130-135 (in Chinese with English abstract).