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Reuse of Reclaimed Water for Irrigation on Paddy Rice Culture and Its Effect

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Abstract □ The effect of reclaimed water irrigation on paddy rice culture was evaluated by pilot study at the experimental field of Konkuk University in Seoul, Korea. The sewage was treated by constructed wetland system, and its effluent was used as irrigation water for four treatments and one control plots with three replications. Irrigation of reclaimed water onto paddy rice cultures did not adversely affect the growth and yield of rice. Instead, experimental rice plots of reclaimed water irrigation displayed about 10 to 50% more yield on average than controls. This implies that reclaimed water irrigation might be beneficial rather than harmful to rice culture as long as the sewage is treated adequately and used properly. The amount of irrigation water had little effect on experimental rice cultures, but its strength was important. The strength of treated sewage was not a limiting factor in this study, and no lodging was observed even with a relatively high nitrogen concentration (up to 160mg/L). In general the paddy soil was not affected by reclaimed water irrigation. However, there was an indication that continuous irrigation with high strength of reclaimed water might cause salt accumulation in the soil. Supplemental use of reclaimed water with existing sources of irrigation water is recommended rather than irrigation with a single source of reclaimed water. Overall, the results demonstrated that reclaimed water could be reused as a supplemental source of irrigation water for paddy rice culture without causing adverse effects as long as it is properly managed. For full-scale application, further investigation should be done on environmental risks, tolerable water quality, and fraction of supplemental irrigation.

Keywords □ Wastewater reclamation, Water reuse, Irrigation, Paddy rice culture.

I. Introduction

Water is one of the most essential prerequisites for sustaining natural ecosystems and human development. Increasing human populations and greater economic development require more water and competition occurs among the water demands of agriculture, residential, and industrial uses. Water stress is critical in the Middle East and North Africa, and it also has affected Europe and North America, which are temperate and typically have plentiful resources. Numerous regions in France, Italy, Spain, and the United Kingdom have suffered the negative impacts of successive droughts during the last few years (Lazarova et al., 2000). Furthermore, the available freshwater is not always satisfactory for intended water uses due to water quality problems associated with increased pollutant discharges.

Under conditions of water shortage, recycling of the resource becomes very important. Reuse also provides a means to reduce sewage impacts to natural systems. Agronomic reuse of sewage water has been practiced for centuries in many parts of the world. The irrigation fields of Paris have been used for 100 years, and the daily flow of treated sewage reaches up to 300,000 m^3/day in summer, helping to reduce pollutant loading to the Seine River thanks to the astonishing purification capacity of the soil (Vedry et al., 2000). In Israel, a semiarid country, about 44 mgd has been reused for agricultural irrigation since 1984 and it is anticipated that reuse soon will replace about 30% of total amount of water for agricultural irrigation (Zoller, 1984). In Australia, a farm located 35 km southwest of Melbourne has utilized treated and untreated wastewater effluent from over 50 municipal facilities since 1897. Land disposal of wastewater at some sites has been practiced in India for up to 160 years ago, and sewage farming as a method of wastewater disposal is reported to take place at more than 200 sites (Rowe and Abedel-Magid, 1995). In Italy, wastewater reuse is mainly focused on irrigation. Several wastewater reuse systems have been implemented not only in the region of arid and semiarid regions of Southern Italy, but also Northern Italy where available water resources generally meet water demands, in this case the goal being control of water pollution (Barbagallo et al., 2000).

Korea is a densely populated country with about 47 million people in 100,000 km^2 and is classified as a country of water shortage. Several regions suffer water stress even with an average annual precipitation of 1,283 mm nationwide. Increasing sewage discharges associated with the growing human population threatens water quality of receiving water bodies, and many areas experience water quality problems. Domestic sewage is known to be one of the major pollutant sources, and legislation on the effluent water quality is forcing sewage treatment plants to meet strict standards. Nevertheless many treatment plants often exceed these standards.

One potential for treatment of sewage water in Korea and other countries is to use it for irrigation of major agricultural crops. Rice is the largest irrigated crop and ranks second only to wheat as the most extensively grown crop in the world (Roel et al., 1999). Rice is a principle staple food for half of mankind, and people of Asia produce and eat 90% of all the rice grown. Rice (Oryza sativa L.) is grown during summer in Korea on about 1,100,000 ha, which is more than half of total arable farmland (MOAF, 1999). Paddy rice production requires a large quantity of water. The fields are flooded before sowing and the water level is held at 4-6 cm in shallow rice fields and as high as 10 cm in continuous flooding irrigation during the growing season (Rath et al, 2000; Anastacio et al, 2000). In the field operation, total of about 1,250 mm is required for the paddy rice crop during the growing season and this water is primarily supplied by irrigation (Chae, 1998). Among the water uses, irrigation for paddy rice culture ranks first and it takes over 50% of the total water consumption in Korea. Not only heavy water use, but also heavy fertilization is practiced to increase the rice productivity. Therefore, irrigation to the paddy rice field could be a practical candidate for treated sewage reuse in both a quantity and quality perspective. Irrigation water in Korea does not need to meet drinking water standards, and irrigation with adequately treated wastewater dose not lead to excess intestinal nematode infections in field workers or crop consumers (Mara and Cairncross, 1989).

A pilot study was performed to examine the effects of treated sewage irrigation on rice culture and its soil characteristics in experimental fields in Korea.

2. Materials and methods

2.1 Experimental Plots

The sewage from a school building of Konkuk University in Seoul, Korea, was first treated by a constructed wetland system. It was pumped from the last compartment of the septic tank into a storage tank, and was then allowed to flow into the wetland. The wetland system was a subsurface flow type, and the basin was filled with sands with transplanted reeds. Theoretical hydraulic loading rate and hydraulic residence times of the system were 6.3 cm/day and 3.5 days, respectively. Effluent from the wetland was used as irrigation water for the paddy rice culture experiment.

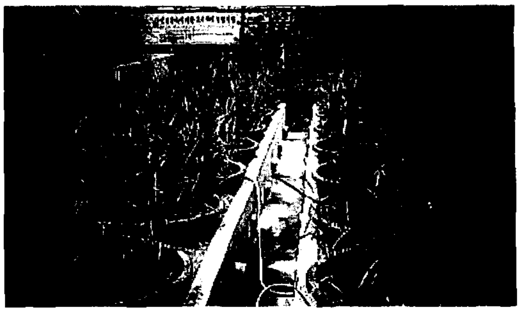

Fig. 1 General view of experimental system for rice cultivation

Paddy rice was grown in an experimental field (Fig. 1) at the College of Agriculture and Life Science, Konkuk University. The size of treatment plots was 90 cm wide 110 cm long 70 cm high with a surface area of about 1 m^2. The bottom 10 cm was filled with gravel. This was covered with a filter cloth and paddy soil was laid on top, leaving a 10 cm space for irrigation water. A drainpipe was installed at the bottom of the plot to control water percolation rate. The exterior of each plot was insulated by soil to prevent possible temperature effects on crop growth.

As a testing material, Illpumbyeo (Korean rice cultivar) was planted at a rate of one plant per hill and 22 hills per plot. Separate plots were subjected to four treatments with one control, with each treatment being replicated three times (15 plots total). A conventional fertilization rate of 110-70-80 kg/ha $N\text{-}P_2O_5\text{-}K_2O$ and other standard cultivation practices of the local district were followed.

Water quality of the irrigation water was analyzed by Standard Methods (APHA, 1995) and specific methods are summarized in Table 1, and soil samples were analyzed by the Methods of Soil Analysis (ASA and SSSA, 1982).

Table 1 Methods used for water quality analysis

Constituents	Methods*	Remarks
DO (dissolved oxygen)	SM 4500-O C	Azide Modification Method
BOD (biochemical oxygen demand)	SM 5210-B	5-day BOD test
TSS (total suspended solids)	SM 2540-D	
T-N (total nitrogen)		
Organic nitrogen	SM 4500-N_{org}-C	
NH_3-N	SM 4500-NH_3-D	BUCHI 435 and B-316
NO_2-N	SM 4110-B	Dionex DX-100
NO_3-N	SM 4110-B	Dionex DX-100
T-P (total phosphorus)	SM 4500-P E	HP8452A Spectrophotometer

*SM: Standard Methods

2.2 First Year Experiment

Nitrogen is known to be a sensitive component in rice culture because excessive nitrogen application can cause lodging of rice plants. The total nitrogen (T-N) concentration of the treated sewage was over 100 mg/L until June. This is much higher than the Korean recommended agricultural water quality standard of 1 mg/L. Therefore, the sewage effluent was diluted to keep T-N below 25 mg/L until June. The effluent T-N was about 30 to 40 mg/L from July onward and during that period the material was used without dilution. The adjusted concentration of treated sewage by dilution during the irrigation period is shown in Fig. 2.

Four treatments were compared with a control: (1) irrigation with treated sewage after concentration adjustment and conventional fertilization (TWCF); (2) irrigation with treated sewage after concentration adjustment and half of the conventional fertilization (TWHF); (3) irrigation with treated sewage after concentration adjustment and no fertilization (TWNF); and (4) irrigation with undiluted treated sewage with no fertilization (SWNF). The control plots (CONTROL) were irrigated with clean water and conventional fertilization was applied.

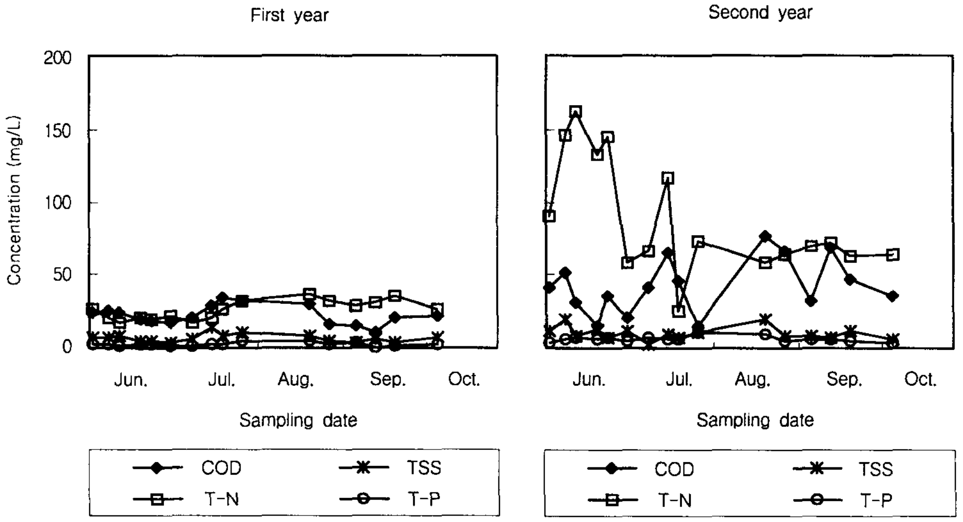

Fig. 2 Treated sewage concentration for irrigation to paddy rice culture

The rice was transplanted on May 22, 1998. Irrigation water was applied at a rate of 20 L each time for 15 times, thus 300 L of irrigated water was applied to the plot of 1 m^2 for the whole crop season in addition to natural precipitation. Triplicate plant samples were collected five times at 7-day interval starting on August 10. Plant height, leaf area and tiller numbers were measured at each stage. The rice was harvested on October 21, and the yield was calculated using yield components and corrected to 14% moisture content.

2.3 Second Year Experiment

The test material of Illpumbyeo rice and conventional fertilization rates were identical to the first year of study. Four treatments in the second year included: (1) daily irrigation with undiluted treated sewage and no fertilization (DSWNF); (2) irrigation with treated sewage after concentration adjustment (as described above) and conventional fertilization (TWCF); (3) irrigation with undiluted treated sewage and half of the conventional fertilization (SWHF); and (4) irrigation with undiluted treated sewage and conventional fertilization (SWCF). The control plot was irrigated with clean water and conventional fertilization, as in the previous year.

In the DSWNF, irrigation with treated sewage occurred daily at a rate of 10 L/day except on wet days. The total irrigated amount was 540 L, which was designed to see if lodging of rice plants occurred in a case of irrigation with high nitrogen inputs. The other plots were irrigated with a total volume of 430 L to keep the water level between 5 and 10 cm. The irrigation rate was similar to the DSWNF but irrigation occurred less frequently. The treated sewage concentrations during the second year experiment are shown in Fig. 2. The sewage was used without dilution except in the TWCF treatment where it was diluted five-fold with water. Therefore, the DSWNF, SWCF, and SWHF plots received more irrigation water and nutrients due to higher strength than the first year treatment plots.

The rice was transplanted on May 24 and harvested on October 25 in 1999, and triplicate samples were taken six times at 7-day intervals starting on July 23 to evaluate growth characteristics.

3. Results and discussion

3.1 Growth Characteristics

Table 2 shows plant height, tiller number, dry

Table 2 Comparison of growth characteristics for treatment plots

Plots*	Plant height (cm)	Tiller number (ea)	Dry weight (g/m^2)	Leaf area (cm^2)
First year				
TWNF	101.5	7.0	474.9	12.6
TWCF	108.1	10.5	1095.4	25.2
TWHF	109.6	10.0	1361.6	23.6
SWNF	92.3	8.8	637.3	14.5
Control	107.7	11.3	1196.8	27.1
LSD	8.1	2.4	282.6	6.5
Second year				
DSWNF	97.3	12.7	2696.5	39.9
TWCF	98.5	12.0	2381.1	36.6
SWHF	99.1	16.8	3889.9	55.5
SWCF	98.4	17.5	3840.4	53.5
Control	97.3	12.7	2267.5	34.4
LSD	5.2	3.8	726.6	10.0

*LSD: least significant difference

weight, and leaf area at the time of final sampling. Plant height is used as a scale of crop growth. Average final plant height was in the order of CONTROL > TWCF > TWHF > TWNF > SWNF in the first year. Analysis of variance indicated that only the SWNF treatment had a significantly different ($p < 0.05$) average plant height than other treatments. The SWNF treatment received no fertilization and nutrients were supplied by treated sewage irrigation alone. This might not be sufficient for crop growth. However, in the second year experiment all of the average plant heights were within the same range and differences were not statistically significant. The greater amount of nutrient supply from the treated sewage might have been sufficient to grow the plants without fertilizer. This implies that nutrient-rich treated sewage irrigation could be beneficial to rice cultivation if the sewage is adequately treated.

Tillering capacity affects the grain yield of paddy rice, but excess tillers induce low yield due to a decreased filling rate. In the first year experiment, the tiller numbers of TWCF, TWHF, and CONTROL treatments were in the same range, but the TWNF and SWNF treatments displayed significantly lower tiller numbers. Overall tiller numbers were greater in the second year than in the first, and more tillers were observed in the SWCF and SWHF treatments than in the others. Generally, more nutrients were supplied in the second year due to the nutrient-rich treated sewage irrigation and greater amounts of irrigation water. Tillering capacity therefore appears to be influenced by amount of nutrients supplied.

The pattern of dry weight was similar to that for plant height and tiller number. Dry weights in the TWCF, TWHF, and CONTROL treatments were in the same range in the first year, while dry weights in the TWNF and SWNF treatments (where no fertilizer was applied) were lower. Dry weights in the second year were significantly greater than in the first year. In the DSWNF and TWCF treatments dry weights were in the same range as the CONTROL, but dry weights in the SWCF and SWHF treatments (where fertilizer was applied along with undiluted treated sewage) were higher. Dry weight is an indirect measure of amount of the carbohydrate, protein, lipid, and inorganic matter, and generally plots with more nutrients showed more dry weight.

The biomass of a rice crop depends on assimilation and respiration, which are closely related to leaf area; the net assimilation increases when plants have a large leaf area and most of the leaves are exposed to sunlight. Therefore leaf area is an important index of crop production. In the first year, the average leaf area of fertilized plots (CONTROL, TWCF, and TWHF) was about double that of unfertilized plots (TWNF and SWNF). Plots with greater nutrient inputs (SWCF and SWHF) also displayed a greater leaf area in the second year. In general the leaf areas in the second year (for all treatments except the CONTROL) were significantly greater than that of the first year. This implies that nutrient-rich irrigation water can produce a greater leaf area and possibly result in a better crop yield.

Leaf area index (LAI) is a ratio of the leaf area per unit ground area. It is a rough measure of leaf area per unit of available solar radiation, and is directly proportional to the amount of

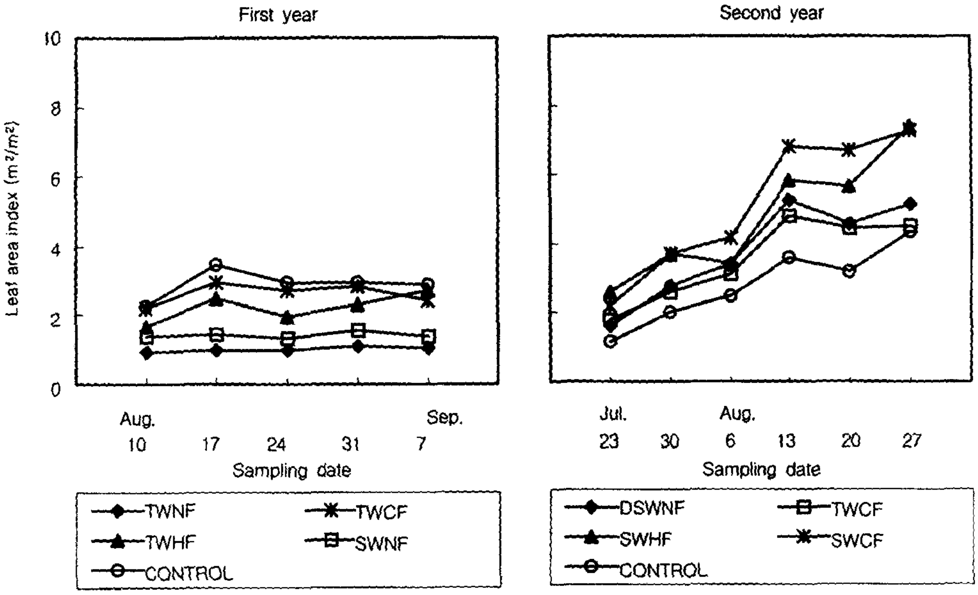

Fig. 3 Comparison of leaf area index with treatment

plant biomass produced. Although as a crop grows and LAI increases, more and more leaves become shaded and a decrease in net assimilation can occur. In the experiments the values of LAI increased less in the first year than in the second (Fig. 3). The leaf area became highest at the first sampling date of August 10 and increased little thereafter in the first year, and that trend was similar in the second year after August 13. Generally, growth characteristics in the second year were superior to the first year, and the greater nutrient supply and more stabilized environment for rice culture in the second year could partly explain the difference.

3.2 Yield

Rice culm and panicle lengths positively affect yield of the grain; with longer culms and panicles, greater yields are expected. In the first year experiment, culm and panicle lengths were shortest in the SWNF treatment (no fertilization), while lengths were similar in the other treatments (Table 3). In the second year, lengths were shortest in the CONTROL. These treatments received relatively fewer nutrients compared to others and the amount of nutrients applied by fertilization and treated sewage irrigation might partly explain the difference in culm and panicle lengths.

The grain yield increases linearly with increasing spikelet numbers per unit area (P.U. (M.S.) while filled spikelet percentages (R.G.) and 1000-grain weight (T.W.) remain fairly constant regardless of spikelet numbers. The average spikelet numbers per unit area for the first and second years were TWCF > CONTROL > TWHF > SWNF > TWNF, and SWCF > SWHF > CSWNF > CONTROL > TWHF, respectively. This order approximately matches that of nutrient supply.

The panicle number per unit area (P.U.) was significantly greater in the TWCF and CONTROL treatments than in others in the first year, and that of the CSWNF, SWCF, and SWHF treatments was the larger in the second year. The variations in M.S. among treatments were less significant.

In the first year experiment, the final yield of rice in the TWCF and CONTROL treatments was significantly larger, and the yield in the TWNF and SWNF treatments was significantly lower than that of others (Table 3). Based on the analysis of variance, yields differing by more than ~80 kg/10a were significantly different. The TWCF and CONTROL treatments received conventional fertilization, while the TWNF and SWNF treatments did not; this implies that rice yield might be more affected by fertilization than irrigation water quality.

Table 3 Comparison of yield components and grain yields for treatment plots

Plots	C.L.(1) (cm)	P.L.(2) (cm)	Yield component				Yields (kg/10a)
			P.U.(3)	M.S.(4)	R.G.(5) (%)	T.W.(6) (g)	
First year							
TWNF	80.5	23.3	109.0	118.0	82.3	24.4	259.3
TWCF	85.9	23.5	266.0	118.0	79.2	23.1	577.9
TWHF	82.1	22.1	173.0	113.0	80.6	23.1	362.1
SWNF	70.2	21.7	108.0	102.0	86.2	25.3	238.5
Control	86.9	22.5	242.0	117.0	79.1	23.5	523.0
LSD	3.6	2.4	31.2	17.4	3.1	0.4	79.5
Second year							
DSWNF	81.2	27.9	369.4	93.5	70.1	24.3	588.6
TWCF	79.6	26.9	198.4	129.5	81.7	23.7	501.5
SWHF	80.7	28.9	310.3	117.5	76.2	24.4	672.8
SWCF	78.4	28.6	323.0	132.2	80.2	23.1	799.6
Control	68.7	23.1	229.7	120.0	83.2	22.9	524.4
LSD	1.7	2.9	69.2	30.8	7.9	1.8	240.0

(1) C.L.: main culm length; (2) P.L.: panicle length; (3) P.U.: panicle number per unit area; (4) M.S.: mean of spikelet number per panicle; (5) R.G.: percent of ripened grain; (6) T.W.: weight of 1000 grain

Generally, the yield in the second year was greater than in the first, probably because more nutrients were supplied by the increased amount of treated sewage irrigation. The average yield of rice in the SWCF treatment was the largest and significantly higher than the CONTROL. Yields in other treatments were not statistically different. In the second year the yield in plots without fertilization (DSWNF) and reduced fertilization (SWHF) were within the same range as the CONTROL. This implies that nutrients contained in the treated sewage irrigation did help the yield and made up for part of the fertilization deficit. The CONTROL plots displayed identical results in both years and this indicates that the amount of irrigation water itself was not a significant factor.

The average yield of rice in the TWCF treatment in the first year and in the SWCF treatment in the second year were about 10% and 50% more than in the CONTROL, respectively. The TWCF and SWCF treatments received conventional fertilization, but differed from the CONTROL in regard to irrigation water quality. Hence, the addition of treated sewage to irrigation water increased the yield of paddy rice crops in this study.

The seed composition was analyzed for nutrients and hazardous elements to examine possible effects of treated sewage irrigation on the seed. There was an indication that seeds from

Table 4 Comparison of soil characteristics for treatment plots

Treatments*		pH (1:5)	EC (μ S/cm)	OM (%)	CEC (meq/100g)	T-N (%)	T-P (mg/kg)	AV.P_2O_5 (mg/kg)
First year								
Initial condition		5.47	54.8	0.790	8.7	0.043	672.9	541.93
TWNF	A.H.	6.02	20.7	0.890	9.1	0.047	617.0	261.11
TWCF	A.H.	6.31	17.7	0.991	11.2	0.045	702.5	280.05
TWHF	A.H.	6.34	18.7	0.840	10.6	0.043	683.4	268.10
SWNF	A.H.	6.14	18.9	0.974	12.3	0.045	609.3	303.03
Control	A.H.	6.32	20.1	1.008	11.8	0.050	693.0	283.17
Second year								
DSWNF	B.T.	6.58	31.6	0.705	9.5	0.049	652.6	280.34
	A.H.	7.58	125.7	0.840	13.3	0.050	662.1	101.32
TWCF	B.T.	6.50	26.9	0.806	15.0	0.060	742.9	283.55
	A.H.	7.64	110.0	0.806	13.6	0.050	674.1	94.19
SWHF	B.T.	6.59	22.3	0.739	15.5	0.049	693.7	304.37
	A.H.	7.41	83.7	0.873	12.8	0.046	672.0	134.42
SWCF	B.T.	6.56	20.7	0.672	13.0	0.041	664.4	325.80
	A.H.	7.88	149.0	0.974	14.5	0.053	722.5	94.59
Control	B.T.	6.45	31.2	0.605	12.0	0.048	703.7	304.11
	A.H.	6.48	25.0	0.840	10.5	0.046	638.5	152.68

*B.T.: before transplanting; A.H.: after harvesting

treatments with treated sewage irrigation showed slight increase in total nitrogen and total phosphorus concentrations. But no specific change among the treatments was observed in hazardous elements, and hazardous element accumulation in the rice may not be a concern in treated sewage irrigation.

3.3 Soil Characteristics

Soil characteristics of the experimental plots were analyzed to examine the effects of treated sewage irrigation (Table 4). The results are expressed as averages of three replicate samples per plot, taken from root zone after clearing the surface organic layer (3~20 cm below the soil surface). The pH of initial soil was slightly acidic, and it increased and became close to neutral as neutral pH irrigation water was added. The electrical conductivity (EC) after the first year experiment decreased compared to the initial condition, but it increased after the second year experiment where more treated sewage was applied (Fig. 2). This implies that continuous irrigation of treated sewage could cause salt accumulation in the soil. However, properly controlled irrigation water quality might ameliorate this problem.

The soil organic matter (OM) content was fairly constant and variation was not apparent. This indicates that the supply and decomposition of organic matter were in a close balance in the treated sewage irrigation system. Generally, the cation exchange capacity (CEC) increased slightly compared to the initial condition but no specific trend was observed. Total nitrogen (T-N) and total phosphorus (T-P) concentrations remained fairly constant during the study period, and the soil nutrient concentrations appeared to be little affected by sewage irrigation as long as it was adequately treated.

Available phosphorus decreased in all the plots including CONTROL as rice culture continued during the study period, which means that rice plants sequestered available phosphorus from the soil in the root zone. The experimental plots were made of upland soil in which paddy rice was never been cultured, and normal fertilization might not be appropriate for the initial stabilization period of the paddy rice plots. And available phosphorus might migrate downward and accumulate below the root zone because of water impoundment. Because T-P concentration was fairly constant, transformation from T-P to available phosphorus could be expected as time passes. Deep plow could be helpful for phosphorus depletion problem, but careful monitoring of long-term effect and further investigation are recommended.

4. Conclusions

Irrigation of treated sewage onto paddy rice cultures did not adversely affect the growth or yield of rice. Instead, experimental rice plots treated with sewage irrigation displayed about 10% (with sewage dilution) or 50% (without dilution) more yield on average than controls. This implies that treated sewage irrigation might be beneficial to rice culture as long as the sewage is treated adequately and used properly.

The amount of irrigation water had little effect on experimental rice cultures, but its strength (in terms of sewage content) was important. The strength of treated sewage was not a limiting factor in this study, and no lodging was observed even with a relatively high nitrogen concentration (up to 160mg/L).

In general the paddy soil was not affected by treated sewage irrigation. However, there was an indication that continuous irrigation with high strength treated sewage might cause salt accumulation in the soil. Supplemental use of treated sewage with existing sources of irrigation water is recommended rather than irrigation with a single source of treated sewage.

Overall, the results demonstrated that treated sewage could be reused as a supplemental source of irrigation water for paddy rice culture without causing adverse effects as long as it is treated adequately and used properly. For full-scale application, further investigation should be done on environmental risks, tolerable water quality, and fraction of supplemental irrigation.

Acknowledgements

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