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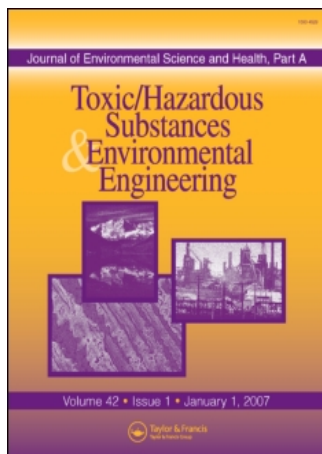
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Assessment of reclaimed wastewater irrigation impacts on water quality, soil, and rice cultivation in paddy fields

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The objective of this research was to monitor and assess the impact of reclaimed wastewater irrigation on water quality, soil, and rice cultivation by comparing the effects of various wastewater treatment levels on the growth and yield of rice. A randomized complete block design was used for the application methods of the wastewater effluents to paddy rice, with five treatments and six replications. The treatments were: control with groundwater irrigation (GW); irrigation with polluted water from a nearby stream (SW); and three treatments of reclaimed wastewater irrigation at different treatment levels. The three levels of wastewater treatments included wastewater effluents: (i) directly from the wastewater plant (WW); (ii) after passing through a sand filter (WSF); and (iii) after passing a sand filter followed by an ultraviolet treatment (WSFUV). Each plot was 4 × 4 m and was planted with rice (*Oryza sativa L.*) in 2002 and 2003. The results indicated that irrigation of rice with reclaimed municipal wastewater caused no adverse effects on the growth and yield of rice. The chemical compositions of the rice from all plots were within the normal ranges of brown rice quality in Korea. No adverse effects were observed on chemical concentrations including the heavy metals Cu, As, Cd, Zn, Hg, and Pb, in either the brown rice or the field. The results showed that treated municipal wastewater can be safely used as an alternative water source for the irrigation of rice, although continued monitoring will be needed to determine the long-term effects with regard to soil contamination and other potential health concerns.

Keywords: Wastewater reuse, irrigation, rice paddy, yield, growth.

Introduction

Farming communities in water-scarce regions increasingly utilize urban wastewater in agriculture.^[1] Reuse of reclaimed water for irrigation enhances agricultural productivity, providing water and nutrients and improving crop yields. Wastewater reuse has already been implemented in many countries. According to Scott et al.,^[2] wastewater reuse has been applied to many practical uses and research is currently being conducted in over 50 countries throughout the world. However, wastewater reuse will require attention to public health protection, appropriate wastewater treatment technology, treatment reliability, water management, and public acceptance and participation.

Although many practical uses and research of wastewater reuse are currently being conducted in over fifty countries throughout the world, most of these countries as yet

have no wastewater reuse standards and guidelines. In order to develop these standards and guidelines, various studies have been conducted on practical applications of wastewater reuse for crop irrigation. According to Cooper,^[3] an estimated 80% of wastewater in developing countries may be used for upland crop irrigation. According to previous researchers, wastewater reuse for agricultural irrigation has been applied to sunflowers,^[4] eggplants,^[5] forest land with *Eucalyptus camaldulensis* plantations,^[6] and tomatoes.^[7] However, there have been a few reports of practical wastewater reuse for rice paddies. Therefore intensive systematic experiments are required before the practical use of reclaimed wastewater for rice paddies.

Rice (*Oryza sativa L.*) is grown during the summer in the Republic of Korea on more than one million hectares (in 2003), which is more than half of the total arable farmland.^[8] Irrigation for rice paddies ranks first among water uses, requiring over 50% of the nation's total water supply. Rice paddy agricultural methods require a large quantity of water. A total of about 1250 mm is required for rice paddies during the growing season, and this water is primarily supplied by irrigation.^[9] Irrigation water

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in Korea does not need to meet the higher drinking water standards, and irrigation with adequately treated wastewater does not cause intestinal nematode infections in either farmers or consumers.^[10] However, using untreated or inadequately treated wastewater for irrigation could adversely affect the environment and, consequently, human health. No guidelines or criteria for reclaimed wastewater irrigation have yet been adopted for rice paddies in Korea. Thus, there is a need to clarify the potential effects and to develop the agricultural reuse technology available for use with municipal wastewater.

The specific objectives of this study are: (i) to conduct field experiments for rice cultivation with treated wastewater at various treatment levels; (ii) to monitor the water quality and soil contamination of the field plots throughout the crop growing cycle; and (iii) to investigate and evaluate the effects of wastewater reuse on the growth and yield of rice.

Materials and methods

Experimental design

The experimental plots are located near the Suwon wastewater treatment plant in Gyeonggi-do, Republic of Korea. In the field experiment, the randomized complete block design

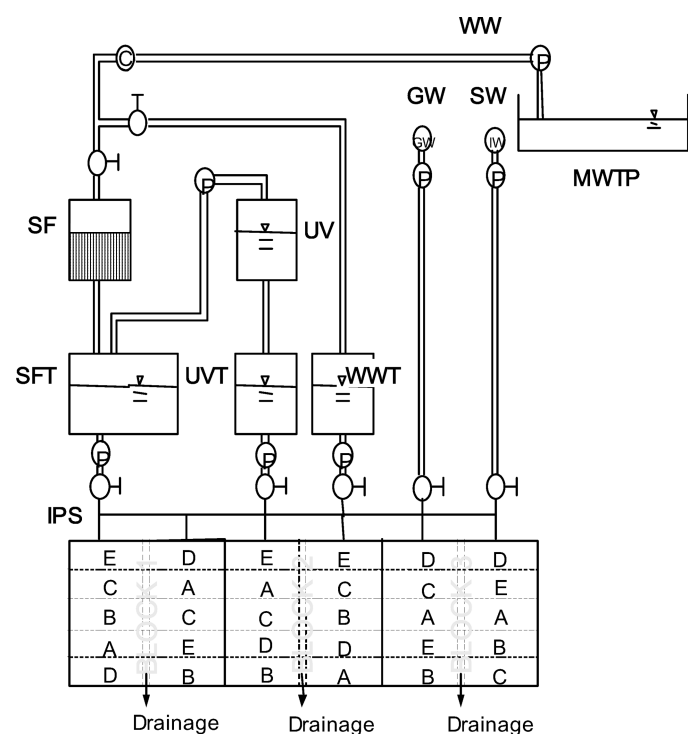


Fig. 1. Schematic diagram of the irrigation facility and experimental design. MWTP; municipal wastewater treatment plant, GW; groundwater, SW; stream water, WW; wastewater, SF; sand-filtering treatment, UV; ultraviolet treatment, WWT; wastewater storage tank, SFT; sand-filtering treatment storage tank, UVT; ultraviolet treatment storage tank, IPS; irrigation pipeline system, A, B, C, D, and E denote the field treatments.^[11]

with split plot arrangements was used with five treatments and six replications on 4 m × 4 m plots (Fig. 1). The five treatments are separated according to the irrigation water: groundwater (GW), stream water (SW), treated wastewater (WW), treated sand-filtered wastewater (WSF), and treated sand-filtered wastewater with UV treatment (WSFUV). A small scale wastewater reclamation system with a sand filter, ultraviolet treatment unit, pipelines to supply irrigation water from the wastewater effluents, and a groundwater well were installed for the experiment. The reclaimed wastewater and the field plots were monitored for soil chemical characteristics and water quality throughout the crop growth cycle. The Gicheon rice paddy field near the experimental plots irrigated from the nearby stream water (SW) was selected as the control in order to compare the test plots with traditionally cultivated rice.

Monitoring and data analysis

A total of 30 test plots, each with plot size of 16 m² (4 m × 4 m), were planted with *Sim-Chu-Chung* rice seedlings. The field plots were prepared by plowing and applying basal fertilization prior to rice transplanting. The seedlings were transplanted manually at 0.25 m × 0.18 m spacing on May 22 in 2002 and May 24 in 2003. Basal fertilization was applied during the field plowing of each season. Nitrogen (N) and phosphorus (P) were applied at an average rate of 44 kg ha⁻¹ and 35 kg ha⁻¹, respectively. Insecticides were sprayed on June 23, 2002 in order to exterminate rice water weevils (*Lissorhptus oryzoophilus* Kuschel), and weeds were controlled manually. Rice was hand-harvested on October 30, 2002 and October 31, 2003. Rainfalls during the growing period (April to September) were 1057.3 mm in 2002 and 1333.6 mm in 2003. The amount of irrigation water used in each plot was 983.6 mm in 2002 and 754.7 mm in 2003.

The water quality, soil, plants, and health hazards of experiment plots were monitored. Water samples of effluent and ponding water were collected at a 2-week interval during the growth period. The water quality of effluent from Suwon municipal wastewater plant, an activated sludge aeration plant, was also monitored and analyzed (Table 1). The monitored values in 2002 and 2003 satisfied all the effluent criteria of the Republic of Korea. The soil in the

Table 1. The yearly average quality of the effluent from the Suwon municipal wastewater treatment plant

Item	BOD (mg L ⁻¹)	COD (mg L ⁻¹)	SS (mg L ⁻¹)	TN (mg L ⁻¹)	TP (mg L ⁻¹)
Effluent criteria*	≤20	≤40	≤20	≤60	≤8
2002	13.2	11.8	8.3	19.1	1.5
2003	12.8	11.4	9.2	22.5	1.63

*Effluent criteria from the municipal wastewater treatment plant of Republic of Korea.^[11]

plots was sandy loam, which is a representative soil for rice paddies in Korea. Soil samples were collected once a month from 0–20 cm depth from each plot for chemical analysis. All soil sampling was performed with a 7.63 cm diameter soil bucket auger and air dried after the sampling. The hand-harvested rice and rice plants were transported immediately to a laboratory for physical and chemical analysis. Standard laboratory methods were used for the analysis.^[12–14]

The results from this study were compared to data from previous research and to reuse criteria of major countries. For the comparisons, reuse criteria from the United State and Tunisia were used for the chemical characteristics of water quality. For yield data, the criteria from the Korea Ministry of Agriculture and Forestry^[8] were used for rice yields, chemical compositions, and hazardous components for brown rice quality.

Statistical analysis

In this study, analyses of variance (ANOVA) was used to compare the treatments. If significant differences were found among the treatments, Least Significant Difference (LSD) and Duncan's Multiple Range Test (DMRT DMRT) were used for multiple comparisons to separate the differences. That is, LSD was applied to compare treatment means for each of the three treatments (WW, WSF, and WSFUV) to the control plots (GW). DMRT was used to assess the total treatment effect and to compare all pos-

sible difference between means when they were ranked in the order of magnitude. LSD and DMRT have traditionally been performed in the field of Botany by previous researchers.^[15,16]

Results and discussion

Water quality

The effects of various levels of wastewater treatment on ponding and effluent paddy water were investigated. The monitored results were compared with the published reuse criteria of wastewater for agricultural irrigation (Table 2). Overall the GW treatment showed lowest values in TN and TP. The heavy metal content of the effluent water was hardly detectable except for zinc. Cations in the effluent water appeared the lowest in GW, but with similar low values in other treatments. Chemical components of the ponding and effluent water in all treatments did not exceed the reuse criteria for irrigation water quality. The reuse criteria for TP and K were not available.

Soil characteristics

The effects of various levels of wastewater treatment on paddy soil were investigated. Figure 2 illustrates the monitored results for EC, TN, TP, and organic matter. During the two growing seasons, the soil electrical conductivity (EC) of the studied wastewater treatment levels ranged

Table 2. Chemical characteristics of the effluent and ponding water and the reuse criteria for wastewater as an irrigation source

Treatment	pH	EC ($\mu\text{S cm}^{-1}$)	(mg L ⁻¹)								
			TN	TP	SS	COD	Cu	Zn	Pb	Cd	K
GW											
Effluent ⁽¹⁾	7.26	294.3	1.0	0.21	40.1	7.4	0.0058	0.1665	0.0020	0.0000	5.73
Ponding ⁽²⁾	6.76	154.8	1.8	0.26	228.4	19.3	0.0060	0.2783	0.0069	0.0007	6.39
SW											
Effluent	7.01	444.9	10.1	1.36	88.5	14.0	0.0060	0.1671	0.0015	0.0000	13.12
Ponding	6.71	295.4	8.4	0.87	260.2	26.8	0.0098	0.3118	0.0088	0.0006	11.91
WW											
Effluent	7.24	469.2	13.6	1.08	34.4	9.4	0.0060	0.2193	0.0007	0.0000	15.51
Ponding	6.69	294.3	6.3	0.65	199.9	18.1	0.0049	0.1967	0.0047	0.0004	12.95
WSF											
Effluent	7.26	464.8	14.7	1.30	29.9	9.3	0.0065	0.1633	0.0011	0.0000	16.10
Ponding	6.64	272.6	6.4	0.65	384.8	23.3	0.0052	0.2639	0.0048	0.0004	11.11
WSFUV											
Effluent	7.30	461.3	13.4	1.03	27.0	9.9	0.0060	0.2212	0.0011	0.0000	16.36
Ponding	6.99	292.4	5.5	0.62	345.5	18.8	0.0121	0.1500	0.0061	0.0004	9.43
Reuse Criteria ^[17,18]	6.5–8.5	<7000	<30	NA	NA	90.0	0.2	2.5	5	0.01	NA

GW; groundwater, SW; stream water, WW; reclaimed wastewater, WSF; sand-filtered reclaimed wastewater, WSFUV; sand-filtered and ultraviolet treated reclaimed wastewater.

NA: not applicable.

⁽¹⁾Means are the average of 12 samples for each treatment plot.

⁽²⁾Means are the average of 16 samples for each treatment plot.

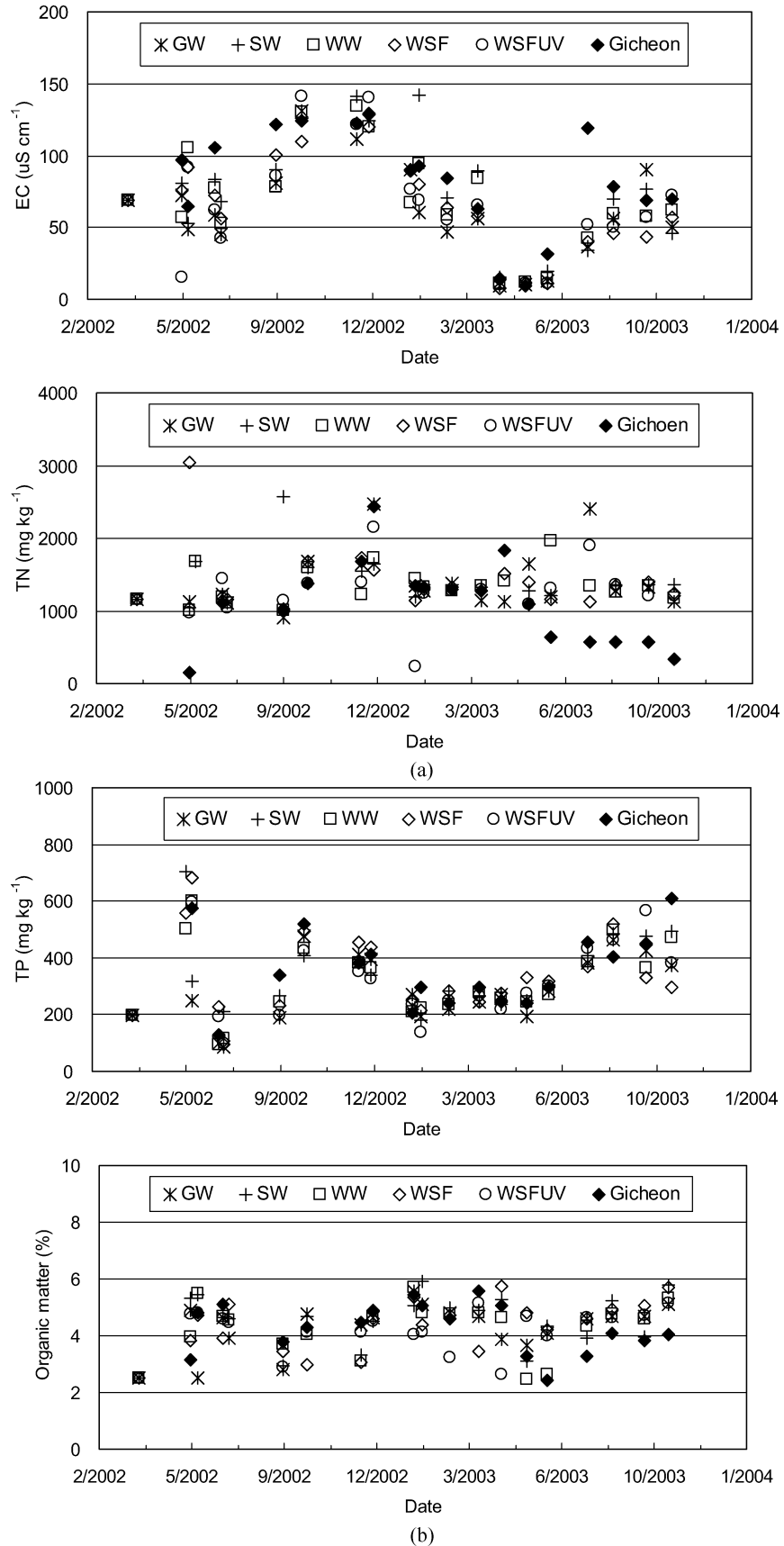


Fig. 2. Changes in the chemical characteristics of the soil during the experimental period. GW; groundwater, SW; stream water, WW; reclaimed wastewater, WSF; sand-filtered reclaimed wastewater, WSFUV; sand-filtered and ultraviolet-treated reclaimed wastewater.

from 8 to 142 $\mu\text{S cm}^{-1}$. The EC gradually increased after the transplanting in each year. The EC values of the GW plots were maintained at a relatively low level compared with that of other treatments due to the low EC values of the GW effluent (see Table 2). Total soil N also increased in the spring of each year in all plots, but declined to the levels of the fallowed plots by the fall of each year (Fig. 2). No variations of total soil N and P were apparent. The soil organic matter (SOM) content increased after rice cultivation for all treatments, but no specific trend was observed. The primary results indicated that rice cultivation with reclaimed wastewater irrigation did not cause adverse effects to the rice paddy soil.

Plant growth and yield

The plots were monitored for the following plant growth components: culm length (CL); panicle length (PL); panicle number per unit area (PU); mean number of spikelets per panicle (MS); thousand grain weight (TW); and percentage of ripened grains (PG). The rice yield (YD) for the harvested rice was also monitored. These components among the treatments were analyzed by ANOVA with LSD and DMRT.

Table 3 illustrates the average plant growth components and rice yield among the treatments during the experimental period. The national average rice yield in Korea was 4710 kg ha^{-1} in 2002 (the first year of the experiment) and 4410 kg ha^{-1} in 2003 (the second year of the experiment).^[8] Rice yield were the highest in the SW plots followed by WSF,

WW, WSFUV, and GW during the first year. There was also a statistically significant increase in rice yields from all wastewater reuse plots compared to the yields from the control plots (GW) in the first and second years. In the second year, average rice yields for all treatments decreased by approximately 28% from the yields of the first year. These trends in plant components and rice yield are probably related to the lack of sunshine hours caused by the frequent and heavy rainfall events during the second year of the study. The rice yield was significantly higher in the treated wastewater with sand-filtering and UV treatment (WSFUV).

DMRT was conducted in order to compare the treatment means at the 5% significance level (Table 3). According to DMRT, rice yields for the SW and WSF treatments were significantly higher than those for the GW treatment. The average rice yields for the WW treatments were approximately 35% and 55% more than those of the GW treatment for 2002 and 2003, respectively.

Brown rice quality

The chemical components of the harvested brown rice from the different treatments are shown in Table 4. Nutrients (TN and TP), the available cations (Na, K, Ca, and Mg), and the heavy metal content of the brown rice in all the plots and the nearby conventional cultivation paddy field (Gicheon) were analyzed. Chemical compositions and hazardous components for brown rice are not specifically prescribed in the Korean Food Code.^[19] However, most of the

Table 3. The plant components and rice yields of 30 rice plant samples for each treatment and the significance level within the treatments computed by LSD and DMRT

Treatment	PL (cm)	CL (cm)	PU (ea)	MS (ea)	TW (g)	PG (%)	YD (kg ha^{-1})
1st year							
GW	21.5 b ⁽¹⁾	70.5 c	8.7 a	75.6 a	22.3 b	93.5 ab	4594 c
SW	22.7*ab	83.6*a	8.8 a	92.1* a	22.3 b	92.6 ab	6219* a
WW	23.4*a	79.8* ab	8.9 a	87.0 a	22.4 ab	91.5 b	5302 bc
WSF	22.4 ab	81.3* ab	8.8 a	83.5 a	23.7* a	94.0 a	5573* ab
WSFUV	22.0 ab	73.4 c	8.7 a	81.7 a	22.3 b	92.7 ab	5281 bc
LSD (0.05)	1.15	4.37	1.04	15.59	1.15	19.4	726
2nd year							
GW	20.9 d	83.3 d	8.2 a	65.9 d	24.0 b	91.8 abc	2392 d
SW	24.6* abc	99.1* bc	8.8 a	87.8* abc	25.0* a	92.2 ab	3706* bc
WW	25.3* ab	106.9* a	8.4 a	88.3* abc	24.1 b	88.1 d	4084* bc
WSF	25.0* abc	102.7* ab	9.1 a	98.9* ab	22.9 c	90.8 bc	4391* ab
WSFUV	26.0* a	100.2* bc	8.9 a	100.5* a	25.0* a	93.3* a	4806* a
LSD (0.05)	1.86	5.72	0.96	11.4	0.69	1.46	810

GW; groundwater, SW; stream water, WW; reclaimed wastewater, WSF; sand-filtered reclaimed wastewater, WSFUV; sand-filtered and ultraviolet treated reclaimed wastewater.

CL-culm length; PL-panicle length; PU-panicle number per unit area; MS-mean number of spikelets per panicle; TW-thousand grain weight; PG-percentage of ripened grains; YD-and yields.

⁽¹⁾Arithmetic means with the same letter are not significantly different from each other at the 5% probability level by DMRT.

* Denotes significance at the 5% probability level.

Table 4. The chemical components of brown rice for thirty rice plant samples per treatment (unit; mg kg⁻¹)

Treatment	TP	TN	Na	Ca	Mg	K	Cu	As	Cd	Zn	Mn	Hg	Pb
Control*	1206.5	3808.0	87.0	60.0	405.0	2415.0	0.00	3.20	0.30	10.30	83.65	1.30	1.85
1st year													
GW	2283.9	4109.0	57.8	58.2	588.3	2296.7	0.53	3.18	0.44	16.55	68.57	2.14	0.42
SW	2180.2	2536.3	38.3	54.8	521.7	2168.3	2.39	2.95	0.45	13.63	65.49	1.48	0.69
WW	2302.2	2858.3	49.8	54.6	567.5	2201.7	1.98	3.33	0.45	15.01	70.50	1.59	0.44
WSF	1850.6	3516.3	37.2	75.1	637.5	2197.5	0.13	4.16	0.43	13.79	71.02	1.72	0.75
WSFUV	2416.2	2905.0	52.3	56.5	593.3	2236.7	2.62	3.21	0.46	15.08	67.79	1.58	0.29
2nd year													
GW	2058.5	3670.6	83.0	67.3	610.3	2028.4	0.45	3.59	0.35	18.28	61.19	1.56	0.23
SW	2183.8	3339.3	69.9	80.4	680.8	2008.4	1.21	2.77	0.23	19.06	68.99	1.36	0.45
WW	2322.2	2947.2	73.1	80.1	611.8	2305.3	1.89	2.65	0.31	15.30	62.74	1.20	0.25
WSF	2162.4	2941.1	74.5	72.9	606.5	2326.8	2.02	2.70	0.48	18.01	54.81	1.44	0.14
WSFUV	2164.7	3035.0	70.8	83.3	666.5	2020.0	1.87	2.19	0.40	15.75	65.32	1.14	0.25

GW; groundwater, SW; stream water, WW; reclaimed wastewater, WSF; sand-filtered reclaimed wastewater, WSFUV; sand-filtered and ultraviolet treated reclaimed wastewater.

*Conventional cultivation.

chemical composition concentrations in the rice from all the plots were within the normal range for brown rice from the conventional cultivation paddy (Gicheon) in Korea. The concentrations of heavy metals (Cu and Zn) for brown rice from the wastewater reuse plots were slightly higher than those found in samples from the conventional cultivation paddy. However, in terms of the chemical components of the brown rice, there were no adverse effects observed due to the use of reclaimed water for irrigating on the rice.

Conclusion

This research evaluated the effects of using treated wastewater for irrigation of rice paddies. The results showed that using treated wastewater from municipal wastewater treatment plants to irrigate rice paddies present no environmental, food safety, or human health risks. Based on our analysis using ANOVA and DMRT, the rice yields for the SW and WSF treatments in 2002 and all the treatments in 2003 were significantly higher than those for the GW treatment at the 5% significance level. In the second year, average rice yields from all treatments decreased by 28% compared to yields from the first year. This was probably due to the shortage of sunshine hours caused by the frequent heavy rainfall events during the second year. The average yields of rice from the WW plot were 35% greater for the first year and 55% greater for the second year than the plots irrigated with GW alone.

Based on the chemical characteristics of the harvested brown rice, there were no adverse effects observed due to the rice irrigation with treated wastewater compared with the characteristics of the conventionally irrigated rice. This implies that treated wastewater may be considered a practical alternative source for rice irrigation. However, a long-term investigation of the soil environment is needed because

continuous irrigation with high levels of reclaimed water is likely to increase the salt accumulation in the soil.

Plant growth and rice yield monitoring results indicated that cultivated rice with treated wastewater irrigation showed no adverse effects in terms of the crop growth and yields. Treated municipal wastewater contains significant amounts of nutrients that can benefit plant growth and reduce the quantity of mineral fertilizers that need to be applied.^[20–25] In certain instances, however, the nutrients in wastewater are in excess of actual plant needs and may cause excessive vegetative growth, delayed or uneven maturity, or even reduced quality.^[26,27] Further research is required to investigate the proper fertilization amount in reclaimed wastewater irrigation.

In general, this study showed that irrigation with reclaimed wastewater is potentially safe for rice cultivation, although long-term monitoring is needed to determine its effects on soil characteristics and health risks. As droughts and population increases continue to place considerable stress on the availability of fresh water supplies, reuse of municipal wastewater will play an ever-increasing role in helping to meet future water demands.

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