Environmental effects analysis of a wastewater reuse system for agriculture in Korea
Tae Il Jang, Seung Woo Park and Hak Kwan Kim

ABSTRACT

The long-term goal of this research is to develop the infra-technologies to reclaim effluents from wastewater treatment plants and reuse them for agricultural water demands. The objectives of this were: 1) to study the effects of various wastewater treatment levels on crop growth and yields; 2) to determine the pollution loads from wastewater applications to paddy fields, and explore potential health hazards; 3) to investigate the treatment efficiencies of three different levels of treatment systems; and 4) to assess the agro-environmental effects of reusable wastewater resources. Wastewater reuse systems can be greatly beneficial for irrigating crops and improving river water quality. Field experiments for cultivating rice with reclaimed wastewater were carried out on the test plots. The effects of various wastewater treatment levels on water quality, paddy soil, crop growth, yields, and the health hazards were investigated.

Key words | crop growth, fecal coliform, irrigation, water quality, wastewater reuse

INTRODUCTION

Many countries presently face water shortages or will experience scarcity in the future because of increasing demand for fresh water (IWMI 2002). The Republic of Korea (ROK) suffers from a limited agricultural water supply because of population growth, urbanization, and economic development. Wastewater reuse has been recommended as an alternative solution, since irrigation water does not usually require the high grade water quality as drinking water (Cooper 1991). Paddy rice production requires a large volume of water. The fields are flooded before plowing and the water level is kept at 4 to 6 cm in shallow rice fields and as high as 10 cm in continuous flooding irrigation during the growing season. Agricultural irrigation is allocated upwards of 48% of the total annual water use in Korea.

Wastewater reuse has already been implemented in many countries. According to Scott et al. (2001), wastewater is currently reused in a variety of applications in over fifty countries throughout the world. At the same time, wastewater reuse requires attention to public health protection, appropriate wastewater treatment technology, treatment reliability, water management, and public acceptance and participation (Kang et al. 2004). Guidelines for reclaimed wastewater irrigation have been adopted for rice paddies in Korea (MOE 2005). As a result, there is more data to help clarify potential human health problems and assess the environmental effects associated with the application of wastewater reuse systems to rice paddy fields.

The specific objectives of this study were: 1) to study the effects of various wastewater treatment levels on crop growth and yields, 2) to determine the pollution loads from wastewater applications to paddy fields and explore the health hazards, 3) to investigate the treatment efficiencies at three different levels of treatment systems, and 4) to assess the agro-environmental effects of reusable wastewater resources.
MATERIALS AND METHODS

Study area

The experimental plots were located near the Suwon wastewater treatment plant in Gyeonggi-do, ROK. A randomized complete block design with split plot arrangements was used with three treatments and four replicates on 5 m × 5 m plots (Figure 1). The three treatments were separated according to the irrigation water: groundwater (TR#1), wastewater (TR#2), and filtered wastewater with UV treatment (TR#3). A small scale wastewater reclamation system with a sand filter, ultra-violet treatment unit, pipelines to supply irrigation water from the wastewater effluents, and a groundwater well was installed for the experiment.

Water samples were collected monthly at the stream flow gauging station. Irrigation and drainage were measured using stage gauges. Irrigation and ponded water samples, soil, plants, and evidence of potential health hazards on the experimental plots were collected on a weekly or biweekly basis. Rainfall samples were collected when storms occurred.

For this experiment, 1-month-old rice seedlings were transplanted in May and harvested in September. Fertilizers were applied three times during the pre-plant, tillering, and panicle growing stages according to the traditional cultivation method.

Analysis methods

The water quality of effluent from the Suwon municipal wastewater plant, an activated sludge aeration plant, was monitored and analyzed. The monitored values in 2002 and 2006 satisfied all effluent criteria of Korea. The soil in the plots was sandy loam, which is a representative soil of rice paddies in Korea. Soil samples were collected once a month from 0–20 cm deep from each plot for chemical analysis. All soil sampling was performed with a 7.63 cm diameter soil bucket auger and samples were air dried after collection. 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 (Chapman & Pratt 1961; APHA 1995).

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

Figure 1 | The study site and field experiments.
Ministry of Agriculture and Forestry (MOAF 2004) were used for rice yields, chemical compositions, and hazardous components for brown rice quality.

## RESULTS AND DISCUSSION

### Effluent irrigation water

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 (Westcot & Ayers 1985; Angelakis et al. 1999). Overall, TR#1 treatment had the lowest values of TN (Total Nitrogen) and TP (Total Phosphorus). The heavy metal content of the effluent water was hardly detectable except for zinc. Cations in the effluent water appeared the lowest in TR#1, but were also low in other treatments. Chemical components of the ponding and effluent water in all treatments did not exceed the reuse criteria for irrigation water quality.

Water quality of the runoff from paddies was found to improve along watercourses to streams. Field data showed that the concentration of soluble nutrient constituents was significantly reduced by the natural purification resulting from biological activities. TN effluent concentrations of TR#3 ranged from 6.8 to 20.2 mg/L over 5 years, while compared to 4.87 – 11.6 mg/L at the ponding paddy fields. The average reduction rate of TN in TR#3 was 55.7%. However, the average reduction rate of TN in TR#1 was –21.7%.

### Soil characteristics

The effects of various levels of wastewater treatment on paddy soil were investigated. During the five growing seasons, the soil electrical conductivity (EC) of TR#3 ranged from 72.1 to 375.3 μS cm⁻¹. The EC gradually increased after the transplanting in each year. The EC values of TR#1 were maintained at a relatively low level compared with that of other treatments due to the low EC values of the TR#1 effluent (see Table 1). Total soil nitrogen (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. No variations of total soil N and phosphorus (P) were apparent. The soil organic matter (SOM) content increased after rice cultivation for all treatments, but no specific trend was observed. However, a high concentration of sodium in wastewater might cause damage the physico-chemical properties of paddy soil, and a long-term investigation of the soil environment is needed. In this study, the soil sodium concentration of TR#3 stabilized gradually from 101.2 to 46.2 mg/kg over 5 years.

### Plant quality, yields and health risk analysis

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) of the harvested rice was also monitored. These components among the

### Table 1 | Chemical characteristics of the effluent and ponded water and the reuse criteria for wastewater as an irrigation source from 2002 to 2006

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH</th>
<th>EC (μS cm⁻¹)</th>
<th>TN (mg L⁻¹)</th>
<th>TP (mg L⁻¹)</th>
<th>SS (mg L⁻¹)</th>
<th>COD (mg L⁻¹)</th>
<th>Cu (mg L⁻¹)</th>
<th>Zn (mg L⁻¹)</th>
<th>Pb (mg L⁻¹)</th>
<th>Cd (mg L⁻¹)</th>
<th>K (mg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR#1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effluent*</td>
<td>6.64</td>
<td>319.4</td>
<td>2.1</td>
<td>0.14</td>
<td>57.0</td>
<td>8.7</td>
<td>0.64</td>
<td>0.60</td>
<td>0.0094</td>
<td>0.0005</td>
<td>3.8</td>
</tr>
<tr>
<td>Ponding†</td>
<td>6.80</td>
<td>193.5</td>
<td>2.6</td>
<td>0.28</td>
<td>182.5</td>
<td>20.4</td>
<td>0.50</td>
<td>0.26</td>
<td>0.0064</td>
<td>0.0005</td>
<td>4.9</td>
</tr>
<tr>
<td>TR#2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Effluent</td>
<td>6.98</td>
<td>532.1</td>
<td>13.9</td>
<td>0.72</td>
<td>49.0</td>
<td>16.0</td>
<td>0.56</td>
<td>0.52</td>
<td>0.0133</td>
<td>0.0006</td>
<td>13.3</td>
</tr>
<tr>
<td>Ponding</td>
<td>6.70</td>
<td>326.1</td>
<td>6.0</td>
<td>0.54</td>
<td>209.0</td>
<td>35.3</td>
<td>0.52</td>
<td>0.18</td>
<td>0.0054</td>
<td>0.0002</td>
<td>9.9</td>
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<tr>
<td>TR#3</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Effluent</td>
<td>7.06</td>
<td>536.7</td>
<td>13.8</td>
<td>0.70</td>
<td>28.7</td>
<td>14.4</td>
<td>0.50</td>
<td>0.62</td>
<td>0.0112</td>
<td>0.0003</td>
<td>13.7</td>
</tr>
<tr>
<td>Ponding</td>
<td>6.80</td>
<td>309.4</td>
<td>6.4</td>
<td>0.48</td>
<td>378.8</td>
<td>41.1</td>
<td>0.46</td>
<td>0.20</td>
<td>0.0052</td>
<td>0.0003</td>
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</tr>
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<td>Reuse Criteria</td>
<td>6.5–8.5</td>
<td>&lt;7000</td>
<td>&lt;30</td>
<td>NA</td>
<td>NA</td>
<td>90.0</td>
<td>0.2</td>
<td>2.5</td>
<td>5</td>
<td>0.01</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA: not applicable.

*Mean of each chemical characteristic of effluent water for each treatment plot from 2002 to 2006.
†Mean of each chemical characteristic of ponded water for each treatment plot from 2002 to 2006.
treatments were analyzed by ANOVA (Analysis of Variance) with LSD (Least Significant Difference) and DMRT (Duncan’s Multiple Range Test). ANOVA tests showed that the yields were statistically significant \( p < 0.05 \) among TR#1, TR#2, and TR#3. This finding implies that wastewater reuses could be used as a practical alternative measure for reclaimed wastewater irrigation.

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 were analyzed. Chemical composition and hazardous components for brown rice are not specifically prescribed in the Korean Food Code (KFDA 2003). However, most of the chemical concentrations in the rice from all the experimental plots were within the normal range for brown rice from the conventionally cultivated paddy (Gicheon). The concentrations of heavy metals (Cu and Zn) from brown rice from the wastewater reuse plots were slightly higher than those found in samples from the conventional cultivated 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.

The national average YD in Korea was about 4,500 kg ha\(^{-1}\). TR#2 and TR#3 appear to be nearly identical on average and in all years except 2003 and 2006, when TP#2 appears better (Figure 2). The average YD for the TR#3 (5,594 kg ha\(^{-1}\)) treatments was approximately 40.5% more than that of the TR#1. These trends are probably related to the irrigation water temperature.

The presence of endocrine-disrupting chemicals in the effluent water and brown rice in all the plots was analyzed. Endocrine-disrupting chemical concentrations in the brown rice form all the plots were present in negligible quantities in the wastewater derived irrigation water.

Microbial risk was quantified to assess the human health risk as a result of exposure to \textit{E. coli} in reclaimed wastewater irrigation. The Beta-Poisson model (Haas et al. 1993) was used to estimate the microbial risk of pathogen ingestion among farmers and neighboring children. TR#3 had a lower risk value than TR#2, and its level was within the range of the actual paddy rice field with surface water. This microbial risk assessment should be viewed as a first step in the application of wastewater reuse in paddy rice culture.

Environmental assessment system for watershed scale

Nonpoint source (NPS) pollutant loading and transport at paddy fields were not adequately depicted in the environmental assessment models that were applied. Therefore, a separate sub-model should be incorporated to accurately simulate the environmental assessment processes in a field or watershed scale model.

Study area for watershed environmental assessment

The Baran watershed (2,979 ha) is located next to a suburb of the city of Suwon, located approximately 6 km northeast of the Byounggem paddy field (Figure 1). Most of the paddy fields located in the Baran watershed’s low-slope farming zones receive irrigation water from either the Gicheon or Baran irrigation reservoirs. An extensive hydrologic and water quality monitoring system has been established in the Baran watershed since 1996.

The study watershed (385 ha) is located in the upstream of gauging station HP#6. Geomorphological characteristics of stream length, slope, maximum relief, and shape of coefficient of the watershed were 3.1 km, 1.493 m km\(^{-1}\), 246 m, and 1.56, respectively. The Gicheon rice paddy field plots, which were irrigated from the nearby stream water and satisfy agricultural water criteria of Korea, were selected as the control in order to compare the experimental plots with traditionally cultivated rice.

Meteorological data were obtained from a Suwon national weather station located approximately 8 km northeast of the study watershed. Hourly pan-evaporation, temperature, wind-speed, and solar radiation, and daily dew point and cloud cover were available from 1996 to 2006.
On-site hourly rainfall data were obtained from a tipping bucket type rain gauge. Stream flow data were collected at the outlet of the study watershed. Stage data were collected using a pressure transducer coupled with an automated data logger and stage-discharge relationships were updated with field observations annually.

Paddy modeling

Unlike unirrigated farming, the dynamics of pollutants in a paddy fields involves more complex transport processes because of the flooding conditions. Some water is consumed by crop uptake, some percolates to the soil mass, and the rest drains. Thus, more comprehensive modeling is needed to reflect the transport processes in paddy fields.

A mathematical model was derived to depict the mass balance of nitrogen and phosphorus. It was then incorporated to CREAMS, while retaining other features in the original form. The resulting model, named CREAMS–PADDY (Chin et al. 2002), was validated reasonably well with field data at test plots. An example of the simulated total nitrogen is shown in Figure 3. The results from CREAMS–PADDY were used to determine input parameters for other NPS models.

Coliform modeling

Effluents from domestic sewage and livestock wastes often contain coliform bacilli, and may present serious health-related problems. In some cases, coliform concentrations may be a limiting factor for water use. Though not at a significantly high level, coliform was detected in irrigation water and in water at paddy fields in the study sites. Coliform concentrations were related to time and water temperature. A first-order decay function was found to be applicable to the fates of coliform at paddy fields. Figure 4 compares simulated and observed coliform concentrations at the wastewater reuse test plots.

Watershed modeling

The simulated daily TN concentrations from HSPF (Hydrologic Simulation Program–Fortran) as compared to the observed data at HP#6 (Kim 2004) are shown in Figure 5. The simulated values were found to be within an order of magnitude difference as compared to the observed data. Similar degrees of success were observed in other NPS model validations as well.

Watershed environmental assessments

The results from this watershed project demonstrate that a sound and sustainable agroecosystem should be assessed using more comprehensive indicators. The insect populations changed drastically with the applications of agricultural chemicals. The selected bioindicator, a spider species, showed an interesting response to the effluent water characteristics of the sampling sites. By 2006, wastewater irrigated plots influenced not only insect and spider community structure but also species distribution patterns. However, the occurrence density of chironomidae (non-pest) was affected by the high organic matter contents in the treatment sites. In addition, high organic matter contents increased pest biodiversity but decreased natural enemy and non-pest biodiversity.
Watershed environments may be better evaluated using a well-planned water quality and biological sampling program. Water quality data can be a good indicator of aquatic health, but sometimes fail to reflect the sustainability of agricultural management. Water quality of streams in a watershed is affected by other sources in addition to agricultural practices. Thus, more comprehensive, interdisciplinary watershed monitoring programs that combine water quality and biological sampling and analyses are needed to better assess watershed environments.

CONCLUSIONS

This research found that using treated wastewater to irrigate rice paddies presented no environmental, food safety, or human health risks.

Based on the chemical characteristics of the harvested brown rice, there were no adverse effects due to the rice irrigation with treated wastewater compared with conventionally irrigated rice. This finding implies that treated wastewater may be considered a practical alternative source for rice irrigation. Plant growth, rice yield, health risks, and bioindicator monitoring results demonstrated that crop growth and yields of rice irrigated with treated wastewater were not adversely impacted.

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 growth continue to place considerable stress on the availability of fresh water supplies, reuse of municipal wastewater will play an ever-increasing role in meeting future water demands.

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REFERENCES


