Nitrogen removal and power generation from treated municipal wastewater by its circulated irrigation for resource-saving rice cultivation

Toru Watanabe, Takuma Mashiko, Rizki Maftukhah, Nobuo Kaku, Dong Duy Pham and Hiroaki Ito

ABSTRACT

This study aims at improving the performance of the cultivating system of rice for animal feed with circulated irrigation of treated municipal wastewater by applying a larger amount of wastewater, as well as adding a microbial fuel cell (MFC) to the system. The results of bench-scale experiments indicate that this modification has increased the rice yield, achieving the target for the rice cultivar used in the experiment. In addition, an assessment of protein content of the harvested rice showed that the value of the rice as animal fodder has improved. Compared with normal one-way irrigation, circulated irrigation significantly enhanced the plant growth and rice production. The direction of the irrigation (bottom-to-top or top-to-bottom) in the soil layer had no significant effect. This modified system demonstrated >96% for nitrogen removal from the treated wastewater used for the irrigation, with approximately 40% of the nitrogen being used for rice plant growth. The MFC installed in the system facilitated power generation comparable with that reported for normal paddy fields. The power generation appeared to be enhanced by bottom-to-top irrigation, which could provide organic-rich treated wastewater directly to the bacterial community living on the anode of the MFC set in the soil layer.

Key words | circulated irrigation, microbial fuel cell, municipal wastewater, nitrogen removal, power generation, rice fodder

ABBREVIATIONS

DO | dissolved oxygen  
EC | electrical conductivity  
MFCs | microbial fuel cells  
MSD | midsummer drainage  
ORP | oxidation-reduction potential  
SPAD | soil plant analysis development  
TN | total nitrogen  
TOC | total organic carbon

INTRODUCTION

In many areas worldwide, it has been recognized that urban wastewater is an important water resource. In addition, as wastewater is rich in the nutrients needed for plant growth, it is ideal for agricultural irrigation (Chung et al. 2011; Norton-Brandão et al. 2013). Reusing wastewater for agricultural irrigation brings about major economic, environmental, and social benefits, as water and nutrients are supplied simultaneously for crop production (Mateo-Sagasta et al. 2013), thereby reducing the need for and the cost of added fertilizer. In addition, the discharge of pollutants to surface water bodies (Jiménez 2006) is avoided. On the other hand, municipal wastewater could have undesirable contents, such as inorganic matters, toxic chemicals, and pathogens that could pose health risks to the consumers and farmers (Singh et al. 2010; Hanjra et al. 2012).

Rice is a major food crop worldwide, especially in Asia and Africa (Chapagain & Hoekstra 2010); however, the cultivation of paddy rice consumes significant volumes of water (Muramatsu et al. 2014). As rice plants grow by consuming...
nutrients in the treated wastewater used for irrigation, the simultaneous removal of nutrients from the wastewater is expected (Xu et al. 2009). In addition, the nitrogen in the irrigation wastewater can be removed by the activities of bacteria, i.e. nitrification and denitrification, in the paddy soils.

The reclamation of untreated or treated wastewater for rice production has been widely examined over the last decade. Laboratory-scale, pilot, and field research on reclaimed wastewater has been conducted to assess the associated financial benefits (Papadopoulos et al. 2009), health risks (Trang et al. 2006, 2007; An et al. 2007; Rhee et al. 2011), contaminants in brown rice (Chung et al. 2011), and the changes in the characteristic of the paddy soil (Yoon et al. 2001). As such a study, we have recently designed a new cultivation system that uses circulated irrigation to remove the nitrogen from the treated wastewater effectively (Muramatsu et al. 2014). We conducted a bench-scale experiment over two farming seasons, successfully demonstrating the feasibility of the system to remove nitrogen from reused wastewater, with efficiency higher than 95%, without the accumulation of harmful metals in the rice and paddy soil. However, based on the standards of practice in normal paddy fields, the nitrogen supply for this system was probably excessive, resulting in rice plant overgrowth, which could cause plant lodging, and reduced eating quality of rice.

Subsequently, we modified the system to cultivate rice for animal feed rather than for human consumption, as the rice cultivars used for animal feed have several advantages compared with those used for human consumption (Muramatsu et al. 2015). These advantages include higher crop yield and plant resistance to lodging. Moreover, the high protein content in this rice, which results from the adsorption of excess nitrogen, is preferable for animal feed, but leads to low quality rice for human consumption. We expect our modified system to contribute to an improvement in the quality of treated municipal wastewater. In addition, it is expected to promote water and nitrogen circulation among urban dwellers who consume animal products and produce wastewater, farmers who produce rice for animal food by reusing treated wastewater, and livestock farmers who use the cultivated rice as fodder for the animals. The bench-scale experiment revealed that our modified system could remove three times the amount of nitrogen from the treated wastewater compared with the system of rice cultivation for human consumption. In addition, the experiment showed that the circulated irrigation increased the nitrogen released to the atmosphere, probably because of enhanced denitrification. On the other hand, the rice yield of this system was not comparable to the target value of the normal paddy fields. Consequently, as a measure to increase the yield, and in view of the significant amount of nitrogen released to the atmosphere, a larger volume of treated wastewater needed to be applied to the system.

The aim of this study was to improve the performance of our system, in terms of yield and the quality of the harvested rice for animal feed, by increasing the volume of treated wastewater used for irrigation in comparison with the previous study (Muramatsu et al. 2015). In addition, we attempted to generate power in our system by applying microbial fuel cells (MFCs). MFCs use the power of respiring microorganisms to recover electricity from organic matters (Kouzuma et al. 2014). MFCs have been applied to wastes (Logan et al. 2005; Oh & Logan 2005; Wang et al. 2008; Behera et al. 2010), marine and river bed sediments (Tender et al. 2002; Reimers et al. 2006), and in wetlands (Ciria et al. 2005; Wang et al. 2012; Liu et al. 2013). In a flooded paddy field, a community of anaerobic microorganisms is formed in the soil layer and a potential gradient between the flooded water and the soil is established. Consequently, paddy fields are suitable for the application of MFCs and such a power-generation system, called paddy-field MFCs (PF-MFCs), has been well investigated (De Schamphelaire et al. 2008, 2010; Kaku et al. 2008; Arends et al. 2014). The present study is based on our hypothesis that electricity can be generated more efficiently in our cultivation system than in normal paddy fields by supplying the organic matters contained in the treated wastewater to the PF-MFCs.

**MATERIALS AND METHODS**

**Experimental apparatus**

The experimental apparatus for rice production with circulated irrigation, which is the same as was used in the previous study (Muramatsu et al. 2015), is illustrated in Figure 1. This apparatus consists of a simulated paddy field, with an area of 0.18 m² (0.3 m × 0.6 m), and a storage tank for the irrigation water. An underdrain was fitted to the bottom of a 15-cm-thick soil layer in the simulated paddy field. In Run A, irrigation water was continuously supplied from the surface of the paddy field at a flow rate of approximately 20 L/d. A part of the irrigation water (7–10 L/d) penetrated through the soil layer and flowed out from the underdrain. The drained water and the overflow...
surface water were returned to the storage tank, from which the water was subsequently repumped to the paddy field. In Run B, the irrigation water was continuously supplied to the paddy field via the underdrain, at the same flow rate as in Run A. The irrigation water passed through the soil layer in an upward direction, overflowed from the paddy field, and returned to the storage tank. Run C was used as a control, with the irrigation water not being circulated as seen in normal paddy fields. Water from the storage tank was added manually to the paddy field to compensate for the loss of surface water because of evapotranspiration. To avoid the effect of rainfall, the paddy fields in all the runs were covered by a transparent roof and occasionally plastic sheets.

The soil sample applied to the apparatus was collected on April 25, 2014, from the surface of a paddy field at the Yamagata University Farm, Tsuruoka, Yamagata, Japan. The paddy field had been used for cultivating rice for human consumption during the previous growing season.

Power generation system

In all the runs, two electrodes, with an area of 0.18 m² and made from carbon graphite felt, were installed in the paddy fields to generate electricity. One electrode, as the cathode, was floated on the surface water, while the other, as the anode, was buried in the soil layer at a depth of 10 cm. The cathode had four 10-cm holes for the transplantation and growth of the rice plants. The electrodes were connected to a 100 Ω external resistor with a coated copper cable, and the voltage across the resistor was continuously monitored by using a data logger (Midi logger GL220; Graphtec, Tokyo, Japan).

Experimental conditions

The treated wastewater for all the runs was obtained from a municipal wastewater treatment plant that employs the standard activated sludge process, followed by chlorine disinfection. This wastewater plant, which is located in Tsuruoka, Yamagata, Japan, discharged the treated wastewater characterized by the annual average suspended solids (SS) (3.1 mg/L) and biochemical oxygen demand (BOD) (4.7 mg/L). An amount of 100 L of wastewater was applied to the storage tank for each run on May 20, at the beginning of the experiment, and 50, 50, and 20 L of treated wastewater were added to the tank on July 3, August 3, and September 11, 2014, respectively. In order to trace the behavior of the nitrogen supplied to the cultivation system, heavy nitrogen (15N), equivalent to 2.46 atm% of total nitrogen (TN), was added to the treated wastewater used for irrigation. The heavy nitrogen was supplied in the form of ammonium ((15NH4)2SO4, SI Science Co., Ltd, Japan) since it was originally dominant (>90%) in the treated wastewater due to the treatment process operation with controlled nitrification. The amounts of heavy nitrogen in paddy soil before and after the experiment,
rice plants, supplied and remained wastewater were measured and then the heavy nitrogen lost during the experiment was regarded to be released to the atmosphere.

According to the recommendations for fertilizer (N, 120 kg/ha; P as P₂O₅, 160 kg/ha; K as K₂O, 140 kg/ha) for the cultivation of rice for animal feed, it was not necessary to apply nitrogen fertilizer, as nitrogen was already present in the treated wastewater. However, chemical fertilizers were applied to compensate for the deficiencies of phosphorus and potassium. Potassium fertilizer (0.85 g) was applied only at the beginning of the experiment, whereas the phosphorus fertilizer (16.2 g total) was applied each time the treated wastewater was added.

The experimental conditions for each run are summarized in Table 1.

**Schedule of cultivation and water management**

After soil puddling, four sets of young rice plants (Oryza sativa L. cultivar ‘Bekoaoba’) were transplanted to the paddy field for each run on May 26, 2014, as shown in Figure 1. In Runs A and B, the depth of the surface water was maintained at 5 cm with continuous irrigation and in Run C by manual irrigation when required, until the harvesting on September 26. The irrigation was intermitted only from July 7 to 16, and the paddy soil was dried up with continuous drainage. This practice is called midsummer drainage (MSD) and is often performed in normal paddy fields to enhance root growth.

**Analyses of water, rice, and soil**

During the experiment, the quality of the irrigation water in the storage tanks, relevant to temperature, electric conductivity (EC), pH, oxidation-reduction potential (ORP) and dissolved oxygen (DO), was monitored routinely by using mobile meters (OM-51 and D-54, Horiba, Japan). The TN and total organic carbon (TOC) concentrations in the irrigation water were analyzed by using a TOC analyzer (TOC-CSV, Shimadzu, Japan), with an attached TN measuring unit (TNM-1, Shimadzu, Japan). The ammonium and nitrate concentrations in the irrigation water were analyzed by using a portable colorimeter (DR/890, HACH, USA). In addition, the growth of the rice plants was recorded by weekly measurements until ear emergence on July 30. The height, number of shoots, and the soil plant analysis development (SPAD) value, which indicates the leaf chlorophyll concentration (Markwell et al. 1995), were measured weekly.

After harvesting, analyses using standard methods were conducted on the yield of brown rice and the dry weight of the entire plant body. The quality of the brown rice was evaluated by measuring the protein content with an automatic high-sensitivity NC analyzer (Sumigraph NC-220F, SCAS, Japan). In addition, the nitrogen contents in the other parts of the rice plant and the paddy soil before/after the experiment were determined with the same analyzer. Furthermore, the heavy nitrogen in the samples of plant and soil was analyzed by an organic elemental analyzer (FLASH 2000, Thermo Scientific).

The total amount of nitrogen removed through the rice cultivation was calculated as the difference from the supplied nitrogen to that remaining in the storage tank at the end of experiment. It should be noted that, in Run C, since the wastewater used for irrigation did not come back except during the MSD and at the end of experiment, almost of all the nitrogen contained in the irrigated wastewater was regarded as being removed.

**Statistical analysis**

We did not prepare replicates of the experiment in any of the runs because of the limited space. Instead, we cultivated four sets of rice plants in each run, as illustrated in Figure 1, and we conducted the statistical analyses on the assumption that a set of rice plants would grow independently from the other sets. Student’s t-test was used to compare the results from the two runs, and Tukey’s test was used for a comparison among the three runs.

**RESULTS AND DISCUSSION**

**Basic parameters of water quality**

Figure 2 illustrates the basic water-quality parameters of the irrigation water in the storage tanks. The temperature fluctuated between 19.6 and 27.5 °C for all the runs.
The pH in Runs A and B was close to the normal range (6–8), irrespective of the three additions of treated wastewater. However, in Run C, the pH was occasionally less than five, and the value decreased with time after the addition of treated wastewater. This could probably be ascribed to an increase in the nitrates because of nitrification, as shown in Figure 3, combined with a higher nitrogen concentration compared with the other runs (the details will be presented later). Although nitrification also happened in Runs A and B, the buffering capacity of paddy soil, through which the treated wastewater were irrigated, may have contributed to keeping its neutral pH in these runs.

The DO in all the runs showed sudden decreases after the addition of treated wastewater, but recovered to >3 mg/L with time. The irrigation water in Runs A and B, which was circulated in the paddy field, had slightly higher DO values throughout the experiment in comparison with that of Run C. Oxygen could have been supplied to the irrigation water both at the surface of the paddy field (via exposure to the atmosphere) and in the soil layer (via the function of the plant roots). The increase in DO appears to have enhanced nitrification.

The ORP in Run C decreased shortly after the additions of treated wastewater and recovered with time to a range of 200 to 300 mV, common to the fluctuation of DO. The ORP
in Runs A and B, which was affected by the paddy field environment, did not show such a clear fluctuation trend.

The EC (data not shown) ranged from 60 to 90 mS/m, without any significant differences among the three runs. The additions of treated wastewater did not affect the value of EC in any of the runs.

**Removal of nitrogen from treated wastewater**

Figure 3(a) shows the TN concentration in the irrigation water in the storage tanks during the experiment. The TN concentrations in Runs A and B decreased significantly from approximately 25 mg/L to <2 mg/L in the first month after the start of the experiment, whereas that for Run C remained constant. After adding new treated wastewater to the storage tanks on July 3, the TN concentrations in all the runs dropped until the end of experiment, except for two rises on August 7 and September 11 after the addition of treated wastewater. This result indicates the effective removal of nitrogen from the irrigation water in the paddy field. In Run C, the TN concentration also decreased, although the irrigation water had not been circulated. This result is ascribed to dilution by the overflowing surface water when irrigation water was manually added to the surface to maintain the water depth. The denitrification inside the tanks was negligible because of the high DO and ORP throughout the experiment (Figure 2).

In parallel with the TN concentration, the volume of the irrigation water in the storage tank markedly declined because of evapotranspiration. The amount of nitrogen contained in the storage tank can be calculated by multiplying the TN concentration and the volume of the irrigation water in the tank. In this manner, we estimated that by adding the treated wastewater four times, a total of 6.7 g of nitrogen was supplied to the system, whereas 97, 96, and 74% of the supplied nitrogen were removed in Runs A, B, and C, respectively (Table 2). This result implies that the direction of the circulated irrigation (i.e. feeding the irrigation water upward or downward) did not affect the removal efficiency of nitrogen in this system. Moreover, the circulated irrigation system was able to achieve a much higher effective rate of nitrogen removal from the treated wastewater. Table 2 shows that the total amount of nitrogen removed in all the runs was nearly twice as large as that removed by the same cultivation system used in the previous study (Muramatsu et al. 2015). This finding demonstrates the possibility of removing a larger amount of nitrogen by applying larger amounts of treated wastewater.

The nitrogen in the irrigation water could be removed by adsorption to the paddy soil, uptake by the rice plants, or release to the atmosphere through nitrification and denitrification. The analysis of heavy nitrogen as tracer revealed that approximately 40% of the nitrogen removed from the treated wastewater in the circulated irrigated system was taken up by the rice plants, regardless of the direction of the irrigation (Figure 4). Our previous study (Muramatsu et al. 2015) has demonstrated that 6 to 16% of the removed nitrogen would be taken up by plants other than rice plants. We can disregard such uptake in the present study, as the growth of other plants was limited by the cathode on the water surface; however, this resulted in the nitrogen being used more effectively for rice production. The irrigation direction appears to have affected the release of nitrogen to the atmosphere, as it was slightly enhanced by the upward irrigation.

**Dry biomass, yield, and quality of harvested rice**

The rice yields in Runs A, B, and C were 8.5, 7.9, and 6.1 t/ha, respectively (Table 3). The circulated irrigation of treated wastewater significantly increased the yield and achieved the target value of 8 t/ha for the cultivar used in this experiment. In addition, compared with the previous study (Muramatsu et al. 2015), a significant increase in the yield

<table>
<thead>
<tr>
<th>Present study</th>
<th>Supplied water (L)</th>
<th>Supplied nitrogen (g)</th>
<th>Removed nitrogen (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run A</td>
<td>220</td>
<td>6.70</td>
<td>6.51</td>
</tr>
<tr>
<td>Run B</td>
<td>220</td>
<td>6.70</td>
<td>6.43</td>
</tr>
<tr>
<td>Run C</td>
<td>220</td>
<td>6.63</td>
<td>4.88</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Previous study*</th>
<th>Supplied water (L)</th>
<th>Supplied nitrogen (g)</th>
<th>Removed nitrogen (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run A</td>
<td>100</td>
<td>3.26</td>
<td>3.52</td>
</tr>
<tr>
<td>Run B</td>
<td>100</td>
<td>3.28</td>
<td>3.26</td>
</tr>
<tr>
<td>Run C</td>
<td>87</td>
<td>2.83</td>
<td>2.80</td>
</tr>
</tbody>
</table>

Nitrogen removed with water sampling was excluded in the supplied nitrogen.

*Muramatsu et al. (2015), which used the same experimental apparatus.
was indicated in Run A by using a larger volume of treated wastewater. Considering the components of the yield in Runs A and B (Table 3), the number of ears per area reached the target value, whereas the number of kernels per ear did not. The low TN concentration in some periods, as shown in Figure 3, could have had a negative impact on the development of the kernels. Accordingly, the yield could be increased probably by maintaining the TN concentration at a high level with more frequent additions of treated wastewater.

The quality of the rice, relevant to the protein content, did not differ significantly among the three runs, but, in comparison with the previous study, it had clearly improved (Muramatsu et al. 2015), as shown in Table 4. The protein content obtained is comparable with the standard value (8.8%) of rice for animal feed in Japan. In view of both the yield and the quality of the rice obtained in our experiment, we conclude that rice of good quality for animal feed can be cultivated in our system as effectively as in the normal paddy field. In addition, we found that the direction of the circulated irrigation did not affect either the yield or the quality of the rice.

In addition to the brown rice, the entire body of the rice plant is sometimes used as silage. In this context, we analyzed the dry mass of the rice plant body (Table 4). We found that body mass was significantly increased by the circulated irrigation in Runs A and B. However, we did not examine the nutrients contained in the plant body.

**Power generation**

Figure 5 illustrates the density of the power generated in the rice cultivation system. As had been reported by previous studies (Kaku et al. 2008; Takanezawa et al. 2010; Watanabe & Nishio 2010), in this study, the density also fluctuated rapidly in all the runs (Figure 5(a)). This is ascribed to the photosynthesis of algae living in the surface water that provides oxygen to the cathode, resulting in power generation being more effective during the daytime. For easier comparison, we calculated the power generation (Figure 5(b)) based on the monitored power density.

In the first month after the start of the experiment, the electric outputs in all the runs of the system were remarkably low. It is assumed that the root system of the rice plants was developing during this period, as well as the microbial communities on the graphite felt in the soil, which, as anode, could affect the power generation significantly. A clear indication of power generation was found in Run B shortly after the addition of the treated wastewater on July 3. However, as regards the other two runs, there was no such indication, as the system was not yet ready at that time. During the MSD, the paddy soil was dried up and the power generation stopped. Subsequently, after the

![Figure 4](https://iwaponline.com/wst/article-pdf/75/4/898/455111/wst075040898.pdf)

**Figure 4** Fate of nitrogen removed from treated wastewater used for irrigation.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Yield and its components of brown rice harvested in each run</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Ears (m²)</td>
</tr>
<tr>
<td>Target</td>
<td>300</td>
</tr>
<tr>
<td>Run A (Previous study**</td>
<td>300</td>
</tr>
<tr>
<td>Run A</td>
<td>350 a</td>
</tr>
<tr>
<td>Run B</td>
<td>367 a</td>
</tr>
<tr>
<td>Run C</td>
<td>500 b</td>
</tr>
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</table>

Different letters indicate a significant difference between runs (p < 0.05, n = 4).

*Kernels with rice.

**Muramatsu et al. (2015), which used the same experimental apparatus irrigated with a smaller volume of treated wastewater.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Protein content in brown rice and dried biomass of whole plant harvested in each run</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Protein content (%)</td>
</tr>
<tr>
<td>Run A</td>
<td>8.4 a</td>
</tr>
<tr>
<td>Run B</td>
<td>8.7 a</td>
</tr>
<tr>
<td>Run C</td>
<td>8.4 a</td>
</tr>
</tbody>
</table>

Different letters indicate a significant difference between runs (p < 0.05, n = 4).

*Muramatsu et al. (2015), which used the same experimental apparatus irrigated with a smaller volume of treated wastewater.
paddy soil was re-flooded, the power generation restarted in all the runs, and stabilized at the beginning of August. Run B constantly exhibited higher power density (up to 12 mW/m²) in comparison with Runs A and C. The implication is that the upward irrigation of treated wastewater, from the bottom to the top of the paddy soil, could enhance power generation. The upward irrigation in Run B, in comparison with downward irrigation, could have supplied the organic matter in the treated wastewater more effectively to the bacterial community developing on the anode. However, no significant difference in the TOC concentration was found in the circulated irrigation water among the three runs (data not shown). The power densities obtained in Run B were comparable to those reported in the previous studies, using a PF-MFC similar to that used in the normal paddy fields (Kaku et al. 2008; Takanezawa et al. 2010). Kouzuma et al. (2013) achieved much higher power density (80 mW/m²) by using the PF-MFC with a platinum-doped cathode. In addition, the position of the anode, which determines the anode/cathode distance and the contact between anode and rice root, and the external load could influence the power generation of the PF-MFC (Takanezawa et al. 2010). Therefore, further modifications in respect of such factors are needed to improve the power generation in our system. In addition to the power generation, the PF-MFC could potentially reduce the methane emission from paddy fields (Kouzuma et al. 2014).

**Feasibility of the proposed system**

As reported here, our system for resource-saving rice cultivation with circulated irrigation of treated municipal wastewater achieved simultaneously an effective removal of nitrogen, a high yield and good quality of rice for animal feeding and power generation comparable to normal paddy fields in the bench-scale experiment. In addition, farmers will get benefit from no application of nitrogen fertilizer. On the other hand, infrastructure for
circulated irrigation may limit the implementation of this system. At least, enough number of underdrain pipes is necessary to collect the infiltrated wastewater below the paddy soil. Insufficient collection would not only require a larger volume of treated wastewater for irrigation, bringing an increased energy and cost for its transportation, but also lead to a risk of groundwater pollution by nitrates which exist in the irrigated wastewater dominantly except just after the addition of new wastewater (Figure 3(c)).

CONCLUSIONS

In this study, we modified a system to cultivate rice for animal feed by using treated municipal wastewater in a circulated irrigation system. In addition, we attempted to generate power in our system by installing a PF-MFC.

We achieved superior crop yield and higher rice protein content in our system by adding larger amounts of treated wastewater. This implies that the circulated irrigation of treated wastewater had significantly enhanced the plant growth, increasing the rice yield and the biomass of the whole plant. The direction of the circulated irrigation had no significant effect on the yield or the quality of the rice.

The nitrogen in the treated wastewater was removed effectively (>96%) in the modified system, with approximately 40% of the removed nitrogen being used for rice plant growth. The release of the nitrogen in the treated wastewater to the atmosphere, ascribed to denitrification in the soil layer, could be enhanced by upward (bottom-to-top) irrigation.

Furthermore, our attempt to generate power in the system achieved power density of up to 12 mW/m² and power generation of up to 192 mWh/m²/d, which is comparable to that of previous studies, using a similar MFC in normal paddy fields. This indicates the negligible contribution of the treated wastewater irrigation to power generation, which, however, appeared to be enhanced by upward irrigation. This finding is ascribed to upward irrigation providing organic-rich wastewater directly to the bacterial community living on the anode of the MFC set in the soil layer. Together with the upward irrigation, optimizing the position and thickness of anode, modifying the cathode with platinum catalyst and using a more appropriate external load have potential to increase electric output from the MFC.

Our system could contribute to improving the quality of the treated municipal wastewater by nutrient removal, as well as to the large-scale circulating of water and materials to the agricultural, livestock breeding, and urban sectors. In the context of global warming, the emissions of methane and nitrous oxides in our system, which could be enhanced with denitrification in the soil layer, are important factors that will be revealed in further studies.

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