Chapter 3

Municipal Wastewater Irrigation for Rice Cultivation

Dong Duy Pham and Toru Watanabe

Additional information is available at the end of the chapter

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Abstract

In scene of worrisome water shortage, municipal wastewater has been gradually accepted as an alternative water resource containing important nutrients for irrigation. Rice cultivation, which is one of the main crops feeding global population and requires plenty of water for its effective growth, has been often irrigated by municipal wastewater in many countries. While irrigation of municipal wastewater for rice cultivation must bring benefits for farmers mainly by increased yield with less amount of fertilizers, it also has potential to cause drawbacks to human health and the environment. This chapter discusses about these aspects based on scientific works and practical experiences of municipal wastewater irrigation for rice production as well as the introduction of our concept to cultivate rice for animal feeding with irrigation of treated wastewater, which can contribute to resource circulation between urban and rural areas. The feasibility study under this concept has demonstrated that the target value of rice yield can be achieved and protein-rich rice preferable for animal feed can be harvested with irrigation of properly treated municipal wastewater.

Keywords: municipal wastewater, rice production, wastewater irrigation, benefit and disadvantage, greenhouse gas, rice for animal feeding

1. Introduction

Climate change and global population explosion put water resources scarcity in many corners of the world to alarming status [1, 2], with around 1.1 billion people lacking access to freshwater in developing countries and nearly 2.4 billion lacking adequate sanitation [3]. It is estimated that two-thirds of the world's population will suffer from moderate to high water stress, and about half of the population will face severe water supply constraints in 2025 [4]. Agriculture is known as the largest consumer of freshwater resources at the beginning of the twenty-first century, and water consumption for agriculture accounts for over 70% of global water withdrawals [5, 6]. However, agricultural irrigation water does not usually require the same high grade of water quality as drinking water [7]. Currently, in approximately 1.5 billion hectares of agricultural land all over the world [8], total fertilizer use ($N + P_2O_5 + K_2O$) is estimated to be around 190.4 million tons [9]. Wastewater can supply a significant amount of nutrients which can improve soil fertility, plant growth and crop production, reducing the consumption of required fertilizers [10]. In this circumstance, municipal wastewater is evaluated as a new resource of water, and the practice of reclaimed wastewater for agricultural irrigation is likely to become more commonly applied in many countries with a vast volume [11–13]. It is not the main objective, but reuse of wastewater also contributes to interrupting discharges of nutrients and organic matters into water environment [14].

Approximately 50% of worldwide irrigation water is used by rice cultivation—one of the agricultural products which need notable amount of water [15, 16]. Although there are a variety of practices of rice cultivation, typically, rice fields are flooded before plowing, and thereafter, water levels are kept at 4–6 cm in shallow rice fields. It sometimes becomes as high as 10 cm when continuous-flooding irrigation is done during the growing season [17]. Rice is one of the leading cereal crops providing around 20% daily calories for more than 3.5 billion people [18]. There are around 150 million hectares of rice land worldwide, which supply 550–600 million tons of rough rice yearly. Irrigated rice cultivation makes up 55% of harvested rice area and contributes to 75% of global rice production [19]. Irrigation of rice paddy using treated or untreated wastewater is extensively practiced and examined in many countries to investigate benefits [20–26] or drawbacks of the practices [12, 27–33].

This chapter provides information about municipal wastewater characteristic as well as discussions about positive and negative effects of its reuse for rice cultivation.

2. Municipal wastewater and its treatment

2.1. Characteristics of municipal wastewater

Municipal wastewater, which is usually conveyed in a combined sewer or sanitary sewer, consists of domestic wastewater, industrial wastewater, and storm water and groundwater seepage entering the municipal sewage network. Domestic wastewater includes effluent from households, institutions, commercial buildings and the like. Industrial wastewater is the effluent discharged from manufacturing units and food processing plants. In general, characteristics of domestic wastewater are not significantly different from one region to another, while there are many types of industrial wastewater based on industrial processes as its origin.

Municipal wastewater mainly consists of water (99.9%) together with relatively low concentrations of suspended and dissolved organic and inorganic solids. Parts of the organic substances present in wastewater are carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and their decomposition products as well as various natural and synthetic organic chemicals from the process industries. **Table 1** shows the levels of the major constituents in municipal wastewater.

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Contaminants	Unit	Range
Total solid (TS)	mg/L	390–1230
Total dissolved solid (TDS)	mg/L	270–860
Total suspended solid (TSS)	mg/L	120–400
Biochemical oxygen demand (BOD_5)	mg/L	110–350
Chemical oxygen demand (COD)	mg/L	250–800
Total organic carbon (TOC)	mg/L	80–260
Total nitrogen (TN)	mg/L	20–70
Total phosphorus (TP)	mg/L	4–12
Total coliform	no./100 mL	10^6–10^9
Fecal coliform	no./100 mL	10^3–10^7

Sources: [34].

Table 1. Typical composition of untreated domestic wastewater.

2.2. Treatment of municipal wastewater

It is not recommended to reuse municipal wastewater directly for rice cultivation due to its drawbacks, which are described in the next section. Treatment of wastewater at any level is required to overcome the drawbacks. The principal objective of wastewater treatment is to remove contaminants such as solids, organic matter and nutrients before the treated wastewater is discharged into water bodies. The quality of treated wastewater depends on the treatment technology and operation.

Although wastewater treatment includes physical, chemical and biological processes, it normally has four basic steps: preliminary, primary, secondary and advanced treatments [35]. Preliminary treatment is designed to remove coarse solids and other large materials, which are often found in raw wastewater. These solids consist of pieces of wood, cloth, paper, plastics, sand, gravel, etc. The objective of primary treatment is to extract organic and inorganic solids from wastewater by the physical process of sedimentation and flotation. Approximately 25–50% of the BOD, 50–70% of the SS and 65% of the oil are removed throughout this treatment step [36].

Secondary treatment, in general, follows primary treatment to do the further treatment. Its objective is removal of biodegradable dissolved and colloidal organic matters from effluent of primary treatment using many different types of microorganisms in a controlled environment. The principal secondary treatment techniques are the trickling filter and the activated sludge process. The latter one, which is used most commonly all over the world, can remove organic matters effectively but cannot do nutrients, especially nitrogen, from wastewater. Hence, the secondary effluent from wastewater treatment plants still has a high content of nutrients available for crop growth.

At most treatment plants, the secondary effluent is discharged into receiving water environment after disinfection with chlorine, ozone or ultraviolet radiation. To prevent eutrophication in the water environment, advanced treatment is sometimes applied to remove specific contaminations such as nutrients in the secondary effluent [37].

2.3. Advantages and disadvantages of wastewater irrigation for rice production

These characteristics of municipal wastewater make us imagine advantages and drawbacks of its irrigation for rice production. Major advantages are:

- Higher crop yields with reduced use of synthetic fertilizers, resulting in saved cost for cultivation.
- Enhanced recycles of nutrients and organic matters, improving soil properties.
- Reduced discharges of pollutants to surface water bodies.
- Decreased freshwater withdraw during irrigation.

On the other hand, we should pay attentions to its drawbacks such as:

- Contamination of irrigated soil with salt, heavy metals and toxic compounds originated from wastewater, resulting in reduced soil productivity.
- Contamination of agricultural products (rice crop) with heavy metals and toxic compounds, posing health risks to consumers.
- Farmers' risk of health problems due to exposure to paddy water contaminated with pathogens, heavy metals and toxic compounds.
- Contamination of groundwater due to infiltration of wastewater used for irrigation.

The following sections describe more detail explanation about the above advantages and drawbacks. Most of them are common to irrigation of the treated wastewater, although its treatment may highlight the advantages and overcome the drawbacks.

3. Potential impacts of municipal wastewater reuse for rice production

3.1. Impacts on crops

In general, wastewater irrigation can affect rice crops in terms of yields and crop quality such as appearance and flavor. Municipal wastewater is a rich source of nutrients necessary for crop growth, so it is expected that crops irrigated with municipal wastewater get higher yield than normal. Yoon et al. [20] examined the effect of treated sewage irrigation on paddy rice cultivation. They found that the irrigation did not adversely affect the growth and yield of rice, resulting in up to 50% greater yield than rice without wastewater irrigation. Thu [38] also reported that wastewater irrigation brought 10–15% higher yield of rice crops.

If nitrogen supplied to the crop exceeds its dose recommended for optimal yields, crop growth may be stimulated together with yield loss and delayed ripening [14]. The study by Nyomora [26] illustrated that wastewater irrigation resulted in four times higher rice yield than tap water irrigation, but, in contrast, wastewater irrigation applied with N-P-K fertilizer depressed the yield potential to 3.2 times of that obtained without its application. This situation can happen accidentally. For example, urea plant effluents, as a rich source of liquid fertilizer in concentrated forms, have adverse effects on rice and corn yields [2]. Also, oversupply of nitrogen may be resulted in overgrowth of rice plants, which triggers their lodging and reduces eating quality of rice due to increased content of proteins [39].

Crops irrigated with wastewater have potential to be contaminated with microbes, heavy metals and organic toxic compounds in wastewater. This effect is discussed separately in the Section 3.5.

3.2. Effects on soil resources

Wastewater can affect paddy soil in two opposite ways: by providing benefits and causing problems. It is usually difficult to predict which effect appears in wastewater irrigation because soil is a very complicated structure involving inorganic and organic matters. One of the most recognizable effects of wastewater irrigation is a rise of yield due to nutrients supplied with wastewater as well as soil texture improved by organic matters in wastewater [40]. Supplying organic matter improves soil texture by enhancing soil humidity and microbial activity [41].

Nitrogen in wastewater consists of several chemical forms such as nitrate, nitrite, ammonia and organic nitrogen. All of these forms are soluble and mobile in water, and when the wastewater is irrigated, all forms of nitrogen except ammonia are easily washed out and may cause pollution of groundwater and surface water receiving the runoff water. Only ammonia in wastewater can attach to soil particles and is retained in paddy fields, but, at the surface of soil layer and rhizosphere with the presence of oxygen, it is gradually converted to nitrite and finally nitrate with bacterial activities. By contrast, phosphorus, which can exist as a trivalent cation, is so stable in soil layer. In addition to this fact, since wastewater contains a smaller amount of phosphorus than that required by crops, its irrigation hardly gives an adverse impact on the water environment [14].

On the other hand, wastewater irrigation may make consequent adverse effects on soils. The most commonly reported impact is accumulation of metals that, depending on the level, may be harmful. Chung et al. [12] indicated that application of domestic wastewater to arable land for 3 years slightly increased the levels of Pb, Cd, Cu and Zn in soil. Kang et al. [21] conducted rice cultivation with groundwater and treated wastewater in different treatment levels. The results showed no adverse effects on chemical concentrations including the heavy metals (Cu, As, Cd, Zn, Hg and Pb) in paddy soil. This indicates the possibility 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.

A field research in Thessaloniki, Greece, during a 2-year period [22] reported no adverse effects on the physicochemical properties of soil, whereas macro and trace elements concentration showed discrepancies between the 2 years and the three treatments (river water with N-P fertilizer, treated wastewater with N fertilization and treated wastewater without fertilizer).

Wastewaters including industrial discharges with a high metal concentration are harmful to crops and eventually to consumers, as a result of metal accumulation in soil. The elements of major concern are heavy metals such as cadmium, copper, molybdenum, nickel and zinc. Yang et al. [27] reported that the paddy soil irrigated with untreated mining wastewater in Lechang lead/zinc mine area was heavily contaminated by Cd and would pose a human/animal health risk through Cd mobility in the food chain. Very high concentrations of As, Cd, Cu, Pb and Zn were found in the paddy soils irrigated by river water, which received wastewater from mining activity [42].

Wastewater, particularly domestic wastewater, normally contains salts which may be accumulated in the root zone with possible harmful impacts on soil health. Increase rate of salinity depends on the salinity of irrigated water, soil transmissivity, organic matter concentration, land drainage, irrigation rate, depth to the groundwater level and the type of soils. Long-term use of wastewater with high salt contents is a potential hazard for soil as it may erode the soil structure, resulting in less productivity. The problem of soil salinity can be settled by the application of natural or artificial solutions, although it is costly and leads to economic constraints.

Wastewater with a large amount of solids may cause soil clogging, depending on soil porosity, concentration (>100 mg/L can cause the problem) and chemical composition. The most concerning components are minerals that are not biodegraded. If soil is clogged, irrigation will become less effective due to dismissed water percolation [43].

3.3. Effects on ground and surface water

The first effect of irrigated agriculture on groundwater resource is aquifer recharge. The recharge happens almost always non-intentionally and has the advantage of increasing the local availability of water [44]. Pescod [36] estimated that 50–70% of the irrigation water could infiltrate to groundwater aquifer in some parts.

Due to this phenomenon, wastewater irrigation can cause adverse effects on groundwater resource. The most famous adverse effect is infiltration of nitrates in irrigated wastewater into groundwater. Groundwater contaminated with nitrates is known to cause methemoglobinemia in infants, so-called blue baby syndrome, if it is used as a source of drinking water [43].

Not only nitrogen but also organic matters and metals may contaminate groundwater in municipal wastewater irrigation. If some of most toxic metals to humans—cadmium, lead, mercury and arsenic—are present in irrigated wastewater at a higher concentration than the acceptable level, groundwater is severely contaminated, posing risk of serious diseases like cancer to the groundwater users. Contamination of groundwater with organic matters brings another type of health risk to its users, through the formation of organochlorides when the groundwater is disinfected with chlorine (the most common method) for drinking purpose [45].

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Long-term irrigation of municipal wastewater may result in a significant increase of salt content in aquifers, although quality of irrigated wastewater, soil characteristics and original quality of the receiving groundwater are all important factors to determine the extent to which the quality of groundwater is impacted. Even though groundwater has a low salt concentration, addition of salts originated from irrigated wastewater may not be considered too adverse if its movement is limited or if it is not used for any purposes. Thus, the impact of increased salts in groundwater by wastewater irrigation, which is sometimes inevitable, needs to be weighed up in consideration with all the risks and benefits from the irrigation [46].

Surface water bodies are also affected due to drainage and runoff from the fields irrigated with municipal wastewater. The inevitable contamination in surface water is almost the same as that in groundwater, but the extent of the impact depends on the strength of wastewater and type of water body (i.e., river, irrigation channel, lake or dam) as well as hydraulic retention time in the fields.

3.4. Effects on quality of irrigated wastewater

Although wastewater irrigation has a potential to contaminate freshwater sources, it is expected that quality of the wastewater is improved by being used for irrigation. Suspended solids including pathogenic microorganisms are trapped and absorbed in upper soil layers and removed from the wastewater. The efficiency of solid removal depends on sizes of soil pore and the solids [44]. Adsorption of microorganisms to soil particles is favored at low pH, high salt concentration in the sewage and high relative concentrations of calcium and magnesium over monovalent cations such as sodium and potassium in soil [14].

Organic matters in wastewater can be rapidly converted in soils to stable and nontoxic ones such as humic and fulvic acids. In fact, we can find biodegradation of a wider variety and greater amount of organic matters in soils than in water bodies. So the organic matters in term of COD and BOD in the irrigated wastewater are significantly decreased after percolation through soil layers.

More significant reduction in nitrogen concentration is expected at paddy fields with wastewater irrigation due to three main reasons: absorption by plants, release to the atmosphere as the result of nitrification and denitrification by nitrogen bacteria such as *Nitrobacter* and *Nitrosomonas*, and adsorption of ammonium to soil particles. Firstly, rice plants grow taking nutrients in wastewater used for irrigation, and nitrogen, one of the fundamental nutrients for plant development, is removed from the wastewater stored in soil layers [15, 24]. Secondly, soil and rice rhizosphere microorganisms contribute to transformation of organic nitrogen or ammonium to nitrogen gas as well as nitrous oxide gas under a variety of redox conditions in soil layers [23]. Nitrogen removal is enhanced if flooding and drying periods are alternated for promoting nitrification/denitrification process, with 75% removal at the maximum [14]. Thirdly, ammonium as a cation has an affinity to the surface of soil particles normally with positive charge. However, a large amount of ammonium is supplied, and as mentioned above, excess nitrogen will be transported to groundwater with infiltrated irrigation water. Nitrites and nitrates, which are anions, are easily lost from paddy fields, resulting in groundwater contamination.

3.5. Effects on human health

As mentioned above, municipal wastewater includes pathogenic microorganisms such as bacteria, viruses and parasites. These microorganisms potentially pose human health risks when the wastewater is reused for some activities. Particularly, human parasites such as protozoa and helminth eggs are of special significance in this concern as they are known as being more difficult to remove by treatment processes [2].

Paddy fields irrigated with municipal wastewater may have unfavorable health effects on farmers. It has been reported that the practice of reuse of raw or even treated wastewater for irrigation may cause epidemiological problems among nearby populations and consumers of uncooked agricultural products [47]. The degree of risk may vary among the various age groups [2], and in a study [31], children were found to have a greater risk of infection with *Escherichia coli*. A study conducted in a province in northern Vietnam [29] assessed the risk of skin disease among farmers occupationally exposed to wastewater, showing that exposure to wastewater is a major risk factor for skin disease, but it is not clear which chemical and biological agents might play the main role in causing the diseases. Rhee et al. [30] examined the concentrations of *E. coli* in a paddy rice field irrigated with reclaimed wastewater and evaluated the risk of its infection among farmers using beta-Poisson dose-response model. The results showed that the risk was lower in irrigation of groundwater and reclaimed wastewater irrigation than in irrigation of direct effluent from wastewater treatment plant.

Municipal wastewater sometimes has harmful metals such as Zn, Cu, Pb, Mn, Ni, Cr and Cd, depending upon the type of activities in the associated area. Continuous irrigation of municipal wastewater may result in heavy metal accumulation in the soil and agricultural products [48]. In case of rice plant, it is well known that Cd is the metal to which a special attention should be paid because it is accumulated so intensively in edible part of rice.

Most of the heavy metals are normally removed well by wastewater treatment processes. Even so, we should take case about heavy metal contamination in the paddy field considering subsequent food chain involving agricultural products and consumers [49]. Due to the nonbiodegradable and persistent nature, heavy metals are accumulated in viscera and born, and are associated with numerous serious health disorders [50]. Singh et al. [51] indicated that rice and wheat grains contained less heavy metals than vegetables, but health risk was more significant due to higher contribution of cereals in the diet.

3.6. Socioeconomic effect

Wastewater irrigation brings various economic benefits. Wastewater for irrigation does not require as high quality as the effluent which is discharged to water bodies. Indeed, thanks to the function of paddy fields to improve water quality as explained in the Section 3.4, the discharge from the field has a better quality than the irrigation water. By using this function effectively, we can save the cost for wastewater treatment.

In addition, when wastewater containing rich nutrients is used for irrigation, we can reduce the amount of fertilizer applied to the field, resulting in cost saving or higher yield obtained.

This must contribute to improvement of economic status of farmers. Papadopoulos et al. [22] reported that the total production cost decreased up to 11.9% by applying municipal wastewater for rice production, compared to the normal paddy field.

3.7. Effects on greenhouse gas emission

Global warming is caused by the emission of greenhouse gases (GHGs) such as methane (CH_4) and nitrous oxide (N_2O). On global scale, agricultural activities accounted for about 50% of CH_4 and 60% of N_2O in the total anthropogenic GHGs emissions in 2005 and nearly 17% increase of these emissions from 1990 to 2005 [52]. In particular, paddy fields and irrigated lowland rice production systems are known to be significant sources of CH_4 and N_2O, which are two important trace gases contributing to an observed increase of approximately 0.6–0.7°C in global surface temperature during the last century.

GHGs emission from paddy fields may be affected by many factors such as water regime, organic matter and nitrogen resource including fertilizer. As introduced above, municipal wastewater is rich in organic matters and also contains an appreciable amount of macronutrients and micronutrients, and thus nutrient levels of soils are expected to increase with its irrigation. Several studies focused on the effects of water regime and fertilizer application on GHGs emission strength; however, to our knowledge, there was only one research [53] examining the effect of wastewater irrigation on CH_4 and N_2O emissions from paddy field. Reports showed that CH_4 and N_2O emissions from rice paddies are closely associated with soil carbon and nitrogen availabilities and transformation processes, which are significantly dependent on soil properties, soil heavy metal contents and soil microbial communities [54–56]. Consequently, Zou et al. [53] hypothesized that wastewater irrigation would significantly increase these gas emissions from rice paddies. The increments of CH_4 and N_2O emissions were 27 and 68%, respectively, compared to paddy fields irrigated by river water.

4. New concept: cultivation of rice for animal feeding with irrigation of municipal wastewater

4.1. Motivation and goal

In previous sections, we discussed the benefits and downsides of municipal wastewater reuse for irrigation, in particular for rice cultivation. Most of the drawbacks are from the contaminants in the irrigated wastewater, and therefore, one of the best ways to reduce its adverse effects is to use treated wastewater after the contaminants are removed to the suitable level. For this purpose, advanced treatments are not necessary and low-cost technologies are preferable to keep the total cost for cultivation acceptable.

Such low-cost technologies, even standard activated sludge process, are difficult to remove nutrients from wastewater, and the application of treated wastewater may lead to overgrowth of rice plants, resulting in lodging [15]. Too much supply of nutrients, especially nitrogen, also reduces the eating quality of rice due to high content of proteins.

These difficulties in irrigation of treated wastewater gave us motivation to propose a new concept to cultivate rice for animal feed rather than for human consumption [39]. The rice cultivars used for animal feed have several advantages compared with those used for human consumption. 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.

We can expect that rice cultivation in this concept contributes to an improvement in the quality of treated municipal wastewater. In addition to this merit in environmental protection, it is also 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 (**Figure 1**). Our goal is to realize this resource circulation based on the new concept for sustainability of our environment. We recognize that it is another advantage of this concept to overcome the psychological hurdle of consumers against eating rice cultivated using treated wastewater.

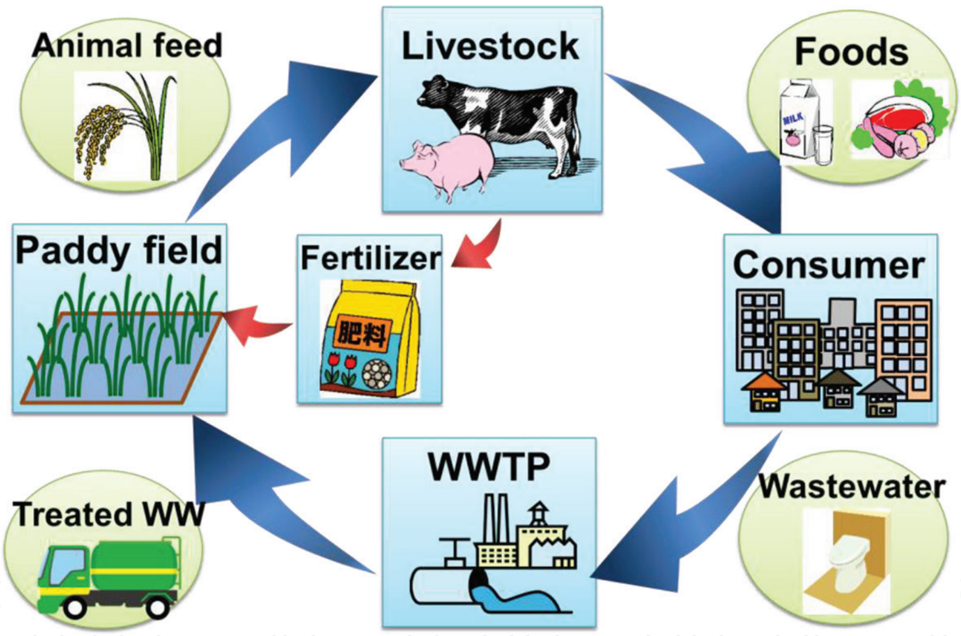

Figure 1. Resource circulation involving urban (consumers) and rural areas (rice and livestock famers), which is realized with cultivation of rice for animal feeding with irrigation of treated municipal wastewater.

4.2. Progress in our research toward implementation of this concept

The bench-scale experiment (**Figure 2**) with dimension of 0.6 × 0.3 m revealed that cultivation of rice for animal feeding could remove three times the amount of nitrogen from the treated wastewater compared with rice cultivation for human consumption [39]. In addition, the experiment showed that upward irrigation called bottom-to-top irrigation, in which treated wastewater is supplied from the pipe fixed at the bottom of the field and then infiltrate up through soil layer to the surface, increased the nitrogen released to the atmosphere, probably

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Figure 2. Bench-scale experiment to reveal the performance of treated wastewater irrigation to cultivate rice for animal feeding.

because of enhanced denitrification. This kind of irrigation seemed to increase the rice yield and biomass of the plants.

The yield of rice reached its target (8t/ha) for the cultivar used for the experiment [57], and the protein content (up to 13.1%) in the rice cultivated with irrigation of treated wastewater was significantly higher than that found in the normal paddy fields [58]. Actually, it may be possible to harvest such a protein-rich rice if a larger amount of nitrogen fertilizer is applied, but it is not cost-effective and attractive to farmers. In this sense, application of treated wastewater, which enables low-cost cultivation, is essential and core in the concept. We are now trying to examine the performance of rice cultivation practice, which was revealed in the bench-scale experiment, in the real fields.

5. Conclusions

Rice, which is a leading cereal crop, demands a huge amount of water, while the exploding urban population needs foods as well as produces wastewater. Reuse of wastewater for rice cultivation has a great potential to contribute to sustainable wastewater management. Several instances of positive and adverse effects of municipal wastewater irrigation for rice cultivation were given in this chapter. To avoid such negative effects on environment and human health, it is highly recommended that municipal wastewater should be reused for irrigation after being treated properly. Supposing it is treated with activated sludge process, a new concept “rice cultivation for animal feeding with irrigation of treated municipal wastewater” was introduced. Until now, our bench-scale experiment has revealed the feasibility of this concept with the data showing the achievement of target value of rice yield and its high protein content which is preferable for animal feed.

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Author details

Dong Duy Pham[1] and Toru Watanabe[2]*

*Address all correspondence to: to-ru@tds1.tr.yamagata-u.ac.jp

1 The United Graduate School of Agricultural Sciences, Iwate University, Morioka, Japan

2 Faculty of Agriculture, Yamagata University, Yamagata, Japan

References

[1] N. W. Arnell. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change. vol. 14, no. 1, pp. 31–52. 2004.

[2] I. Hussain, L. Raschid, M. A. Hanjra, F. Marikar and W. van der Hoek. Wastewater use in agriculture: Review of impacts and methodological issues in valuing impacts. Working Paper 37. International Water Management Institute, Colombo, Sri Lanka. 2002.

[3] S. P. Simonovic. World water dynamics: global modeling of water resources. Journal of Environmental Management. vol. 66, no. 3, pp. 249–267. 2002.

[4] V. Lazarova, B. Levine, J. Sack, G. Cirelli, P. Jeffrey, H. Muntau, M. Salgot and F. Brissaud. Role of water reuse for enhancing integrated water management in Europe and Mediterranean countries. Water Science and Technology. vol. 43, no. 10, pp. 25–33. 2001.

[5] UNESCO. Agriculture, food and water: A contribution to the World Water Development Report. 2013.

[6] S. H. Gheewala, T. Silalertruksa, P. Nilsalab, R. Mungkung, S. R. Perret and N. Chaiyawannakarn. Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand. Water (Switzerland). vol. 6, no. 6, pp. 1698–1718. 2014.

[7] T. Jang, M. Jung, E. Lee, S. Park, J. Lee and H. Jeong. Assessing environmental impacts of reclaimed wastewater irrigation in paddy fields using bioindicator. Irrigation Science. vol. 31, no. 5, pp. 1225–1236. 2013.

[8] FAO. World agriculture: towards 2015/2030—An FAO perspective. p. 432. 2003.

[9] FAO. Current world fertilizer trends and outlooks to 2015. 2011.

[10] M. A. Hanjra, J. Blackwell, G. Carr, F. Zhang and T. M. Jackson. Wastewater irrigation and environmental health: implications for water governance and public policy. International Journal of Hygiene and Environmental Health. vol. 215, no. 3, pp. 255–269. 2012.

[11] UNEP. Water and Wastewater reuse: An Environmentally Sound Approach for Sustainable Urban Water Management. 2005.

[12] B. Y. Chung, C. H. Song, B. J. Park and J. Y. Cho. Heavy metals in brown rice (*Oryza sativa* L.) and soil after long-term irrigation of wastewater discharged from domestic sewage treatment plants. Pedosphere. vol. 21, no. 5, pp. 621–627. 2011.

[13] D. Norton-Brandão, S. M. Scherrenberg and J. B. van Lier. Reclamation of used urban waters for irrigation purposes: a review of treatment technologies. Journal of Environmental Management. vol. 122, pp. 85–98. 2013.

[14] B. Jiménez. Irrigation in developing countries using wastewater. International Review for Environmental Strategies. vol. 6, no. 2, pp. 229–250. 2006.

[15] A. Muramatsu, T. Watanabe, A. Sasaki, H. Ito and A. Kajihara. Rice production with minimal irrigation and no nitrogen fertilizer by intensive use of treated municipal wastewater. Water Science and Technology. vol. 70, no. 3, pp. 510–516. 2014.

[16] T. P. Tuong and B. A. M. Bouman. Rice production in water-scarce environments. Water. vol. 5, pp. 53–67. 2003.

[17] A. K. Rath, B. Swain, B. Ramakrishnan, D. Panda, T. K. Adhya, V. R. Rao and N. Sethunathan. Influence of fertilizer management and water regime on methane emission from rice fields. Agriculture, Ecosystems and Environment. vol. 76, no. 2, pp. 99–107. 1999.

[18] Sustainable Rice Platform. Rice facts. [Online]. Available: http://www.sustainablerice.org/rice_facts.html. [Accessed 2016. 10. 30].

[19] J. McLean, D. Dawe, B. Hardy and G. Hettel. Rice Almanac: Third Edition. CABI Publishing. Oxford. England. 2002.

[20] C. G. Yoon, S. K. Kwun and J. H. Ham. Effects of treated sewage irrigation on paddy rice culture and its soil. Irrigation and Drainage. vol. 50, no. 3, pp. 227–236. 2001.

[21] M. S. Kang, S. M. Kim, S. W. Park, J. J. Lee and K. H. Yoo. Assessment of reclaimed wastewater irrigation impacts on water quality, soil, and rice cultivation in paddy fields. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering. vol. 42, no. 4, pp. 439–445. 2007.

[22] F. Papadopoulos, G. Parissopoulos, A. Papadopoulos, A. Zdragas, D. Ntanos, C. Prochaska and I. Metaxa. Assessment of reclaimed municipal wastewater application on rice cultivation. Environment Management. vol. 43, no. 1, pp. 135–143. 2009.

[23] S. Li, H. Li, X. Liang, Y. Chen, Z. Cao and Z. Xu. Rural wastewater irrigation and nitrogen removal by the paddy wetland system in the Tai Lake region of China. Journal of Soils Sediments. vol. 9, no. 5, pp. 433–442. 2009.

[24] T. I. Jang, H. K. Kim, C. H. Seong, E. J. Lee and S. W. Park. Assessing nutrient losses of reclaimed wastewater irrigation in paddy fields for sustainable agriculture. Agricultural Water Management. vol. 104, pp. 235–243. 2012.

[25] K. Jung, T. Jang, H. Jeong and S. Park. Assessment of growth and yield components of rice irrigated with reclaimed wastewater. Agricultural Water Management. vol. 138, pp. 17–25. 2014.

[26] A. M. Nyomora. Effect of treated domestic wastewater as source of irrigation water and nutrients on rice performance in Morogoro, Tanzania. Journal of Environment and Waste Management. vol. 2, no. 2, pp. 47–55. 2015.

[27] Q. W. Yang, C. Y. Lan, H. B. Wang, P. Zhuang and W. S. Shu. Cadmium in soil-rice system and health risk associated with the use of untreated mining wastewater for irrigation in Lechang, China. Agricultural Water Management. vol. 84, no. 1–2, pp. 147–152. 2006.

[28] D. T. Trang, W. van der Hoek, P. D. Cam, K. T. Vinh, N. Van Hoa and A. Dalsgaard. Low risk for helminth infection in wastewater-fed rice cultivation in Vietnam. Journal of Water and Health. vol. 4, no. 3, pp. 321–331. 2006.

[29] D. T. Trang, W. Van Der Hoek, N. D. Tuan, P. D. Cam, V. H. Viet, D. D. Luu, F. Konradsen and A. Dalsgaard. Skin disease among farmers using wastewater in rice cultivation in Nam Dinh, Vietnam. Tropical Medicine and International Health. vol. 12, no. Suppl. 2, pp. 51–58. 2007.

[30] H. P. Rhee, C. G. Yoon, Y. K. Son and J. H. Jang. Quantitative risk assessment for reclaimed wastewater irrigation on paddy rice field in Korea. Paddy and Water Environment. vol. 9, no. 2, pp. 183–191. 2011.

[31] Y.-J. An, C. G. Yoon, K.-W. Jung and J.-H. Ham. Estimating the microbial risk of *E. coli* in reclaimed wastewater irrigation on paddy field. Environmental Monitoring and Assessment. vol. 129, no. 1–3, pp. 53–60. 2007.

[32] V. Mukherjee and G. Gupta. Toxicity and profitability of rice cultivation under wastewater irrigation: the case of the East Calcutta Wetlands. South Asian Network for Development and Environmental Economics (SANDEE). vol. 62–11, pp. 292–300, 2011.

[33] Y. K. Son, C. G. Yoon, H. P. Rhee and S. J. Lee. A review on microbial and toxic risk analysis procedure for reclaimed wastewater irrigation on paddy rice field proposed for South Korea. Paddy and Water Environment. vol. 11, no. 1–4, pp. 543–550. 2013.

[34] Metcalf & Eddy, Inc. and AECOM Company, T. Asano, F. L. Burton, H. L. Leverenz, R. Tsuchihashi and G. Tchobanoglous. Water reuse: Issue, Technology, and Application. McGraw Hill, New York, USA. 1570pp. 2007.

[35] A. Sonune and R. Ghate. Developments in wastewater treatment methods. Desalination. vol. 167, no. 1–3, pp. 55–63. 2004.

[36] M. B. Pescod. Wastewater treatment and use in agriculture. FAO Irrigation and Drainage Paper. vol. 47, pp. 169. 1992.

[37] United States Environmental Protection Agency (EPA). Wastewater Treatment Works: The Basics. EPA 833-F-98-002. 1998.

[38] N. N. Thu. Urbanization and wastewater reuse in peri-urban areas: a case study in Thanh Tri District, Hanoi City. IWMI Work. Paper. no. 30, pp. 16–17. 2001.

[39] A. Muramatsu, H. Ito, A. Sasaki, A. Kajihara and T. Watanabe. Cultivation of rice for animal feed with circulated irrigation of treated municipal wastewater for enhanced nitrogen removal: comparison of cultivation systems feeding irrigation water upward and downward. Water Science and Technology. vol. 72, no. 4, pp. 579–584. 2015.

[40] D. Mara. Domestic wastewater treatment in developing countries. Earthscan, London, England. pp. 32. 2004.

[41] M. P. Ortega-Larroceaa, C. Siebe, G. Bécard, I. Méndez and R. Webster. Impact of a century of wastewater irrigation on the abundance of arbuscular mycorrhizal spores in the soil of the Mezquital Valley of Mexico. Applied Soil Ecology. vol. 16, no. 2, pp. 149–157. 2001.

[42] N. Rogan, T. Serafimovski, M. Dolenec, G. Tasev and T. Dolenec. Heavy metal contamination of paddy soils and rice (*Oryza sativa* L.) from Kocani Field (Macedonia). Environmental Geochemistry and Health. vol. 31, no. 4, pp. 439–451, 2009.

[43] WHO. WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Volume 2: Wastewater Use in Agriculture. vol. II, pp. 222. 2006.

[44] Stephen Foster, Héctor Garduño, Albert Tuinhof, Karin Kemper and Marcella Nanni. Sustainable groundwater groundwater management?: management urban wastewater as groundwater recharge evaluating and managing the risks and benefits. World Bank Briefing Note Series. vol. 12, pp. 6. 2005.

[45] H. Gallard and U. Von Gunten. Chlorination of natural organic matter: kinetics of chlorination and of THM formation. Water Research. vol. 36, no. 1, pp. 65–74. 2002.

[46] S. Toze. Reuse of effluent water—benefits and risks. Agricultural Water Management. vol. 80, no. 1–3 SPEC. ISS., pp. 147–159. 2006.

[47] A. Peasey, U. Blumenthal, D. Mara and P. G. Ruiz-palacios. A review of policy and standards for wastewater reuse in agriculture: A Latin American perspective. No. 68, Part II. Water and Environmental Health at London and Loughborough (WELL), London, England. 74p. June 2000.

[48] K. P. Singh, D. Mohan, S. Sinha and R. Dalwani. Impact assessment of treated/untreated wastewater toxicants discharged by sewage treatment plants on health, agricultural, and

environmental quality in the wastewater disposal area. Chemosphere. vol. 55, no. 2, pp. 227–255. 2004.

[49] K. Fytianos, G. Katsianis, P. Triantafyllou and G. Zachariadis. Accumulation of heavy metals in vegetables grown in an industrial area in relation to soil. Bulletin of Environmental Contamination and Toxicology. vol. 67, no. 3, pp. 423–430, 2001.

[50] J. O. Duruibe, M. O. C. Ogwuegbu and J. N. Egwurugwu. Heavy metal pollution and human biotoxic effects. International Journal of Physical Sciences. vol. 2, no. 5, pp. 112–118. 2007.

[51] A. Singh, R. K. Sharma, M. Agrawal and F. M. Marshall. Risk assessment of heavy metal toxicity through contaminated vegetables from waste water irrigated area of Varanasi, India. Food and Chemical Toxicology. vol. 51, no. 2 Suppl., pp. 375–387. 2010.

[52] IPPC. Mitigation of climate change: Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. 2007.

[53] J. Zou, S. Liu, Y. Qin, G. Pan and D. Zhu. Sewage irrigation increased methane and nitrous oxide emissions from rice paddies in southeast China. Agriculture, Ecosystems and Environment. vol. 129, no. 4, pp. 516–522. 2009.

[54] Y. Jiao, Y. Huang, L. Zong, X. Zheng and R. L. Sass. Effects of copper concentration on methane emission from rice soils. Chemosphere. vol. 58, no. 2, pp. 185–193. 2005.

[55] M. A. Ali, J. H. Oh and P. J. Kim. Evaluation of silicate iron slag amendment on reducing methane emission from flood water rice farming. Agriculture, Ecosystems and Environment. vol. 128, no. 1–2, pp. 21–26. 2008.

[56] Y. Xu, J. Ge, S. Tian, S. Li, A. L. Nguy-Robertson, M. Zhan and C. Cao. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. Science of Total Environment. vol. 505, pp. 1043–1052. 2015.

[57] T. Watanabe, T. Mashiko, R. Maftukhah and Nobuo Kaku, D. D. Pham and H. Ito. Rice cultivation and power generation circulated irrigation of treated municipal wastewater. Water Science and Technology in press.

[58] T. Watanabe, S. Kurashima, D. D. Pham, K. Horiguchi, T. Sasaki and J. Pu. Nutrient characteristics of rice for animal feed cultivated with continuous irrigation of treated municipal wastewater. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research), vol. 72(7), III_505-III_514 (in Japanese).