Summary of Doctoral Thesis

Enrollment year: 2018, April
UGAS Specialty: Agricultural and Environmental Engineering
Name: Phung Duc Luc

Title	Reuse of treated wastewater for rice cultivation through continuous sub-irrigation: Assessment on greenhouse gas emissions and heavy metal contamination in the plant-soil system.

Introduction

Rice paddy fields are among the most important anthropogenic sources of CH_4 and N_2O, two of the most potent greenhouse gasses (GHGs) in the atmosphere, due to the traditional flooding irrigation and the increasing use of mineral fertilizers in paddy soils. In the shade of water shortage, the reuse of treated wastewater (TWW) for irrigation in rice paddy fields has become a reliable practice that could free up large amounts of fresh water currently used for agricultural irrigation, making this resource available for other purposes. However, it was argued that irrigation with wastewater would increase GHG emissions from rice paddy fields. In addition, irrigation with wastewater has raised concerns about heavy metal contamination in rice plant-soil systems, which could potentially lead to risks to human health. It is therefore necessary to develop a sustainable wastewater irrigation practice that can reduce GHG emissions from rice paddy fields and reduce the use of mineral fertilizers while improving rice productivity without any potential risks to human health.

An innovative rice cultivation system, namely continuous sub-irrigation with TWW (hereinafter, referred to as CSI), has recently been developed to promote the recycling of resources from municipal wastewater treatment plants (WWTPs) and the cost-effective production of forage rice in Japan. This continuous sub-irrigation system has been shown to have attractive advantages in terms of rice productivity and the nutritional quality of rice grains. However, in order to ensure the sustainable adoption of the novel cultivation system, its environmental footprint needs to be thoroughly investigated. This dissertation therefore acts as a follow-up study based on the body of recent findings, to provide further insight into the practice of CSI with respect to the performance of rice plants, GHG emissions from paddy fields, and heavy metal contamination in the plant-soil system.

Experimental setup, results and discussion

A microcosm experiment was conducted in 2018 to investigate emissions of CH_4 and N_2O and yield capacity of a local forage rice, Bekoaoba, between a conventional cultivation fertilized with high doses of mineral fertilizers (Control) and three CSI systems using different water regimes with zero fertilizer use. The examined water regimes included a constant supply rate of 25 L m^{-2} day $^{-1}$ throughout the crop season (R1), a supply rate of either 25 (R2) or 36 L m^{-2} day^{-1} (R3) from 31 to 114 days after transplantation (DAT) combined with a lower rate of 8.3 L m^{-2} day^{-1} for the other growing periods. The results showed that the CSI systems produced higher yields (10.4 - 11.0 t ha $^{-1}$) with higher rice protein contents (11.3 - 12.8%) than Control (8.6 t ha^{-1} and 9.2%, respectively). All CSI systems markedly reduced CH_4 emissions but the higher supply rates in R1 and R3 significantly increased N_2O emissions compared with Control. The regime R2, which used the appropriate supply rates at the suitable timeframes to meet the N demand of rice plants, was identified as the optimal regime to effectively reduce both CH_4 and N_2O emissions by 84% and 28%, respectively. Furthermore, no adverse effects of TWW irrigation on the accumulation of possible toxic heavy metals, including As, Cr, Cu, Cd, Pb and Zn, was detected in rice grains.

The next phase of this study was to investigate changes in the community structure of CH_4- and N_2O-related soil microorganisms affected by CSI and to link these changes to the gas emissions in order to understand the underlying mechanisms for the GHG mitigation identified in the first experiment. A further experiment was conducted in 2019 to examine two treatments: the CSI system using the optimized water regime R2 and the Control system. The results showed that CSI reduced CH_4 and N_2O emissions by 80% and 66%, respectively, compared with Control. The microbial compositions of methanogenic archaea, methanotrophic, nitrifying and denitrifying bacteria were not significantly affected by the treatments. However, during the reproductive stage, CSI not only markedly inhibited the growth of methanogens in the lower soil layer, but also vastly reduced the abundance of methanotrophs in the upper soil layer, which corresponded significantly to the effective mitigation of CH_4. On the other hand, compared with Control, CSI stimulated a higher abundance of nitrifying and denitrifying bacteria, but this difference did not lead to a marked variation in N_2O emissions between the two treatments, suggesting that the N_2O emission gap between CSI and Control was probably not due to the changes in nitrifying and denitrifying communities, but more likely due to the availability of N in soils and N uptake of rice plants. In addition, soil analysis results showed that CSI significantly increased soil pH, SOM, and SOC ($p < 0.05$) while maintaining soil EC, CEC, N, K, and other macro- and micronutrients at comparable levels ($p > 0.05$) relative to Control. This indicated that CSI was able to effectively fertilize paddy soils despite the elimination of mineral fertilizers. However, a slight decrease in P content in paddy soils under CSI suggested, if necessary, a regular supplementation of P fertilizers. Importantly, the contents of the heavy metals examined in paddy soils were below the maximum permissible levels in agricultural soils recommended by WHO, demonstrating that there was no concern for heavy metal build-up in paddy soils under CSI.

Afterwards, this study expanded its framework to include potential contamination of CuO nanoparticles (NPs) in TWW that could harm rice plants and paddy soils, and subsequently pose risks to human health through the food chain. A follow-up experiment was conducted in 2020 to evaluate the effects of CuO NPs contained in TWW on the rice plant-soil system under CSI. Four hypothetical scenarios of CuO NP contamination in TWW, including 0, 0.02, 0.2, and 2 mg Cu L^{-1} (T1-Control, T2, T3, and T4, respectively) were examined. Another CSI system using TWW contaminated with a bulk source of Cu ($CuSO_4$) at 0.2 mg Cu L^{-1} (T5) was also tested for comparison with T3. The results showed that the contamination of Cu in TWW did not adversely affect rice growth and yield capacity, probably due to the low levels tested. However, a significant accumulation of Cu in paddy soils, roots, and rice grains under T4 compared with the rest of the treatments indicated the concern that Cu could be build up in the plant-soil system under higher levels of CuO NP contamination. Health risk assessment using a Hazard Quotient (HQ) revealed that adults who consume the rice grains harvested in all treatments have a negligible risk of non-cancer health problems caused by Cu.

Conclusion

This study focused on a number of key scientific issues, such as the efficient reuse of wastewater for irrigation, the reduced use of mineral fertilizers, the mitigation of GHG emissions, and the contamination of heavy metals in rice and paddy soils. The application of CSI in rice paddy fields has been shown to be an innovative solution for the cost-effective recovery of valuable resources from effluents, i.e. plant nutrients and irrigation water, which certainly promotes the transition of WWTPs from pure sewage treatment facilities to an important part of a circular economic model focusing on sustainable agricultural production and consumption, resilient management of water and sanitation, and climate change adaptation.