

## Effects of River Sludge Application on Heavy Metal Content in Rice and Soil and Nitrogen Utilization in Rice: Postprint

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### Abstract

From 2013 to 2014, using river sludge from a waterway in Wangting Town, Xiangcheng District, Suzhou City as the research material, with main treatments of farmland application of sludge at  $20 \text{ kg} \cdot \text{m}^{-2}$  and no sludge application, and sub-treatments of nitrogen fertilizer application at  $120 \text{ kg(N)} \cdot \text{hm}^{-2}$  (LN) and  $240 \text{ kg(N)} \cdot \text{hm}^{-2}$  (NN), the japonica rice variety ‘Wuyunjing 24’ was planted for two consecutive seasons to investigate the effects of river sludge application on heavy metal content in rice and soil and nitrogen utilization in rice. The results showed that: 1) River sludge application to farmland significantly increased soil organic matter content, readily available nitrogen content, and heavy metal Cu, Zn, and Pb contents in paddy soil; rice yield increased by an average of 7.05%; heavy metal Cu, Zn, and Pb contents in rice grains increased by 53.66%, 18.71%, and 802.29%, respectively; rice nitrogen uptake increased significantly, while nitrogen use efficiency decreased significantly. 2) After river sludge application, the higher nitrogen application rate (NN) increased soil organic matter content and readily available nitrogen content in paddy soil, had little effect on heavy metal content in paddy soil and heavy metal content in rice grains, significantly increased rice yield and rice nitrogen uptake, but significantly decreased nitrogen use efficiency. 3) Under sludge treatment conditions, compared with the first season, heavy metal Cu, Zn, and Pb contents in paddy soil in the second season decreased by approximately 5.0% on average, and heavy metal Cu, Zn, and Pb contents in grains decreased by 7.27%-12.65%, but all were still significantly greater than those in the control treatment without river sludge application. 4) The interaction effects of sludge  $\times$  nitrogen fertilizer, sludge  $\times$  year, nitrogen fertilizer  $\times$  year, and sludge  $\times$  nitrogen fertilizer  $\times$  year on soil nutrient content, heavy metal content, rice yield, grain heavy metal content, and nitrogen uptake and utilization in rice did not reach significant levels.

## Full Text

# Effects of Dredged Sludge Application on Heavy Metal Content and Nitrogen Use Efficiency in Rice-Soil System

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## Abstract

A field experiment was conducted during 2013–2014 to investigate the effects of dredged sludge application from a river in Wangting Town, Xiangcheng District, Suzhou City, on heavy metal content and nitrogen use efficiency in a rice-soil system. The experiment employed a split-plot design with two main treatments: sludge application at  $20 \text{ kg} \cdot \text{m}^{-2}$  and no sludge application (control). Subplots consisted of two nitrogen application rates:  $120 \text{ kg(N)} \cdot \text{hm}^{-2}$  (low nitrogen, LN) and  $240 \text{ kg(N)} \cdot \text{hm}^{-2}$  (normal nitrogen, NN). The japonica rice variety ‘Wuyunjing 24’ was cultivated for two consecutive seasons. The results showed that: (1) Sludge application significantly increased soil organic matter, available nitrogen, and heavy metal (Cu, Zn, Pb) contents in paddy soil, while rice yield increased by 7.05% on average. However, Cu, Zn, and Pb concentrations in rice grains increased by 53.66%, 18.71%, and 802.29%, respectively. Total nitrogen uptake by rice increased significantly, but nitrogen use efficiency decreased markedly. (2) Under sludge application, higher nitrogen rate (NN) increased soil organic matter and available nitrogen contents but had minimal effects on heavy metal concentrations in soil and rice grains. Rice yield and nitrogen uptake increased significantly, while nitrogen use efficiency decreased. (3) In sludge-treated plots, heavy metal concentrations in soil and rice grains decreased by approximately 5.0% and 7.27–12.65%, respectively, in the second season compared to the first season, but remained significantly higher than the control. (4) Interaction effects of sludge  $\times$  nitrogen, sludge  $\times$  year, nitrogen  $\times$  year, and sludge  $\times$  nitrogen  $\times$  year were not statistically significant for most parameters including soil nutrient content, heavy metal concentrations, rice yield, grain heavy metal content, and nitrogen uptake and utilization.

**Keywords:** Dredged sludge; Nitrogen application rate; Heavy metal; Rice; Rice yield; Nitrogen use efficiency

## Introduction

To increase crop yields, fertilizer inputs in the Taihu Lake region have been continuously increasing. Excess fertilizers applied to farmland are partially lost through runoff to surrounding rivers, and combined with domestic waste and industrial wastewater discharge, have led to elevated nitrogen and phosphorus

concentrations and eutrophication in Taihu Lake watershed. Water quality surveys indicate that in 2008, total nitrogen and total phosphorus concentrations in Taihu Lake reached  $3.5 \text{ mg} \cdot \text{L}^{-1}$  and  $0.2 \text{ mg} \cdot \text{L}^{-1}$ , respectively [1]. Pollutants entering water bodies gradually accumulate in sediments, contaminating the bottom mud. Under certain conditions, contaminants in sediments can be released back into the water through sediment-water exchange, causing secondary pollution and threatening aquatic ecosystem security [2]. Due to their high nutrient and organic matter content, dredged sediments can improve soil fertility and promote crop growth, making agricultural utilization a widely adopted practice in many countries [3-7].

Domestic research on sludge land application has primarily focused on vegetable fields and grasslands [8-13], demonstrating that municipal sludge can increase soil nutrient content and vegetable yields [9-10]. Studies on sludge application in maize (*Zea mays*) fields show that sludge can sustain nutrient requirements for three consecutive maize seasons, significantly increasing yield compared to control [14]. However, research on river dredged sludge is limited, possibly due to the massive engineering and financial requirements for collection and treatment, as well as heavy metal contamination risks. Dai et al. [15] reported that wheat field application of sewage sludge had minimal effects on soil heavy metal content, but sludge-soil mixing ratios exceeding 15% affected wheat (*Triticum aestivum*) growth. To investigate the effects of river dredged sludge from the Taihu Lake region on soil properties, rice yield, and nitrogen utilization, this study combined polluted river remediation efforts in economically developed areas of Jiangsu Province. After determining that the dredged sludge met agricultural application standards, we designed field experiments with and without sludge application to examine effects on heavy metal content in paddy soil and growth and nitrogen utilization of rice (*Oryza sativa*) variety ‘Wuyunjing 24’, providing experimental evidence for energy conservation, emission reduction, and polluted river sludge management in Chinese agriculture.

## Materials and Methods

### 1.1 Experimental Materials

The experiment was conducted in 2013 and 2014 at the Xianglu Village Agricultural Demonstration Park in Wangting Town, Suzhou City, Jiangsu Province ( $31^{\circ}27' \text{ N}$ ,  $120^{\circ}25' \text{ E}$ ). The region has a north subtropical monsoon climate with annual precipitation of approximately 1,100 mm, annual sunshine duration exceeding 2,000 h, mean annual temperature of about  $15.7^{\circ}\text{C}$ , and a frost-free period greater than 230 days. The cropping system follows a winter wheat-rice rotation. The experimental soil is classified as yellow loam. Basic physicochemical properties of the experimental soil and dredged sludge are presented in . Heavy metal concentrations in the dredged sludge were all below the standards specified in the Ministry of Construction’s “Disposal of Sludge from Municipal Wastewater Treatment Plants—Land Improvement” (GB/T24600–2009).

## 1.2 Experimental Design

A split-plot design was employed with four treatment combinations. Main plots consisted of sludge treatments: (1) sludge application (dredged river sludge was air-dried, crushed, and sieved in May 2013, then applied uniformly at  $20 \text{ kg} \cdot \text{m}^{-2}$  before rice season tillage, and mixed with the 0-15 cm soil layer using a rotary tiller), and (2) no sludge application (control). Rice was cultivated for two consecutive seasons in 2013 and 2014. Subplots consisted of nitrogen application rates:  $120 \text{ kg} \cdot \text{hm}^{-2}$  (low nitrogen, LN) and  $240 \text{ kg} \cdot \text{hm}^{-2}$  (normal nitrogen, NN) per season. Each plot measured  $15.0 \text{ m}^2$  with three replications. The rice variety 'Wuyunjing 24' was sown on May 20 and transplanted manually on June 15 at a density of  $24 \text{ hills} \cdot \text{m}^{-2}$  with row spacing of 25 cm and hill spacing of 16.7 cm (3 seedlings per hill). Nitrogen fertilizer was applied in three splits: base fertilizer on June 13, tillering fertilizer on June 20, and panicle fertilizer on July 28. Base and tillering fertilizers accounted for 60% of total nitrogen, while panicle fertilizer accounted for 40%. Phosphorus and potassium were applied at  $60 \text{ kg} \cdot \text{hm}^{-2}$  and  $90 \text{ kg} \cdot \text{hm}^{-2}$ , respectively, as base fertilizers. A compound fertilizer (N-P O -K O: 15-15-15) was used, with supplemental urea (46% N) and potassium chloride (60% K O) to achieve target rates. Water management consisted of maintaining a shallow water layer (approximately 5 cm) from June 14 to July 10, multiple light drying periods from July 11 to August 5, and intermittent irrigation from August 6 to 7 days before harvest. Pest, disease, and weed control were conducted as needed to ensure normal rice growth and development.

## 1.3 Measurement Methods

### 1.3.1 Soil Organic Matter Content

Soil organic matter content was determined using the potassium dichromate method [16]. Soil samples from 0-20 cm depth were collected at mid-tillering, jointing, heading, and maturity stages from each plot. Samples were air-dried, ground, and sieved. Soil organic carbon was oxidized using excess potassium dichromate-sulfuric acid solution under heat, reducing  $\text{Cr O}^2$  to  $\text{Cr}^3$ . The remaining potassium dichromate was titrated with ferrous sulfate standard solution. Organic carbon content was calculated based on potassium dichromate consumption and multiplied by 1.724 to obtain organic matter content.

### 1.3.2 Soil Available Nitrogen Content

Representative soil samples from 0-20 cm depth were collected at mid-tillering, jointing, heading, and maturity stages, then air-dried, ground, and sieved for available nitrogen determination. Soil nitrate-N was measured using  $2 \text{ mol} \cdot \text{L}^{-1}$  KCl extraction followed by UV spectrophotometry, while ammonium-N was measured using  $2 \text{ mol} \cdot \text{L}^{-1}$  KCl extraction followed by indophenol blue colorimetry.

### 1.3.3 Soil Heavy Metal Content

Soil heavy metal (Cu, Zn, Pb) concentrations were determined by HCl-HNO<sub>3</sub>-HF-HClO<sub>4</sub> digestion followed by inductively coupled plasma optical emission spectrometry [17]. The HCl-HNO<sub>3</sub>-HF-HClO<sub>4</sub> acid system with sealed high-pressure digestion vessels was used to extract heavy metals from soil. Inductively coupled plasma optical emission spectrometry detected characteristic radiation emitted by excited atoms or ions of target elements for qualitative and quantitative analysis. The main instruments used were an ETHOSI microwave digestion system (Milestone, Italy) and an ELAN DRC-e inductively coupled plasma mass spectrometer (PerkinElmer, USA).

### 1.3.4 Plant Heavy Metal and Total Nitrogen Content

Plant samples were oven-dried, weighed, ground, and sieved. For analysis, samples were placed in digestion vessels with concentrated nitric acid and hydrogen peroxide, digested using a low-pressure microwave program, cooled to room temperature, transferred to 50.0 mL volumetric flasks, diluted to volume, and mixed thoroughly for measurement [18-21]. National standard plant samples (GSV-1) were used for quality control during heavy metal analysis, with recovery rates for Cu, Zn, and Pb within the acceptable range (93-96%). Total nitrogen content in plants was determined using the semi-micro Kjeldahl distillation method [22].

### 1.3.5 Rice Yield and Yield Components

At maturity, panicle number was surveyed in 100 hills per plot. Based on average panicle number, 10 representative hills were sampled to determine grains per panicle. The water flotation method was used to separate filled grains (sinking) from unfilled grains (floating) to calculate seed-setting percentage and 1,000-grain weight of filled grains, from which grain yield was determined.

## 1.4 Statistical Analysis

Data were analyzed using SPSS 13.0 software, and figures were prepared using Microsoft Excel. Treatment comparisons were performed using the least significant difference (LSD) test. Differences exceeding LSD<sub>0.05</sub> or LSD<sub>0.01</sub> were considered significant or highly significant, respectively.

## Results

### 2.1 Effects of Dredged Sludge Application on Soil Organic Matter Content

The effects of dredged sludge application on soil organic matter content are shown in . The results indicate that: (1) Sludge application increased soil organic matter content by 17.21%, 18.46%, 19.84%, and 18.12% at mid-tillering, jointing, heading, and maturity stages, respectively, compared to the control. (2) Higher nitrogen rate (NN) slightly increased soil organic matter content at different growth stages under both sludge and non-sludge conditions compared

to lower nitrogen rate (LN). (3) Under sludge treatment, soil organic matter content decreased by 7.04%, 11.02%, 13.02%, and 13.58% at mid-tillering, jointing, heading, and maturity stages, respectively, in 2014 compared to 2013. (4) Statistical analysis showed that sludge treatment and year had highly significant effects on soil organic matter content, while nitrogen treatment and interactions of sludge  $\times$  nitrogen, sludge  $\times$  year, nitrogen  $\times$  year, and sludge  $\times$  nitrogen  $\times$  year were not significant. These results demonstrate that dredged sludge application increased paddy soil organic matter content, with higher nitrogen rates favoring organic matter accumulation. Under sludge treatment, soil organic matter content decreased significantly in the second season compared to the first season. Overall, soil organic matter content increased from mid-tillering to jointing, then gradually decreased after jointing.

## 2.2 Effects of Dredged Sludge Application on Soil Available Nitrogen Content

The effects of dredged sludge application on soil available nitrogen content are presented in . The findings show that: (1) Sludge application increased soil available nitrogen content by 26.91%, 28.48%, 36.61%, and 27.60% at mid-tillering, jointing, heading, and maturity stages, respectively, compared to the control. (2) Higher nitrogen rate (NN) significantly increased soil available nitrogen content at all growth stages under both sludge and non-sludge conditions, with average increases of 10.72%, 19.55%, 14.43%, and 13.72% at mid-tillering, jointing, heading, and maturity stages, respectively, compared to LN. (3) Under sludge treatment, soil available nitrogen content increased by 8.52%, 2.84%, and 10.26% at mid-tillering, heading, and maturity stages, respectively, in 2014 compared to 2013, while decreasing by 2.51% at jointing. (4) Statistical analysis revealed that sludge treatment, nitrogen treatment, and year had significant or highly significant effects on soil available nitrogen content, while interactions of sludge  $\times$  nitrogen, sludge  $\times$  year, nitrogen  $\times$  year, and sludge  $\times$  nitrogen  $\times$  year were not significant. These results indicate that both dredged sludge application and higher nitrogen rates increased soil available nitrogen content. Overall, soil available nitrogen content increased from mid-tillering to jointing, then gradually decreased after jointing, following an inverted parabolic trend closely related to fertilizer management, nutrient release patterns from sludge, and crop nutrient uptake.

## 2.3 Effects of Dredged Sludge Application on Soil Heavy Metal Content

The effects of dredged sludge application on heavy metal concentrations in soil at rice maturity are shown in . The results demonstrate that: (1) Sludge application increased soil Cu, Zn, and Pb concentrations by 147.02%, 41.62%, and 36.39%, respectively, compared to the control. (2) Higher nitrogen rate (NN) had minimal effects on soil Cu, Zn, and Pb concentrations under both sludge and non-sludge conditions compared to LN. (3) Under sludge treatment, soil Cu,

Zn, and Pb concentrations decreased by 5.50%, 5.03%, and 5.52%, respectively, in 2014 compared to 2013. (4) Statistical analysis indicated that sludge treatment had highly significant effects on soil heavy metal concentrations, while year had significant or highly significant effects on Cu and Pb. The interaction of sludge  $\times$  year was highly significant for Cu and Pb, whereas nitrogen treatment and other interactions were not significant. These findings show that dredged sludge application increased soil heavy metal concentrations, which decreased in the second season compared to the first season under sludge treatment but remained significantly higher than the control.

#### 2.4 Effects of Dredged Sludge Application on Rice Yield

The effects of dredged sludge application on rice yield are presented in . The results show that: (1) Sludge application increased rice yield by an average of  $63.12 \text{ g} \cdot \text{m}^{-2}$  (7.05% increase) compared to the control. (2) Higher nitrogen rate (NN) increased rice yield by an average of 8.01% under both sludge and non-sludge conditions compared to LN. (3) Under sludge treatment, rice yield decreased by an average of 3.62% in 2014 compared to 2013. (4) Statistical analysis revealed that sludge treatment, nitrogen treatment, year, and the sludge  $\times$  nitrogen interaction had significant or highly significant effects on rice yield, while sludge  $\times$  year, nitrogen  $\times$  year, and sludge  $\times$  nitrogen  $\times$  year interactions were not significant. These results indicate that both sludge application and higher nitrogen rates increased rice yield.

Analysis of yield components showed that: (1) Sludge application increased panicles per unit area, grains per panicle, seed-setting rate, and 1,000-grain weight by 2.96%, 3.55%, -0.05%, and 0.47%, respectively, compared to the control. (2) Higher nitrogen rate (NN) increased panicles per unit area, grains per panicle, seed-setting rate, and 1,000-grain weight by 4.19%, 4.55%, -1.90%, and 1.15%, respectively, compared to LN. (3) Under sludge treatment, panicles per unit area, grains per panicle, seed-setting rate, and 1,000-grain weight decreased by 0.54%, -0.64%, 8.25%, and -4.23%, respectively, in 2014 compared to 2013. (4) Statistical analysis showed that sludge treatment had highly significant effects on panicles per unit area and grains per panicle, nitrogen treatment had highly significant effects on all yield components, and year had highly significant effects on seed-setting rate and 1,000-grain weight. Most interactions were not significant. These results demonstrate that sludge application increased rice yield primarily by increasing panicle number and grains per panicle.

#### 2.5 Effects of Dredged Sludge Application on Heavy Metal Content in Rice Grains

The effects of dredged sludge application on heavy metal concentrations in rice grains are shown in . The results indicate that: (1) Sludge application increased Cu, Zn, and Pb concentrations in rice grains by 53.66%, 18.71%, and 802.29%, respectively, compared to the control. (2) Higher nitrogen rate (NN) had minimal effects on grain Cu, Zn, and Pb concentrations under both sludge and non-

sludge conditions compared to LN. (3) Under sludge treatment, grain Cu, Zn, and Pb concentrations decreased by 12.65%, 7.27%, and 7.83%, respectively, in 2014 compared to 2013. Except for Pb, concentrations met food hygiene standards (GB 2762–2005) for heavy metals (Cu  $10 \text{ mg} \cdot \text{kg}^{-1}$ , Pb  $0.2 \text{ mg} \cdot \text{kg}^{-1}$ , Zn  $50 \text{ mg} \cdot \text{kg}^{-1}$ ). (4) Statistical analysis revealed that sludge treatment had highly significant effects on grain Cu, Zn, and Pb concentrations, while year had highly significant effects on Cu and Pb. Most interactions were not significant. These findings show that dredged sludge application significantly increased heavy metal concentrations in rice grains, which decreased in the second season compared to the first season under sludge treatment but remained significantly higher than the control.

## 2.6 Effects of Dredged Sludge Application on Rice Nitrogen Uptake and Utilization

The effects of dredged sludge application on rice nitrogen uptake and utilization are presented in . The results demonstrate that: (1) Sludge application increased total nitrogen uptake, nitrogen use efficiency for biomass production, nitrogen use efficiency for grain production, and nitrogen harvest index by 9.70%, -4.80%, -8.21%, and -1.61%, respectively, compared to the control. (2) Higher nitrogen rate (NN) increased these parameters by 24.39%, -7.98%, -9.00%, and -2.03%, respectively, compared to LN. (3) Under sludge treatment, total nitrogen uptake, nitrogen use efficiency for biomass production, nitrogen use efficiency for grain production, and nitrogen harvest index decreased by 3.72%, 0.44%, 3.96%, and 0.10%, respectively, in 2014 compared to 2013. (4) Statistical analysis showed that sludge treatment had highly significant effects on total nitrogen uptake, nitrogen use efficiency for biomass production, and nitrogen use efficiency for grain production. Nitrogen treatment had significant or highly significant effects on all nitrogen utilization parameters, and year had highly significant effects on nitrogen use efficiency for biomass and grain production. Most interactions were not significant. These results indicate that dredged sludge application and higher nitrogen rates significantly increased total nitrogen uptake but decreased nitrogen use efficiency.

## Discussion

Soil organic matter is a crucial soil fertility component that continuously supplies various nutrients required for crop growth and improves plant nutrition. Previous studies [23–24] have shown that appropriate municipal sludge application significantly increases soil organic matter content, improves soil structural properties, and positively affects agricultural production. Our study demonstrated that dredged sludge application significantly increased soil organic matter content at different rice growth stages, consistent with previous findings. Higher nitrogen rates also favored soil organic matter accumulation, possibly because adequate nitrogen supply met crop nutrient demands and slowed soil organic matter decomposition. Soil available nutrients are essential elements

readily absorbed by crops and represent a primary factor for evaluating natural soil fertility. Our results showed that higher nitrogen rates significantly increased soil available nitrogen content at different growth stages, consistent with numerous studies. Bai et al. [25] reported that municipal sludge application doubled available nitrogen content in coastal tidal flat soil. In our study, dredged sludge application increased soil available nitrogen content by 20–30% during rice growth, a smaller increase than previous studies, likely because the tidal flat soil in earlier research had lower initial nitrogen content. Additionally, our results showed that soil available nitrogen content in sludge-treated plots remained significantly higher than the control during late rice growth stages, consistent with Zhai et al. [9] who found that sludge application increased soil phosphatase activity and soluble phosphorus content during late cabbage growth stages, indicating that sludge can continuously supply nutrients throughout crop development.

Multi-point surveys indicate that rural river sediments in southern Jiangsu have experienced mild heavy metal contamination, with some sampling sites showing moderate pollution of Cu, Zn, and Pb [26], consistent with our sludge characteristics. Regarding sludge effects on soil heavy metals, Dai et al. [15] reported that sludge application significantly increased soil Cu, Zn, and Pb concentrations but remained below the Grade II standards of China's soil environmental quality standard (GB15618–1995) for neutral soils. Our study showed that although the dredged sludge met land improvement standards, its application significantly increased Cu, Zn, and Pb concentrations in paddy soil at different growth stages, while nitrogen application had minimal effects, consistent with previous research. Xu et al. [14] investigated long-term effects by continuously growing maize and found that after two years and four maize seasons, total Zn and Pb concentrations in sludge-treated soil showed no significant differences from the control. Our study found that under sludge treatment, heavy metal concentrations in soil at rice maturity decreased significantly in the second season compared to the first season but remained significantly higher than the control. Further research is needed to investigate the long-term effects of dredged sludge application on heavy metal content in paddy soil.

Regarding sludge effects on crop yield, Zhai et al. [9] reported that combined application of municipal sludge and phosphorus fertilizer significantly increased cabbage yield while reducing environmental risks from soil phosphorus accumulation. Yang et al. [10] found that municipal sludge alone or combined with urea increased celery (*Apium graveolens*) yield by approximately 15%. Long-term effect studies showed that sludge application sustained maize growth for three seasons with significantly higher yields than the control [14]. Our study demonstrated that dredged sludge application significantly increased rice yield in both 2013 and 2014, primarily by increasing panicle number and grains per panicle, indicating that sludge application improved soil fertility and sustained nutrient supply for crop growth. However, rice yield decreased by 3.62% in the second season compared to the first season under sludge treatment, warranting further investigation into subsequent effects on rice growth and yield. Higher nitrogen

rates increased rice yield under conventional cultivation conditions, consistent with our findings.

Regarding sludge effects on crop heavy metal content, Chen et al. [12] reported that after growing zoysiagrass (*Zoysia japonica*) in sludge-amended soil for three months, Cd uptake in aboveground biomass was approximately 1% of the total Cd applied. Xu et al. [14] found that heavy metal concentrations in maize grains and stems met feed standards after sludge application, and decreased significantly after three consecutive maize seasons to meet food standards. Our study showed that dredged sludge application significantly increased heavy metal concentrations in rice grains. In 2013, Zn and Cd (not detected) concentrations in grains from sludge-treated plots met food hygiene standards, while Cu and Pb exceeded the limits (Cd  $0.1 \text{ mg} \cdot \text{kg}^{-1}$ , Cu  $10 \text{ mg} \cdot \text{kg}^{-1}$ , Pb  $0.2 \text{ mg} \cdot \text{kg}^{-1}$ , Zn  $50 \text{ mg} \cdot \text{kg}^{-1}$ ) [27] but met feed standards [28]. Therefore, rice produced in the first season after sludge application poses food safety risks and should be used as feed. In the second season, grain Cu, Zn, and Pb concentrations decreased by 12.65%, 7.27%, and 7.83%, respectively, with Cu and Zn meeting food hygiene standards, though Pb remained above the limit, restricting use to feed applications. Nitrogen application had minimal effects on grain heavy metal concentrations under both sludge and non-sludge conditions, indicating that fertilizer rates cannot influence soil heavy metal content. Further research is needed on heavy metal accumulation in rice grains from subsequent plantings.

Regarding sludge effects on crop nitrogen accumulation, previous studies showed that lake sediment increased wheat grain nitrogen accumulation by 35.6–292.8% compared to the control, with significant differences among treatments [29]. Our study demonstrated that dredged sludge application and higher nitrogen rates significantly increased nitrogen accumulation in rice plants at maturity, consistent with previous findings. Few studies have reported on nitrogen use efficiency after municipal sludge or lake sediment application. Research on celery growth using composted municipal sludge showed maximum nitrogen use efficiency at nitrogen application rates of  $0.15\text{--}0.38 \text{ g} \cdot \text{kg}^{-1}$  soil [10]. Our study found that dredged sludge application significantly decreased nitrogen use efficiency for both biomass and grain production, indicating that despite similar nitrogen uptake, sludge-treated plots did not show advantages in biological or economic yield compared to the control. This suggests that when combining sludge with chemical fertilizers, appropriate total nitrogen application rates are necessary to improve nitrogen use efficiency, consistent with previous vegetable studies. Therefore, when applying dredged sludge, nitrogen fertilizer rates should be appropriately reduced to improve rice nitrogen use efficiency, minimize nitrogen losses causing groundwater pollution and eutrophication, and enhance both economic and ecological benefits of rice production.

## Conclusions

1. Dredged sludge application significantly increased soil organic matter and available nitrogen contents at different rice growth stages. Although sludge

application increased several heavy metal concentrations in paddy soil, all remained below land improvement standards.

2. Dredged sludge application significantly increased rice yield, primarily through substantial increases in panicle number and grains per panicle. Sludge application significantly increased heavy metal concentrations in rice grains but all remained within feed standards.
3. Under sludge treatment, heavy metal concentrations in both soil and rice grains decreased significantly in the second season compared to the first season but remained significantly higher than the control.
4. Dredged sludge application significantly increased total nitrogen uptake by rice but significantly decreased nitrogen use efficiency. How to balance the contradiction between nitrogen uptake and utilization under sludge application requires further research.
5. The long-term subsequent effects of dredged sludge application on paddy soil properties and rice growth warrant further investigation.

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*Note: Figure translations are in progress. See original paper for figures.*

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