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Research article

Assessing the nutrient removal performance from rice-crayfish paddy fields by an ecological ditch-wetland system

Jun R. Yang [a,b,*], Shihao Tang [a], Yiqi Li [a], Jianqiang Zhu [a,b,**], Zhangyong Liu [a,b]

[a] College of Agriculture, Yangtze University, Jingzhou, 434025, China
[b] Engineering Research Center of Ecology and Agricultural Use of Wetland (Ministry of Education), College of Agriculture, Yangtze University, Jingzhou, 434025, China

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ABSTRACT

Agricultural drainage from catchments significantly impacts aquatic ecosystems due to high nitrogen and phosphorus concentrations in runoff. While original ecological ditches and wetlands have demonstrated effectiveness in nutrient load removal, the overall impact of an ecological ditch-wetland system (EDWS) on agricultural nutrient removal has received limited attention. This study conducted a field experiment to investigate the physicochemical conditions and nutrient removal efficiency of an EDWS for purifying nutrient discharge from rice-crayfish paddy fields. Variations in water temperature (WT), dissolved oxygen (DO), pH, and total suspended solids (TSS) within the EDWS were assessed. Nutrient concentrations—including total nitrogen (TN), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), and soluble reactive phosphorus (SRP)—were monitored from the tillering to the ripening stage of the rice growth cycle. The evaluation of nutrient removal efficiencies in the EDWS revealed that ecological ditches exhibited higher removal efficiencies compared to wetlands. The average total removal efficiencies for TN, NH_4-N, NO_3-N, TP, and SRP were 37.50 %, 39.38 %, 38.62 %, 37.94 %, and 39.51 %, respectively, with peak removal efficiencies observed at specific growth stages of the rice crop. Furthermore, the study explored the influence of hydraulic retention time on nutrient removal efficiency in the EDWS, indicating higher nutrient discharge removal efficiencies under low water discharge rates. Linear regression analysis identified water discharge, influent nutrient loads, and TSS as significant factors affecting nutrient removal efficiency in the EDWS. This study provides valuable insights into the effectiveness of EDWS in purifying nutrient discharge from rice-crayfish paddy fields, highlighting their potential as sustainable solutions for nutrient management in agricultural landscapes.

1. Introduction

Nutrient losses, particularly nitrogen and phosphorus, through runoff from agricultural fields are significant sources of non-point pollution in rural areas [1,2]. Agricultural drainage is often released directly into downstream water bodies without treatment due to fragmentation and inadequate management, leading to water quality degradation and risks to aquatic ecosystems and human health [3,4]. In China, the Bulletin of the Second National Pollution Source Census revealed that agricultural total nitrogen (TN) and total

* Corresponding author. College of Agriculture, Yangtze University, Jingzhou, 434025, China.
** Corresponding author. College of Agriculture, Yangtze University, Jingzhou, 434025, China.
E-mail addresses: junyang2@yangtzeu.edu.cn (J.R. Yang), zyjb@sina.com (J. Zhu).

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phosphorus (TP) discharges accounted for 46.5 % and 67.2 % of total pollutant discharges, respectively [5]. Effective strategies are essential to mitigate the negative effects of agricultural drainage on water quality and to ensure sustainable agricultural practices.

Ecological ditches and wetlands have emerged as promising approaches for nutrient removal from paddy fields while promoting sustainable agriculture [6,7]. These systems mimic natural wetland ecosystems and leverage their ability to remove nutrients from paddy fields. Ecological ditches often serve as canals, while wetlands function as temporary reservoirs for agricultural drainage [8]. Numerous studies have demonstrated the effectiveness of ecological ditches [4,9] and wetlands [7,10] in reducing nutrient discharge from paddy fields. However, most studies on nutrient removal from agricultural drainage specifically by ecological ditches and wetlands have been conducted independently across various countries [11]. Only recently has attention been given to the combined impact of an ecological ditch-wetland system (EDWS) on agricultural nutrient removal [8,12,13].

EDWS comprises a network of strategically placed ditches and wetlands within or adjacent to paddy fields [8,14]. These components facilitate the natural processes of nutrient uptake, transformation, and retention as agricultural drainage flows through them [10,15]. Vegetation within EDWS, including emergent macrophytes and submerged plants, extracts nutrients through their roots, effectively removing nutrients from paddy field discharge [8]. However, nutrient removal efficiency in EDWS can be influenced by factors such as hydraulic characteristics, plant types, sediments, and microbial communities [4,6,16]. Consequently, the nutrient removal process after agricultural drainage enters the ecological ditches and wetlands may exhibit variability. For instance, Soana et al. [17] observed fluctuating nitrogen removal efficiencies based on water retention time and internal environment in ecological ditches. Therefore, further research and practical applications are needed to prioritize the sustainable operation of EDWS and ensure its long-term effectiveness in nutrient removal.

In recent years, integrated rice-crayfish farming systems have gained popularity as innovative and sustainable agricultural practices in China [18]. This integrated farming system, which covered a total area of 1.57×10^6 hm^2 in China in 2022, constitutes 83.93 % of the crayfish aquaculture area [19]. While offering benefits such as increased productivity and enhanced biodiversity, the system also raises concerns about potential environment risks [20]. Excreta and leftover feed from crayfish may elevate nitrogen and phosphorus levels in water, leading to contamination of nearby aquatic ecosystems [21]. Therefore, this study constructed an EDWS to evaluate nutrient removal from rice-crayfish paddy fields in the Jianghan Plain of central Hubei Province, China. The main objectives were (1) to assess EDWS performance in removing nutrients from rice-crayfish paddy fields and (2) to examine the influence of physicochemical variables on nutrient removal in the system.

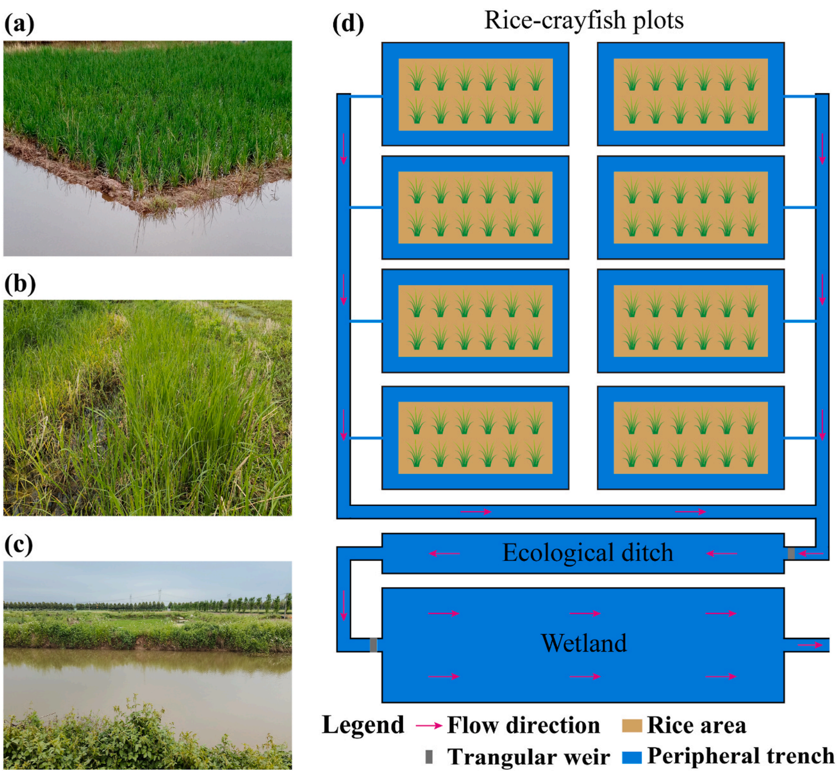

Fig. 1. The test scene of (a) rice-crayfish plots, (b) ecological ditch, (c) wetland, and (d) schematic diagram of the ecological ditch-wetland system (EDWS).

2. Material and methods

2.1. Study area

The experiment was conducted in 2023 at the Taihu Farm in Jingzhou City, Hubei Province, China. The test area is situated in the Jianghan Plain of the middle Yangtze River basin and is characterized by a typical subtropical monsoon climate, with an annual mean temperature ranging from 15.9 to 16.6 °C and annual mean precipitation between 1100 and 1300 mm [22]. The region experiences concentrated precipitation from April to August, coinciding with the hot weather season [23]. Abundant rivers and lakes in this region make it particularly suitable for agriculture activities such as rice cultivation and freshwater aquaculture. The practice of rice-crayfish farming has seen rapid expansion in the region, with approximately 2.0 × 10^5 hm^2 of paddy fields allocated for crayfish breeding (Hubei Statistics Office 2023).

2.2. Experimental design

The EDWS was designed and constructed by interconnecting an ecological ditch and a wetland, with the experimental study

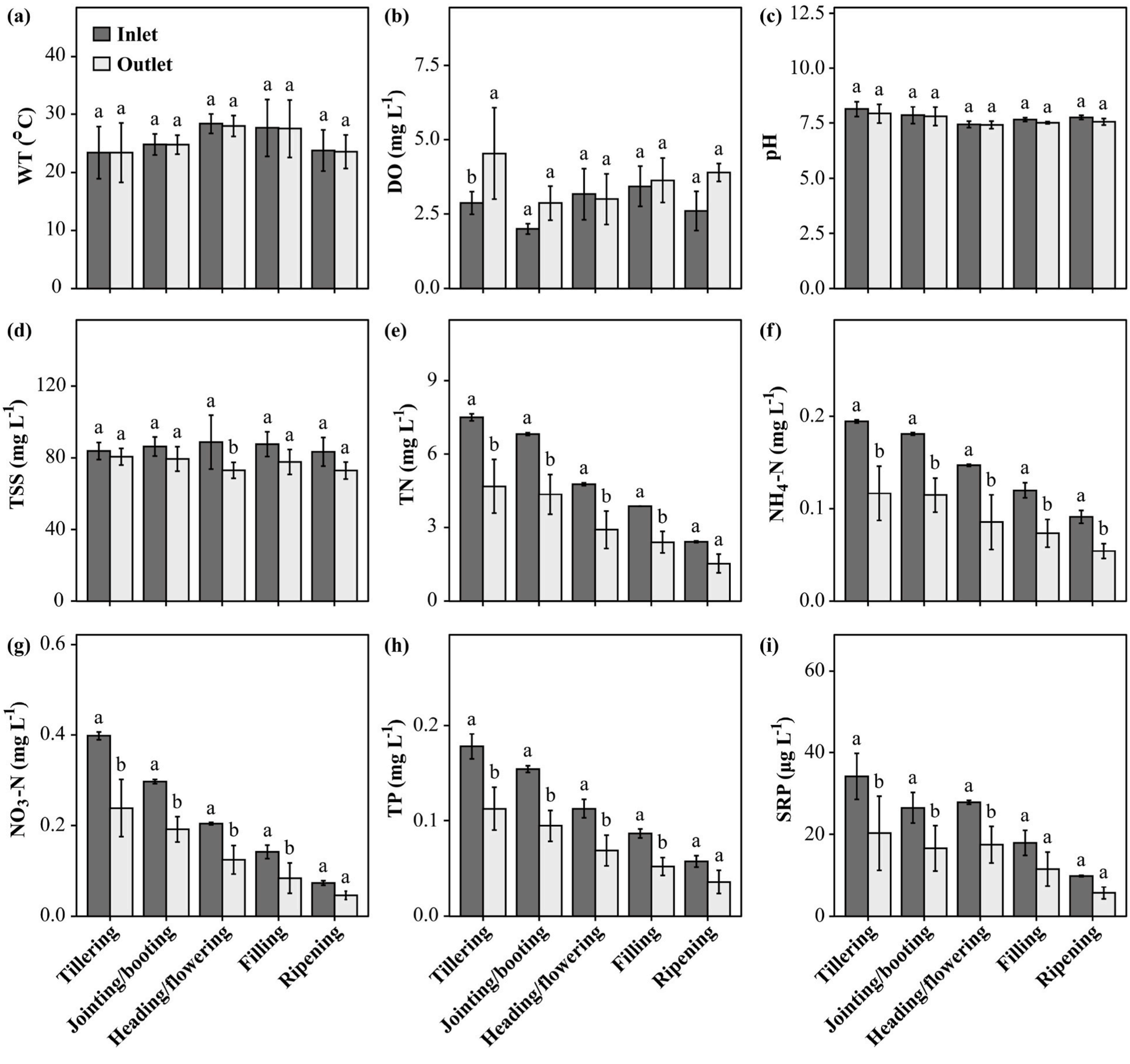

Fig. 2. Physicochemical variables in EDWS. All data are mean ± standard error (SE, n = 3). Different letters indicate significant differences between inlet and outlet water.

conducted during the rice-growing season. The test area consisted of 8 rice-crayfish plots and two discharge ditches (Fig. 1a and d). Each plot was surrounded by four peripheral trenches. The drainage from the rice-crayfish plots first entered the ecological ditch and then proceeded to the wetland for further purification before being discharged into nearby water bodies. Fertilization primarily occurred at sowing and at the "end of tillering" stage.

Each rice-crayfish plot covered an area of 0.9 hm^2, with peripheral trenches measuring 4.6 m wide by 1.1 m deep. The ecological ditch, planted with *Zizania latifolia*, extended 90 m, with top, bottom, and depth widths of 1.5 m, 0.8 m, and 0.5 m, respectively. *Zizania latifolia* coverage exceeded 90 % (Fig. 1b). A lifting triangle weir was installed at the ditch outlet to regulate water flow velocity. The wetland spanned an area of 0.1 hm^2 with a depth of 0.8 m (Fig. 1c), cultivating *Potamogeton crispus* and *Ceratophyllum demersum*. Mid-season rice (Anjingyou 1) was transplanted in mid-May and harvested in late September in all plots.

To assess the impact of rainfall on nutrient removal in the EDWS, an in-situ dynamic water flow simulation test was conducted at five rice growth stages: tillering (from 12 May to 8 June), jointing/booting (from 9 June to 7 July), heading/flowering (from 8 July to 3 August), filling (from 4 August to 28 August), and ripening (from 29 August to 25 September). Three water discharge (Q) levels were established: Q1 (1 $m^3 h^{-1}$), Q2 (10 $m^3 h^{-1}$), and Q3 (20 $m^3 h^{-1}$).

2.3. Sampling and sample analysis

Water samples were collected weekly from both the inlet and outlet of the ecological ditch and wetland after achieving steady water flow in the EDWS. Chemical analyses were performed on 1-L surface water samples collected at each site. In-situ measurements of dissolved oxygen (DO), water temperature (WT), pH, and total suspended solids (TSS) were conducted using a Hydrolab DS5 multi-parameter water quality analyzer (Hach, Loveland, CO, USA). Samples were refrigerated before laboratory analysis. Standard methods [24] were employed to determine chemical parameters in the water samples, including total nitrogen (TN), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), and soluble reactive phosphorus (SRP).

2.4. Statistical analysis

Nutrient removal efficiency in the EDWS was calculated using the following formula:

$$R = (C_{in} - C_{out}) / C_{in} \times 100\%$$

where R represents nutrient removal efficiency, %; and C_{in} and C_{out} denote the nutrient concentrations at the inlet and outlet of the ecological ditch or wetland, respectively, mg/L.

Statistical analyses included one-way analysis of variance (ANOVA) to assess variations among means and T-tests for comparisons

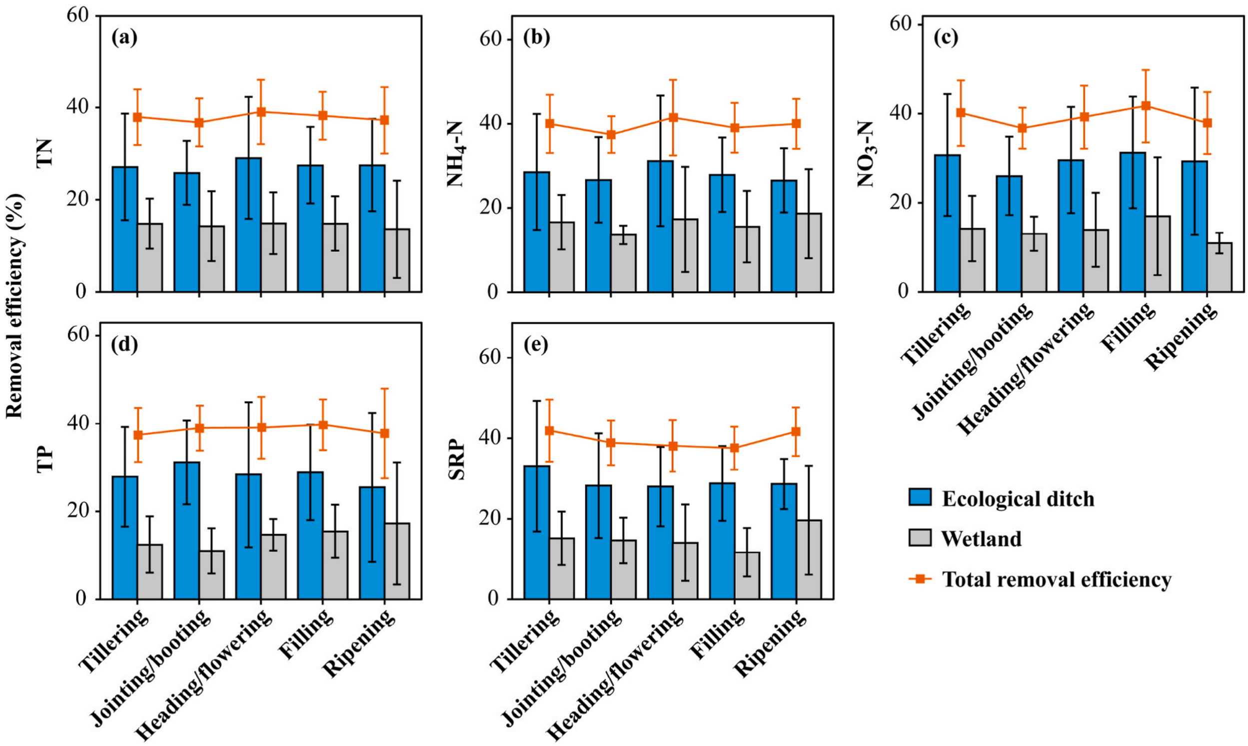

Fig. 3. Changes in nutrient removal efficiencies in ecological ditch and wetland during the study period. All data are mean ± SE (n = 3).

between sampling sites, inlet and outlet nutrient concentrations, and water discharge levels as necessary. A stepwise regression method with forward variable selection was used to evaluate the key physicochemical variables influencing nutrient removal efficiencies in the EDWS. Physicochemical parameters such as DO, WT, TSS, Q, TN, NH_4-N, NO_3-N, TP, and SRP underwent logarithmic transformations to meet homogeneity and variance normality requirements. All statistical analyses were performed using SPSS software (IBM SPSS Statistics 19.0).

3. Results

3.1. Physicochemical conditions in EDWS

WT fluctuated between 17.4 and 32.3 °C (Fig. 2a), with the highest and lowest values recorded during the filling and tillering stages, respectively. The average DO values at the inlet and outlet of the system increased from 2.81 to 3.59 mg L^{-1}, with a minimum of 1.80 mg L^{-1} noted during the jointing/booting stage (Fig. 2b). Water pH remained relatively stable throughout the study period within the EDWS (Fig. 2c). Average TSS concentrations in the inlet and outlet decreased from 85.96 to 76.77 mg L^{-1} (Fig. 2d).

Nutrient concentrations peaked during the tillering stage and declined as rice growth progressed, reaching minimum levels during the ripening stage (Fig. 2). TN and NO_3-N concentrations varied from 1.14 to 7.64 mg L^{-1} and from 0.04 to 0.41 mg L^{-1}, respectively (Fig. 2e–g). Notably, NH_4-N levels decreased significantly from 0.20 to 0.05 mg L^{-1} during the rice growth stages (Fig. 2f). Average TP concentrations remained below 0.2 mg L^{-1} throughout the study period (Fig. 2h), while SRP concentrations ranged from 4.22 to 39.16 μg L^{-1} (Fig. 2i).

3.2. Nutrient removal by EDWS

The purification capacity of the EDWS for nutrient removal from rice-crayfish paddy fields was evaluated (Fig. 3). Nutrient removal efficiencies varied within the system, with ecological ditches exhibiting higher removal efficiencies than wetlands. The average total removal efficiencies for TN, NH_4-N, NO_3-N, TP, and SRP were 37.50 %, 39.38 %, 38.62 %, 37.94 %, and 39.51 %, respectively. Peak removal efficiencies for TN and NH_4-N were observed during the rice heading/flowering stage, while NO_3-N and TP removal efficiencies peaked during the filling stage. The optimal removal efficiency for SRP occurred during the tillering and ripening stages. Furthermore, the average removal efficiencies for TN (27.43 %), NH_4-N (28.20 %), NO_3-N (29.40 %), TP (28.37 %), and SRP (29.36 %) in the ecological ditch exceeded those in the wetland, which were TN (14.48 %), NH_4-N (16.35 %), NO_3-N (13.82 %), TP (14.19 %), and SRP (15.03 %).

Nutrient removal efficiency in the EDWS varied with water discharge (Fig. 4). The highest removal efficiencies under different water discharge conditions were observed for NH_4-N (ranging from 24.67 % to 64.84 %) and SRP (ranging from 23.68 % to 61.80 %),

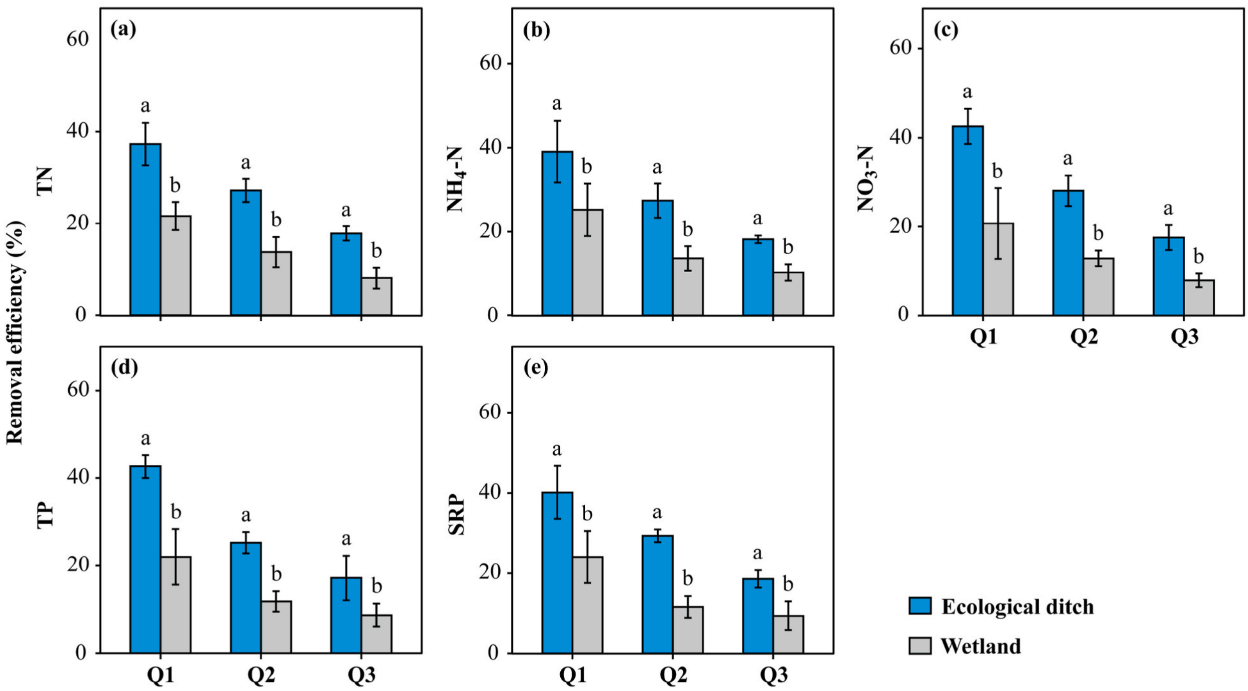

Fig. 4. The nutrient removal efficiency in ecological ditch and wetland under different water discharge conditions. All data are mean ± SE (n = 5). Different letters indicate significant differences between ecological ditch and wetland water.

while TN exhibited the lowest removal efficiencies (ranging from 20.87 % to 56.84 %). Significantly ($P < 0.05$) higher nutrient removal efficiencies were noted in the ecological ditch compared to the wetland. The average removal efficiencies for TN, NH_4-N, NO_3-N, TP, and SRP under different water discharge conditions followed the order of Q1 > Q2 > Q3, indicating that increasing water discharge led to decreased nutrient removal efficiencies.

3.3. Factors influencing the nutrient removal in EDWS

Linear regression models highlighted the significant impact of water discharge, influent nutrient levels, and TSS on nutrient removal efficiency in the EDWS (Table 1). Water discharge showed a significant inverse correlation with the removal efficiency of TN, NH_4-N, NO_3-N, TP, and SRP, explaining most of the observed variability. Additionally, influent NH_4-N loads were positively associated with the efficiencies of TN, NO_3-N, TP, and SRP removal, while influent TSS positively correlated with TN and NH_4-N removal efficiency. Moreover, influent TN, NO_3-N, and TP loads each exhibited negative correlations with their respective removal efficiencies, with influent TP and WT adversely affecting SRP removal efficiency.

4. Discussion

4.1. Effects of rice-crayfish farming system on nutrient discharge from paddy fields

Previous studies have shown that the expansion of the rice-crayfish farming system in China can increase farmers' incomes while posing potential environmental and food security risks [20,21]. For instance, this farming may elevate the risk of gleiing [25], increase nutrient concentrations in surface water [26], and contribute to higher emissions of methane and nitrous oxide [27,28]. The rice-crayfish system requires considerable feed inputs and involve field flooding, which can substantially alter the characteristics of water in paddy fields.

Water temperature varied significantly throughout the rice crop growth stages, peaking during the filling stage and reaching its lowest during the tillering stage. These fluctuations may affect various biological and chemical processes within the ecosystem, including microbial activity and nutrient cycling [27]. The lowest levels of DO recorded during the jointing/booting stage suggest increased oxygen demand at this critical growth phase, potentially impacting microbial activity and nutrient transformations, given that oxygen availability is essential for aerobic processes [29]. The system maintained a relatively neutral pH range, favorable for biological processes [30]. Additionally, there were notably high levels of TSS within the system. TSS serve as a significant indicator of pollutants, particularly nutrients and metals that may be transported on suspended particles. The transfer of these pollutants from solid to aqueous phases could facilitate their entry into the food chain, leading to potential bioaccumulation in surrounding biota [31].

In this study, the concentrations of nutrients—specifically TN, NH_4-N, NO_3-N, TP, and SRP—exhibited fluctuations throughout the various stages of rice growth. High nutrient concentrations were observed during the tillering stage, followed by rapid declines in subsequent growth periods. Farmers often apply substantial amounts of fertilizers to enhance the number of tillers [32] and to offset yield reductions due to low planting densities [33], leading to elevated nutrient levels during the tillering stage.

4.2. Nutrient removal effects in EDWS

Few studies have comprehensively investigated the overall impact of EDWS on nutrient removal from agricultural fields to date (Table 2). Most of these studies have been conducted in China, likely due to the country's significant agricultural status and high levels of pollutants. Generally, the findings suggest that EDWS effectively reduces nitrogen (N) and phosphorus (P) discharges from paddy fields. In this study, the average removal efficiencies for N and P were consistent with those reported by Xue et al. [13] and Han et al. [8], however, they were relatively lower compared to other studies. This difference is primarily attributed to the low hydraulic retention times in the EDWS [13].

Nutrient removal in the EDWS primarily occurs through physical interception, plant uptake, and microbial nitrification and denitrification [8,34]. In this study, the average total removal efficiencies for nitrogen and phosphorus within the EDWS were greater

Table 1
Linear regression models explaining the nutrient removal efficiency of EDWS.

Variables	Linear model	r^2	F
TN	$-4.34 - 0.98^{c}\log Q + 444.58^{c}\log NH_4\text{-}N - 8.96^{c}\log TN + 245.39^{a}\log TSS$	0.90	57.73
NH_4-N	$-8.27 - 1.02^{c}\log Q + 504.95^{b}\log TSS$	0.64	23.55
NO_3-N	$9.26^{a} - 1.15^{c}\log Q + 394.59^{c}\log NH_4\text{-}N - 123.42^{c}\log NO_3\text{-}N$	0.78	30.66
TP	$13.22^{c} - 1.34^{c}\log Q + 552.72^{c}\log NH_4\text{-}N - 453.66^{c}\log TP$	0.83	40.84
SRP	$37.12^{c} - 1.41^{c}\log Q + 527.90^{c}\log NH_4\text{-}N - 450.53^{c}\log TP - 0.84^{a}\log WT$	0.77	21.07

Notes: The models result from a stepwise regression procedure with forward selection of variables. Physicochemical variables used in the models were dissolved oxygen (DO), water temperature (WT), pH, total suspended solids (TSS), water discharge (Q), total nitrogen (TN), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), and soluble reactive phosphorus (SRP).

[a] $0.01 < P < 0.05$.

[b] $0.001 < P < 0.01$.

[c] $P < 0.001$.

Table 2
Summary of studies that investigated the nutrient removal from agricultural drainage by EDWS.

Reference	Ecological ditch (%)		Wetland (%)		Total (%)	
	N	P	N	P	N	P
This study	27.43	28.37	14.48	14.19	37.50	37.94
[8]	18.93	–	25.47	–	48.60	–
[11]	64.61	56.13	75.24	48.84	90.85	77.80
[12]	63.70	30.80	31.10	22.20	74.99	46.16
[13]	8.00–50.40	12.00–69.70	10.00–78.00	5.00–68.40	28.90	21.90
[14]	–	19.67	–	46.60	–	57.10
[34]	49.95	53.22	18.40	23.35	59.60	60.92

'–' no data.

than 35 %, indicating the system's effectiveness in reducing nutrient loads from agricultural runoff [13]. Observations of peak removal efficiencies for nitrogen and phosphorus at different rice growth stages revealed that maximum efficiencies occurred during the mid and late stages of growth, respectively. Reduced drainage from paddy fields and lower rainfall during these stages led to extended hydraulic retention time in the EDWS, allowing for comprehensive nutrient absorption and removal [35]. Notably, the nutrient removal efficiency in the EDWS was relatively lower compared to other studies. This may be attributed to the crayfish waste providing organic fertilizer for the rice, which resulted in comparatively lower nutrient discharge and removal efficiency than traditional farming systems [18,34]. Consequently, these removal efficiencies underscore the potential of EDWS as a sustainable and efficient approach for treating nutrient-rich water from rice-crayfish paddy fields.

Our evaluation of the EDWS for purifying nutrient discharge from rice-crayfish paddy fields demonstrated variations in nutrient removal efficiencies between ecological ditches and wetlands. The results indicated that ecological ditches exhibited higher nutrient removal efficiencies than wetlands throughout the study period. This finding suggests that ecological ditches play a crucial role in nutrient removal within the EDWS, likely due to factors such as hydraulic residence time, substrate characteristics, and microbial activity [4,6,17]. This aligns with findings by Zhu et al. [34], which suggest that ecological ditches are more effective in removing nitrogen and phosphorus from farmland drainage. Given that agricultural drainage initially flows into the ecological ditches, it naturally exhibits higher removal efficiency compared to wetlands. Furthermore, the purification capacity of wetlands is influenced by various factors including pollutant load rates, hydraulic retention time, wetland vegetation, and the ratio of wetland area to field area, resulting in significant performance variability [10,36]. Understanding the specific mechanisms that drive nutrient removal in ecological ditches and wetlands can provide valuable insights for designing and managing strategies to enhance EDWS efficiency for water quality improvement in agricultural environments.

4.3. Factors influencing nutrient removal

4.3.1. Hydraulic retention time

Previous research has established a strong relationship between hydraulic retention time and the nutrient interception process in ecological ditches and wetlands [4,6,36]. This study underscores that water discharge is a significant factor influencing nutrient removal efficiency in the EDWS. Nutrient removal efficiencies were observed to improve as water discharge levels decreased. This trend suggests that higher water discharge rates could dilute and wash away nutrients from the EDWS [37], resulting in lower nutrient concentrations and reduced removal efficiencies. This correlation highlights the importance of managing water flow rates within the EDWS to maintain optimal treatment capacity and effectiveness.

In comparison, ecological ditches consistently demonstrated notably higher nutrient removal efficiencies than wetlands across a range of water discharge scenarios, emphasizing the critical role of specific EDWS components in enhancing nutrient treatment [4]. The superior performance of ecological ditches may result from the robust root systems and high tillering of aquatic plants, which effectively mitigate erosion of the ditch walls and extend hydraulic retention time [38,39].

4.3.2. Influent nutrient loads

The nutrient removal efficiency of aquatic plants is significantly influenced by influent nutrient loads [40]. Generally, higher influent nutrient levels can enhance phosphorus removal, however, exceeding a certain threshold may negatively affect nitrogen removal. Furthermore, insufficient influent organics for denitrification can lead to reduced efficiencies in both nitrogen and phosphorus removal [41]. In this study, the positive correlations between influent TSS levels and the removal efficiencies of TN and NH_4-N suggest that elevated TSS can stimulate nitrogen removal through various physical and biological processes. This occurs because high influent TSS concentrations can increase organic matter levels in the system [42]. Conversely, initial concentrations of nitrogen and phosphorus were negatively correlated with their respective removal efficiencies, suggesting that higher initial nutrient concentrations may lead to diminished removal rates in the EDWS. This finding contrasts with previous studies on nutrient removal from municipal wastewater [43,44]. The presence of crayfish in the rice fields limits fertilizer application, resulting in lower nutrient discharges compared to conventional rice or crayfish farming systems [18]. Consequently, the influent organics in agricultural drainage entering the EDWS are generally low.

4.4. Prospects for EDWS application

Based on the findings of this study, the EDWS has been shown to effectively remove nutrient discharges from rice-crayfish paddy fields. However, various factors, such as hydraulic conditions and nutrient ratios, influence nutrient removal efficiency [41]. This study emphasizes the complex interactions among water discharges, influent nutrient loads, and nutrient removal efficiencies in EDWS. The variability in nutrient removal efficiencies observed under different water discharge conditions and influent nutrient loads highlights the crucial role of hydraulic parameters and nutrient ratios in the design and operation of EDWS for optimal performance. Understanding and leveraging these relationships can enable practitioners and researchers to design and manage EDWS more effectively to alleviate nutrient discharge and enhance water quality in rice-crayfish paddy fields. Therefore, field-specific conditions should be considered when applying EDWS for nutrient removal.

5. Conclusions

This study evaluated the physicochemical conditions and nutrient removal efficiencies of the EDWS in purifying nutrient discharge from rice-crayfish paddy fields. Fluctuations in physicochemical parameters such as WT, DO, pH, and TSS were observed throughout the study period. Nutrient concentrations, including TN, NH_4-N, NO_3-N, TP, and SRP, peaked during the tillering stage and declined as the rice crop matured. The study demonstrated varying nutrient removal efficiencies within the EDWS, with ecological ditches exhibiting higher removal efficiencies compared to wetlands. The average total removal efficiencies for TN, NH_4-N, NO_3-N, TP, and SRP were 37.50 %, 39.38 %, 38.62 %, 37.94 %, and 39.51 %, respectively, with peak efficiencies occurring at specific stages of the rice growth cycle. Additionally, hydraulic retention time was identified as a key factor influencing nutrient removal efficiency in the EDWS, with higher discharge rates correlating with lower removal efficiencies. The significant impacts of influent nutrient loads and TSS on nutrient removal highlighting the intricate interactions of various factors in nutrient removal processes within the EDWS. Our findings underscore the potential of EDWS as an effective and sustainable solution for nutrient removal from rice-crayfish paddy fields. Future research and optimization of EDWS design and operation will be essential for enhancing nutrient removal efficiency and improving water quality in agricultural landscapes.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Jun R. Yang: Writing – original draft, Supervision, Methodology, Conceptualization. **Shihao Tang:** Investigation. **Yiqi Li:** Investigation. **Jianqiang Zhu:** Writing – review & editing, Supervision, Funding acquisition. **Zhangyong Liu:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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