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Original Research

Effects of Irrigation and Nitrogen Management on the Growth and Nitrogen Concentration of Paddy Soil and Rice Plants

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Abstract

Traditional fertilization and irrigation methods have resulted in low nitrogen (N) use efficiency and large N loss. Reducing N fertilizer input is a necessary condition for environmental protection. We investigated the effects of different irrigation and fertilization on rice growth and soil N dynamics. Results showed that the growth of rice under two irrigation regimes was not significant, while the effect of fertilization on growth was significant. The combined application of organic and inorganic fertilizers was beneficial to the conversion of N in the soil, and reduced the N concentration in the paddy soil, as well as reduced the risk of N loss. Compared to the unfertilized control, the application of combined organic and inorganic fertilizers, as well as a controlled irrigation method, promoted N use efficiency, improved rice production, and decreased N pollution to the environment. Taking the indices of the growth of rice, nitrogen accumulation, nitrogen use efficiency into account, the combination of organic and inorganic fertilizer applications and controlled irrigation are recommended to be a proper irrigation and N application strategy for paddy soil and rice plants.

Keywords: irrigation regimes, fertilizer regimes, soil nitrogen, nitrogen accumulation, nitrogen use efficiency

Introduction

Rice is an important staple food worldwide. With global population growth, farmers need to produce more and higher quality rice to meet people's demands. However, the yield of rice is lower than its production potential, which may be due to inappropriate use of chemical fertilizers. Nitrogen (N) is still one of the main factors that restrict agricultural production. The availability of N positively influences crop the growth, N utilization and yield [1]. With the excessive use of chemical fertilizers, more and more serious consequences have been caused, such as nutrient imbalance in the soil, seriously water loss and soil erosion, loss of nitrogen fertilizer and [2].

As the largest nitrogenous fertilizer-consuming country, the utilization efficiency of N fertilizer in China is very low due to surface run-off and leaching. Researchers have suggested that the N fertilizer

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utilization rate of the main grain crops range from 10.8 to 40.5%, with an average of 27.5%, which is far below the international level of 40-60% [3]. The serious loss of soil N and low utilization rates of N fertilizer are serious problems that restrict the development of high-yield, high-efficiency, and high-quality agriculture in China [3]. Instead of conventional application of inorganic fertilizers in agriculture, several studies have recently investigated the combination of inorganic and organic fertilizers as a means of preventing environmental degradation caused by the overuse of fertilizers. Research has shown that combining the application of organic and inorganic fertilizers does only improved the utilization rate of nutrients [3-5] and characteristics of the soil N supply but also, it promoted N, phosphorus (P), and potassium (K) nutrient uptake of rice plants when compared to single applications of chemical fertilizers [6-8]. The combined application of organic and inorganic fertilizers has proven to be a sound method in soil fertility management in many countries [9-11]. For example, grain yield significantly increased by combining inorganic fertilization and irrigation management with crop cultivation technologies in the Taihu Lake region [10]. In addition, the use of organic fertilizer may significantly reduce nutrient-leaching losses and groundwater pollution, thereby protecting the ecological environment [12, 13].

Most studies in recent years have focused on N fertilizer use efficiency in relation to rice growth and yield, while research on the combined application of organic and inorganic fertilizers has mostly focused on the impact of submerged irrigation for rice. With the popularization of water-saving irrigation techniques, controlled irrigation has been widely used in paddy fields in southern China. However, little research has been conducted on the effects of different irrigation and fertilization conditions on the environmental benefits and grain yield. And there are very few studies on the impact on rice growth and nitrogen use efficiency with the combined application of organic and inorganic fertilizers under controlled irrigation conditions. Thus, in this study, we examined the dynamic changes of soil N concentration and the growth and yield of rice under different irrigation and fertilization conditions, including the mechanism of crop N utilization. The aim of this study was to provide a theoretical basis for the efficient utilization of N fertilizers and the reduction of environmental pollution in agricultural production systems [14].

Experimental

Site and Conditions

The experiment was conducted during the 2015-2016 rice-growing season at the Vegetables and Flowers Institute of Jiangning (32°13′N, 119°04′E), Nanjing, China. The experimental site is located in a subtropical humid region, with an average annual rainfall of 1106.5 mm, which falls mostly in the rainy season from the end of June to the middle of September. The average annual evaporation was 1472.5 mm, and the average annual sunshine was 2017.2 h. In addition, the average annual temperature was 15.7ºC, the maximum average humidity was 81%, and the average wind speed was 19.8 m/s.

Experimental Design

We used a split-plot design to study the influence of fertilizer and irrigation regimes on soil physicochemical properties and paddy rice yield. There were two irrigation regimes (conventional irrigation (C1) and controlled irrigation (C2)), and three fertilizer regimes: inorganic fertilizer alone (S1), organic and inorganic fertilizer (S2), and unfertilized control (S3). Rice (cv. Kaohsiung, Taiwan 139) plants were transplanted with a density between 703,500 and 825,000 seedlings per hectare. The sub-plots were 10 m^2, and each treatment was replicated three times. Each plot had isolated irrigation and drainage ditches to prevent the spread of water and fertilizers between plots.

Controlled irrigation technology is a type of water-saving irrigation technology; it allows water to be delivered to crops based on demand during different stages of growth thereby saving water while benefiting crops. It avoids the past practice of continuously flooding rice fields; instead, in the controlled irrigation treatment, maximum soil water content is limited to 70% of saturation. The inorganic fertilizer treatment was $N:P_2O_5:K_2O$ = 15:13:17. It was split-applied at transplanting and approximately 30 days after transplanting (i.e., tillering fertilizer) to give a final level of N in soil. The mixed fertilizer consisted of the inorganic formulation described above plus chicken manure (1.8%N; 28% organic matter). The two fertilizer sources were mixed in a ratio of 6:4 to give N in soil such that the levels of P and K in treatments were consistent. The water and fertilizer treatment designs during the different growth stages of the paddy rice are shown in Table 1.

Measurements and Indicators

Three representative rice plants were sampled every seven days in each plot to determine their plant heights. The plant heights were measured as the average height of plants in the three heights. A leaf area meter was used to measure the green leaf area at the full heading stage. The leaf area index (LAI) was calculated as follows:

$$LAI = A_s / S, \quad (1)$$

...where A_s was the leaf area, and S was the ground area. LAI is an important agronomic parameter that reflects potential crop growth and can be used when predicting

Table 1. The irrigation and fertilizer regimes for different treatments.

Treatment	Irrigation	Fertilizer
C1S1	Conventional irrigation	Inorganic fertilizer
C1S2	Conventional irrigation	Organic and inorganic fertilizer
C1S3	Conventional irrigation	Unfertilized control
C2S1	Controlled irrigation	Inorganic fertilizer
C2S2	Controlled irrigation	Organic and inorganic fertilizer
C2S3	Controlled irrigation	Unfertilized control

crop yield [15]. In fact, the relationship between LAI and rice yield was studied by Zhu et al. [16], who determined that a LAI that was either too big or too small would affect rice growth.

The soil samples were collected using the five-point method from the 0-20 cm and 20-40 cm soil layers. After air-drying and crushing, the soil was passed through a 100-mesh sieve. The total N content was measured using the semi-micro Macro Kjeldahl method, nitrate N was measured with the phenol-disulfonic acid method, and ammonium N was measured with a KCl solution extraction-indophenol blue spectrophotometry method. The specific methods used in this study were followed methods described by Borgognone et al. [17]; Bao et al. [18].

Dry matter accumulation was measured using the drying and weighing method [19]. Samples were separated into leaf, stem, and panicle, and then dried to a constant weight in an oven at 75ºC.

The quantitative indicators of nitrogen use efficiency include agronomy efficiency of nitrogen (AE_N), physiological efficiency of nitrogen (PE_N), surface appearance efficiency of nitrogen (SE_N), and efficiency of nitrogen (E_N). Nitrogen fertilizer use efficiency indices were calculated as follows:

$$AE_N = (Y_N - Y_0) / F_N, \quad (2)$$

$$PE_N = (Y_N - Y_0) / (U_N - U_0), \quad (3)$$

$$SE_N = (U_N - U_0) / F_N, \quad (4)$$

$$E_N = Y_N / U_N, \quad (5)$$

...where F_N is the amount of N fertilizer applied, Y_N is the grain yield in the plot that received N fertilizer, Y_0 is the grain yield in the non-fertilized control plot, U_N is the total N accumulation in plants in the plot that received N fertilizer, and U_0 is the total N accumulation in plants in the non-fertilized control plot.

The yield components for panicle number, kernel weight, and kernel number per panicle were determined in a sample area of 1 m^{-2}. Theoretical rice yield was calculated using formula (6), while the actual yield was recorded from each experimental plot.

$$Y = P \times TGP \times TGW \times 10^{-2} \quad (6)$$

...where *Y* is theoretical yield, kg·hm^{-2}; *P* is productive panicles, m^{-2}; *TGP* is total grains per panicle; *TGW* is thousand grain weight, g.

Statistical Analysis

All data were statistically analyzed using analysis of variance (ANOVA) with SPSS statistical software. The mean differences among treatments were analyzed using Duncan's Multiple Range Test. The homogeneity of variance was tested before the ANOVA analysis. Graphical analyses were done using Excel software [20].

Results

Plant Growth Metrics

Plant Height and Leaf Area Index

Plant height revealed the overall vegetative growth of the crop in response to various management practices. In general, the rice plants grew slowly and exhibited uniformity at the beginning of the growth period, but started showing differences at the tillering stage (Fig. 1). In the jointing-booting and heading-flowering

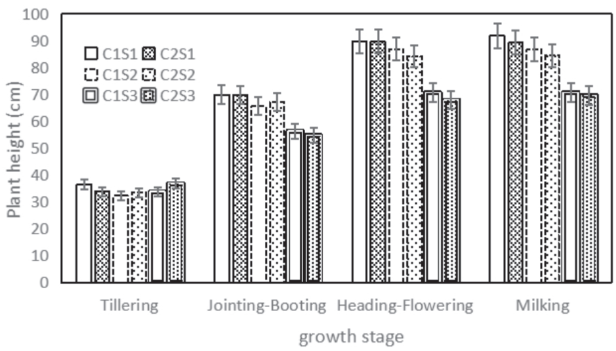

Fig. 1. Plant height of rice subjected to different irrigation and fertilization treatments.

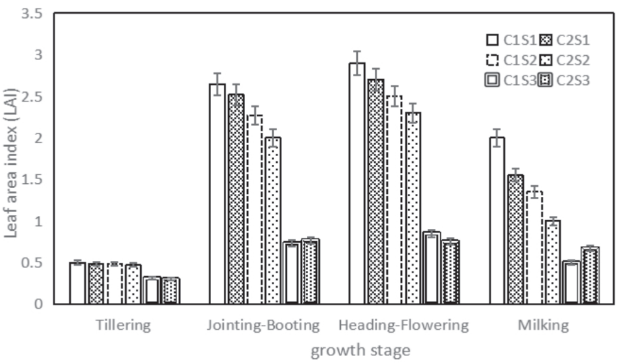

Fig. 2. Leaf area index of rice plants in various growth stages under different treatments.

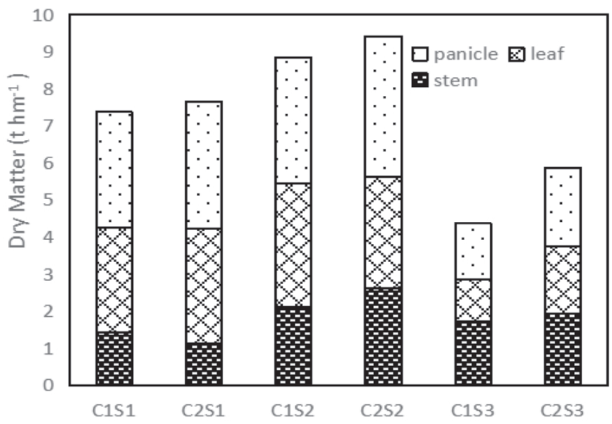

Fig. 3. Accumulated dry matter of rice (by panicle, leaf and stem) subjected to different fertilizer and irrigation treatments.

stages, the differences in plant height were significant (P≤0.05), while in the milking stage, the difference was not obvious relatively. Beginning in the tillering stage, under the same fertilizer application amount, in comparison with the conventional irrigation treatment, the plant height was slightly lower in the controlled irrigation treatment conditions. Under the same irrigation application amount, the fertilizer treatments had a significant effect (P≤0.05) on plant growth during all the different growth stages.

Leaf area index (LAI) was a good indicator of the rice population growth. As shown in Fig. 2, the LAI of all the treatments showed variation, first increasing and then decreasing over the course of the whole growth period. At the beginning of tillering, the rice grew rapidly, establishing a strong root system that transportation a high water and fertilizer uptake ability, and the LAI increased rapidly.[21] LAI reached its maximum in the heading-flowering stage, after which there was leaf senescence and the LAI decreased rapidly. Under the same fertilizer application amount, the peak value for C1S2 and C2S2 were 2.7 and 2.9. while under the same irrigation conditions, the peak value for C2S1, C2S2 and C2S3 were 2.5, 2.9, 0.77. The results of this study showed that the effect of irrigation mode on the LAI was not obvious, and there was a significant effect among the effect of fertilization mode on the LAI.

Dry Matter Accumulation

Dry matter accumulation increased significantly with the application of organic and inorganic fertilizer to rice under all growth stages (Fig. 3). In general, dry matter accumulation increased at a slow rate for the 30 days following transplanting, and then increased at a faster rate up until harvest. The proportion of total dry matter that was panicle dry matter in the the treatment C1S2 and the treatment C2S2 accounted for 49.5% and 42.2%, respectively, under the organic and inorganic fertilizers. The treatment C2S2 did not differ from the treatment C1S2 in the peak amount of dry matter, although the treatment C2S2 had a numerically higher panicle dry matter than the treatment C1S2. Dry matter weights differed significantly among the different fertilization treatments within the controlled irrigation treatment, with higher weights correlated with the organic and inorganic fertilizers (C2S2) compared to the plants receiving inorganic fertilizer alone (C2S1) (Fig. 3). The treatments C2S1 and C2S2 had significantly increased dry matter as compared to the treatment C2S3 by 26.3% and 60.4%, respectively.

At harvest time, on the condition of same fertilization, the total dry matter accumulation in the conventional irrigation treatment (C1S2) was slightly lower than that of the controlled irrigation treatment (C2S2), and under the same irrigation, the treatments that used organic and inorganic fertilizers showed a greater dry matter than those that used inorganic fertilizer alone. The treatment C2S2 achieved the highest dry matter in all treatments.

Yield

The yield of rice is composed of three components: productive panicles per m^2, total grains per panicle, the thousand-grain weight. We found that effective panicles, total grains per panicle, and thousand-grain weight were all significantly increased with controlled irrigation and organic fertilizer additions (Table 2). Under the combined application of organic and inorganic fertilizer, the number of effective panicles, the thousand-grain weight and the grain yield in the treatment C2S2 were higher than in the treatment C1S2, but the total grains per panicle in the treatment C2S2 was lower than in the treatment C1S2. While, under the inorganic fertilizer alone, the number of effective panicles, the total grains per panicle and the grain yield in the treatment C2S1 were lower than in the treatment C1S1, the thousand-grain weight in the treatment C2S1 were higher than in the treatment C1S1. Furthermore, in the unfertilized control treatment, the treatment C2S3 had a lower number of effective panicles, but the total

Table 2. Rice yield and composition by treatment.

Treatment	Yield Composition			Theoretical Yield ($kg \cdot hm^{-2}$)	Grain Yield ($kg \cdot hm^{-2}$)
	Effective Panicles (m^{-2})	Total Grains per Panicle	Thousand-grain Weight ($g \cdot 1000^{-1}$)		
C1S1	270	97	28.64	7500.8	7038.2 Aa
C2S1	259	89	30.15	6949.9	6715.3 Ba
C1S2	261	102	28.07	7472.8	7100.5 Ab
C2S2	277	98	30.62	8312.0	7585.4 Bab
C1S3	217	62	25.47	3426.7	3014.4 Ac
C2S3	206	70	26.83	3868.9	3421.5 Bc
Irrigation × Fertilizer	ns	*	ns	*	*

ANOVA results of no significance (ns) at $P>0.05$ or significant differences (*) at $P\leq0.05$.
For the same fertilization treatment, significantly effects of different irrigation conditions on yield were shown by capital letters (A or B), while for the same irrigation method, the effect of different fertilization treatment on yield were shown by lowercase letters (a, b, or c).

grains per panicle, higher the thousand-grain weight and the grain yield with the treatment C1S3. When compared with the treatment C1S1 , the treatment C2S2 increased the number of effective panicles by 2.6%, the thousand-grain weight by 6.9% and the grain yield by 7.8%. Therefore, the treatment C2S2 showed a clear increase in production when compared to the treatment C1S1. Overall, the different fertilization methods had a significant impact on the yield ($P\leq0.05$), the yield effects of the irrigation method were not significant ($P>0.05$); while the combined yield effect of irrigation and fertilizer application was significant ($P\leq0.05$).

Interaction

Generally, the results showed that the interaction between irrigation regimes and fertilizers was significant on the plant growth metrics (plant height, leaf area index, dry matter accumulation and yield) (Figs 1-3). According to previous studies, the effects of different fertilizer compounds on rice yield and dry matter accumulation were significant [22-24]. Controlled irrigation could increase the nitrogen fertilizer absorption ability of the rice, improving the distribution of dry matter and increasing production [25-29], which we found to be true in this study. The interaction between irrigation and fertilizer regimes could enhance the positive effect on panicle numbers per $\cdot$ m^{-2}, as well as promote rice production. Our results are in agreement with Fazli Hameed et al. [30] who reported that there was still a scope of high yield with lower nitrogen and water applications. The rice plots in the C2S2 treatment showed increased production effects when compared to other treatments, which was likely due to soil moisture under the conditions of the controlled irrigation being more conducive to the efficient use of the organic fertilizer.

N Concentration in Different Soil Layers

The changes in total N (TN), ammonium N (NH_3-N), and nitrate N (NO-N) concentrations in the soil after fertilization are shown in Figs 4-6. Overall, after applying fertilizer, the changes of nitrogen concentrations with different forms in the soil decreased with time afterward. Under the same fertilizer application amount, the TN content in the soil of the conventional irrigation treatment was slightly higher than that of the controlled irrigation treatment. In inorganic fertilizer treatment, the soil TN content in the 0-20 cm layer decreased by 37.9% and 49.2% for C1S1 and C2S1, respectively, and decreased by 31.7% and 42.3% in the 20-40 cm layer, respectively, within 11 days after fertilization. In organic and inorganic fertilizer treatment, TN concentration in soil presents a trend from increase gently within the first three days, and to decrease sharply thereafter. Overall, the soil TN content in the 0-20 cm layer decreased by 37.9% and 49.2% for C1S2 and C2S2, respectively, and decreased by 31.7% and 42.3% in the 20-40 cm layer, respectively, within 11 days after fertilization. Under the same irrigation application amount, TN content decreased with increased soil depth and also decreased with time under each fertilization treatment. The TN content of soil in the combined application of organic and inorganic fertilizer treatment was higher than that in the single-application chemical fertilizer and no fertilizer treatments. The results showed that the soil N absorbed and utilized by rice was not mainly from the chemical fertilizer, and that the combined application of organic and inorganic fertilizer could significantly improve N fertility. In the combined application of organic and inorganic fertilizer treatment, the TN content in the soil was relatively high, but it decreased rapidly with time. Therefore, organic fertilizer promoted the decomposition and transformation of TN in the soil. In

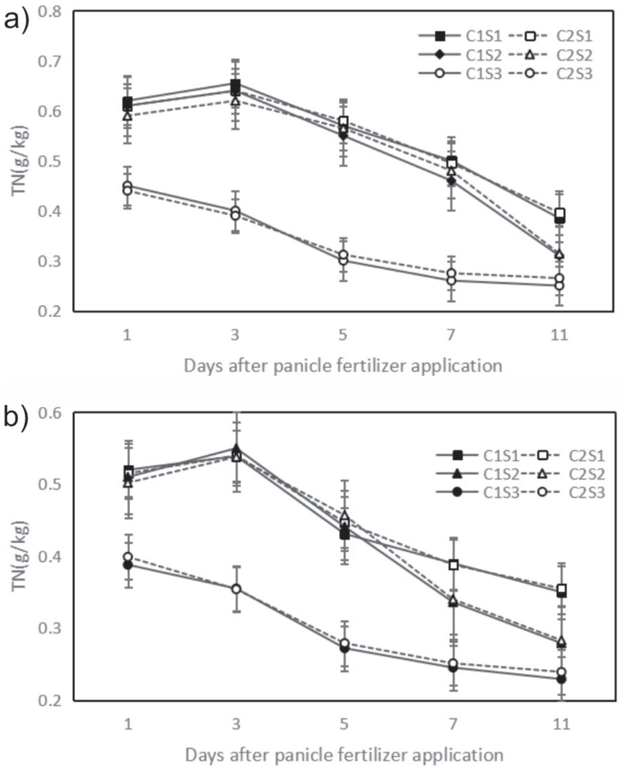

Fig. 4. Variation of the total nitrogen content in different soil layers after panicle fertilizer application: a) 0-20 cm; and b) 20-40 cm.

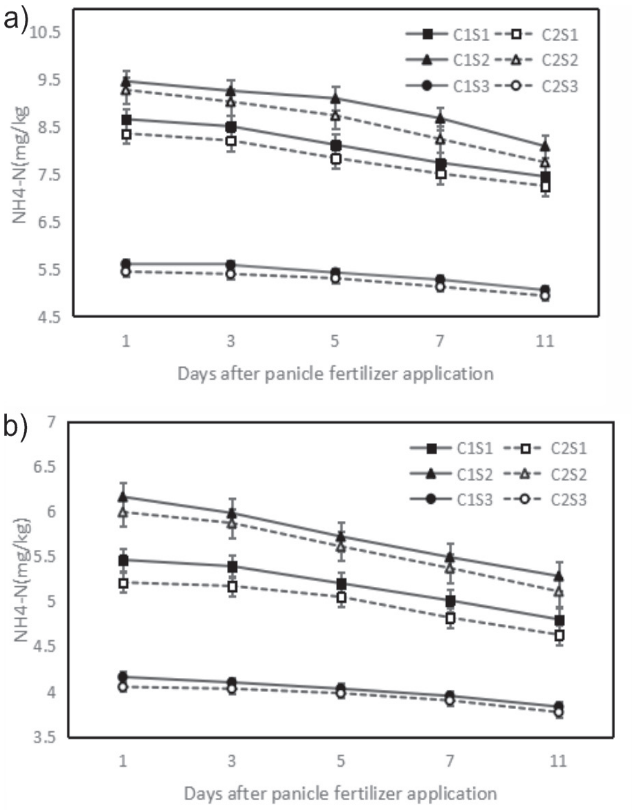

Fig. 5. NH_3-N concentrations in different soil layers: a) 0-20 cm; and b) 20-40 cm.

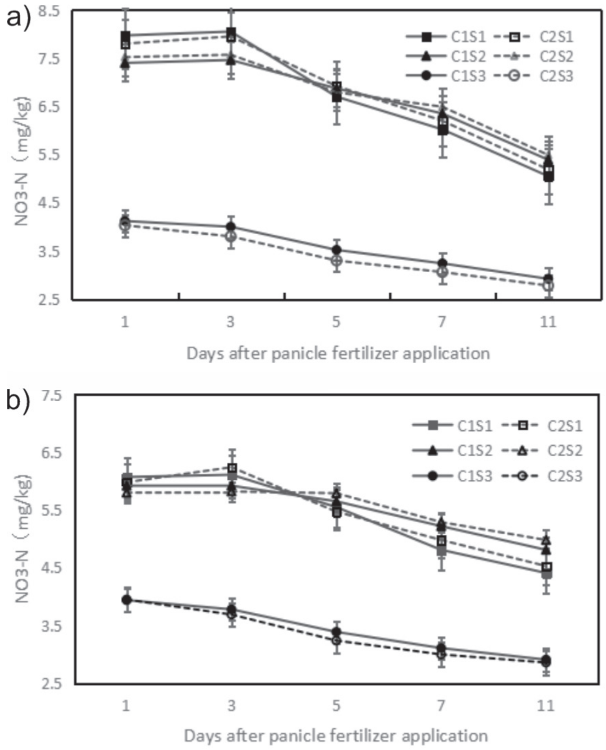

Fig. 6. NO-N concentration concentrations change curve in different soil layers: a) 0-20 cm; and b) 20-40 cm.

the C2S2 treatment, the C2S1 treatment and the C2S3 treatment, the TN contents in the 0-20 cm soil layer decreased by 46.7%, 35.1%, and 39.8%, respectively, and decreased by 43.6%, 31.1%, and 40.1% in the 2 0-40 cm soil layer, respectively. The changes in TN content were the most obvious ($P \leq 0.05$). Within the controlled irrigation, the effect orders of nitrogen factors on TN were as follows, C2S2>C2S1>C2S3. This was because the microbial activity in the soil after the combined application of organic and inorganic fertilizers was relatively large, inducing rapid N transformations and migrationInorganic N in the soil mainly consisted of ammonium N and nitrate N. As shown in Fig. 5, the soil nitrate-N content was decreasing with time because of crop uptaking, nitrogen leaching and denitrification. Under the same fertilizer application amount, the content of ammonium N, the soil nitrate nitrogen content under conventional irrigation was lower than controlled irrigation treatment because of nitrate nitrogen migration deeper into soil with water. In the monitoring stage, the content of nitrate N in the 0–20 cm soil layer decreased by 37.3% and 37.0% in the treatment C1S2 and C2S2. And it showed that the content of nitrate N decreased by 23.5% and 16.6% under the treatment C1S2 and C2S2, in the 20-40 cm soil layer. There is was not a significant difference of nitrate nitrogen content in each soil layer under two irrigation modes. Under the same irrigation conditions, the content of nitrate nitrogen with combined application of organic fertilizer in each soil layer at the beginning was lower than that of single application of chemical fertilizer, while at the end of monitoring cycle which was higher than that of in the application of chemical fertilizer alone. In the monitoring stage, the content of nitrate N in the 0-20 cm soil layer decreased by 50.3% and 37.0% in the treatment C2S1 and C2S2. And it showed that the content of nitrate N decreased by 32.0% and 16.6% under the treatment C2S1 and C2S2, in the 20-40 cm soil layer.

The content of ammonium N treated with the treatment C2S2 was higher than that for the treatments C2S1 and C2S3, and the gap of ammonium N content between the treatment C2S2 and C2S1 decreased gradually with increasing soil depth. Under the same irrigation conditions, the content of ammonium N in the 0-20 cm soil layer decreased by 16.5% in the treatment C2S2 in the monitoring stage, decreased by 13.2% in the treatments C2S1, and decreased by 9.4% in the treatment C2S3. And it showed that the content of ammonium N decreased by 14.7%, 11.1%, and 7.0% under the treatment C2S2, C2S1, and C2S3, respectively, in the 20-40 cm soil layer. The C2S2 was beneficial for the conversion of ammonium N in the topsoil, causing less residue in the soil.

Nitrogen Accumulation

The N accumulation in the straw and grain at harvest is shown in Fig. 7. The total accumulative N uptake ranged from 49.27 kg/ha to 93.52 kg/ha, the treatment C2S3 had the lowest N accumulation. The total accumulation of N in above-ground biomass under different irrigation regimes was in the following order: under the combined organic and inorganic fertilizer was C1S2>C2S2; while under the chemical fertilizer alone was C2S1>C1S1. Under the same irrigation application amount, the total accumulation of N in the above-ground biomass was in the following order: combined organic and inorganic fertilizer>inorganic fertilizer alone>no fertilizer. Therefore, combined applications of organic and inorganic fertilizer were beneficial to N accumulation in the above-ground biomass, but the effect of water conditions on N accumulation varied with fertilizer conditions. The total accumulation of N in rice grains and the total accumulation of N in the above-ground biomass at harvest in the treatment C1S1, the treatment C2S1, the treatment C1S2, the treatment C2S2, the treatment C1S3, and the treatment C2S3 accounted for 67.62%, 67.20%, 69.10%, 68.75%, 58.43%, and 57.75%, respectively. Fertilizer status had a significant effect on the accumulation of N content in grains ($P\leq0.05$), while the irrigation mode had no significant effect on the accumulation of N in the grains or straws ($P>0.05$).

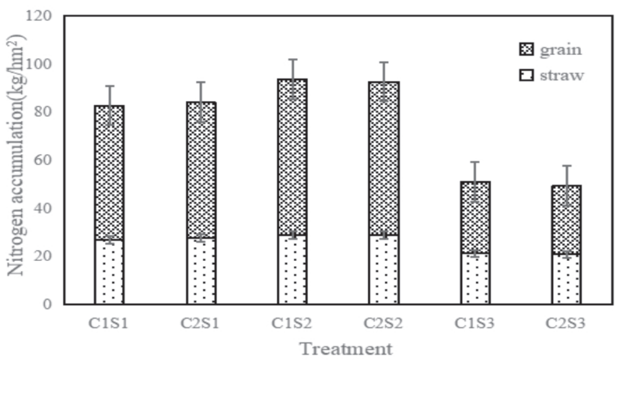

Fig. 7. Nitrogen accumulation and distribution in harvested rice (straw and grain) for different treatments.

Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) refers to the percentage of the applied chemical N fertilizer that is absorbed by rice in the current season, which is an important indicator of rice N utilization [16, 31]. The agronomy efficiency of N under the combined application of organic and inorganic fertilizer was significantly higher than for the single application of a chemical fertilizer. As shown in Table 3, the average NUE in the combined application of organic and inorganic fertilizer treatment was 12.8% higher than in the inorganic fertilizer alone treatment. The conventional irrigation treatment was 8.8% higher than the controlled irrigation treatment. The average physiological efficiency of N in the organic and inorganic fertilizer treatment was 15.3% lower than that of the inorganic fertilizer alone treatment, and the controlled irrigation treatment was 17.0% lower than the conventional irrigation treatment. The NUE values showed that the organic and inorganic fertilizer treatment was higher than the inorganic fertilizer alone treatment, and the controlled irrigation treatment was higher than that of the conventional irrigation treatment. Thus, changes in the N efficiency were the result of the water-fertilizer coupling.

Discussion

In this study, in comparison with the conventional irrigation treatment, the plant height was slightly lower in the controlled irrigation treatment conditions, and the similar conclusion was drawn by Liu. [32] This disparity in plant height with irrigation treatment was because the water-saving irrigation condition in the middle and late stages promoted the transformation of vegetative growth to reproductive growth, thus inhibiting any excessive increases in plant height, and facilitating the formation of compact bottom dwarf inter-nodes of rice. These effects were beneficial to increase the formation of photosynthetic products, which was conducive to increasing the yield potential of the rice plants.

Wei et al. [20] found that water and fertilizer coupling promoted growing development of rice, and the LAI increased rapidly. As expected, the controlled

Table 3. Indicators of nitrogen fertilizer use efficiency.

Treatment	F_N*	Yield	U_N	AE_N	PE_N	SE_N	E_N
	(kg hm^{-2})	(kg hm^{-2})	(kg hm^{-2})	(kg kg^{-1})	(kg kg^{-1})	(0.01kg kg^{-1})	(kg kg^{-1})
C1S1	210	7038.2Aa	82.71	19.16 Aa	127.01 Aa	15.09 Aa	75.09 Aa
C2S1	210	6715.3Ba	84.05	15.68 Ba	94.70 Ba	16.56 Ba	79.9 Ba
C1S2	210	7100.5Ab	93.52	19.46 Ab	96.17 Ab	20.23 Ab	75.92 Ab
C2S2	210	7585.4Bab	92.58	19.83 Bb	96.14 Bb	20.62 Bb	81.93 Bb
C1S3	–	3014.4Ac	51.03	–	–	–	59.07 Ac
C2S3	–	3421.5Bc	49.27	–	–	–	69.44 Bc

With each column, values followed by different letters are significantly different at the 0.05 probability level according to ANOVA.
*F_N = the amount of N fertilizer applied.
U_N = Total N accumulation plants in the plot that received N fertilizer.

irrigation had less effect on the plant height, while the organic and inorganic fertilizers significantly reduced the plant height. And The C2S2 treatment had a significantly higher the plant height and LAI compared with the other treatments. The reason might be that the controlled irrigation condition promoted the transformation of vegetative growth to reproductive growth, thus inhibiting any excessive increases in plant height, and to improved soil ventilation making the root system more developed. These effects were beneficial to increase the formation of photosynthetic products, which was conducive to increasing the yield potential of the rice plants. In addition, the organic and inorganic fertilizers made soil nutrients abundant, which was conducive to rice plant and leaf growth and delayed a decrease in the LAI, thus, this treatment was conducive to the accumulation of photosynthate.

Anzona et al. [33] found that a larger LAI was one important factor to enhance rice photosynthesis, productive panicles and, an increased grain yield. Jun et al. [19] found that the productive panicles per m^2 was influenced by the tiller number and total grains per panicle, thus with the increasing of the tiller number and total grains per panicle, may lead to the increase of the grain yield. Huang et al. [34] also found panicle per m^2 played a critical role in increasing grain production. In this study, under the same fertilizer application amount, there was no significance on total grains per panicle, thousand-grain weight and the yield for the irrigation treatment. Under the same irrigation application amount, the fertilizer treatments had a significant effect on total grains per panicle growth during all the different growth stages, while the thousand-grain weight and the yield were not significant. Also, the interaction between irrigation and fertilization was significant. It was clear that nitrogen fertilizer played an important role in rice yield formation.

Table 4. Correlation matrix for grain yield, productive panicles, thousand-grain weight, total N uptake, and soil total nitrogen.

	GY	PP	TGW	TNU	STN
GY	1	0.87**	0.67*	0.89**	0.53*
PP		1	0.53^{ns}	0.65^{ns}	0.028^{ns}
TGW			1	0.62*	0.52*
TNU				1	0.71**
STN					1

*, ** and ns denote significance at the 5% and 1% level of probability and non-significance, respectively.
GY, PP, TGW, TNU and STN represent grain yield, productive panicles, thousand-grain weight, total N uptake, and soil total nitrogen, respectively.

Effects of Irrigation and Fertilization on Nitrogen Accumulation and Utilization

In our study, the pathways for N loss in the topsoil of the paddy fields mainly included absorption and utilization by the rice, ammonia volatilization, and loss via surface runoff. In contrast, the pathways for deep soil (20-40 cm) N loss were mainly due to absorption and utilization of rice as well as and leaching, which coincided with the research of Jun et al. [19]. Many previous studies have highlighted that an application of inorganic fertilizer alone causes high losses of nutrients, especially N. These high N losses lead to environmental pollution, including water eutrophication, groundwater pollution, and emissions of greenhouse gases [35]. Sun et al. [36] indicated that nitrate N was the main form of N in the soil, and the input of organic fertilizer was effective at reducing the soil ammonium N content in the soil. The papers on the same experiment have showed that organic fertilizers application increased the total nitrogen content and the nitrate nitrogen content, and it was effective at reducing the soil ammonium N content in the soil. [36, 37] These research results are the same with the present study. Wang et al. [38] found that water and fertilizer were important factors determining nitrate leaching. Rational applications of organic fertilizer could help to reduce the accumulation of nitrate N in soils, and also reduce the risk of nitrogen loss [39]. This result also occurred in the present study, the controlled irrigation was conducive to the absorption and utilization of nutrient elements by roots, causing the residual N content in the soil to be relatively low. Maintaining the same N rate and replacing chemical fertilizers with organic fertilizers could effectively reduce the N concentration in paddy soils, thereby reducing the risk of N loss. To alleviate the losses of N and improve fertilizer efficiency, using a combination of organic-inorganic fertilizer applications and controlled irrigation was recommended. The combined application of organic and inorganic fertilizers combine the quick-acting characteristics of chemical fertilizers with the persistence of organic fertilizers. This combination has been shown to improve land productivity and soil properties [40-43].

According to some studies, optimization of water and nitrogen management for paddy soils could significantly enhance water and fertilizer use efficiency [44,45]. In this study, we observed that N fertilizer use efficiency increased in the C2S2 treatment, while the N utilization efficiency varied with water conditions. Therefore, the efficient use of N fertilizer in a paddy field was the result of the combined effect of water and N, which coincided with the research of other researches. We observed that the N accumulation, N use efficiency, and there were significant correlations between grain yield, productive panicles, thousand-grain weight, total N uptake, and soil total N (Tables 3 & 4). As shown in Table 4, productive panicles were significantly related to grain yield with a correlation coefficient of 0.87, and total N uptake was most significantly related to grain yield with a correlation coefficient of 0.89. In the present study, internal N utilization efficiency was influenced by irrigation and fertilization. With inorganic fertilizer application alone, the fertilizer efficiency response to rice was very low, while the combined application of organic and inorganic fertilizers was beneficial to nutrient accumulation and promoted nutrition resource utilization efficiency. Given this situation, it was easy to understand the recommendation of S.K. White [46] to stop applying chemical fertilizer alone, and instead maintain organic inputs. As such, it is necessary to increase both yields and N use efficiency to avoid environmental problems associated with excessive inorganic fertilizer applications and irrigation, as well as to improve the profitability of rice production.

The application of organic fertilizer plays an active role in regulating nitrogen fertilization supply and nitrogen distribution, thus contributing to improving N use efficiency. Although the N supply capacity in the early stage is not as good as that in the single application of chemical fertilizers, the N nutrition status of the rice in later growth periods was better than that of the chemical fertilizer application alone, particularly with the release of organic fertilizer N. Organic fertilizers not only supplement the soil nutrients in the paddy field, but also regulate the release intensity and rate of soil and chemical fertilizer nutrients. As a result, the rice receives more balanced nutrition during each growing stage.

Conclusions

In this study, we highlighted that the integrated application of organic and inorganic fertilizers and controlled irrigation is effective at enhancing the growth, yield, and yield components of rice. The C2S2 treatment showed the best performance in terms of N use efficiency, growth parameters, and rice yield. The controlled irrigation and organic and inorganic combination of fertilization used in our study had a number of advantages, including promoting N use efficiency, effectively reducing the N concentration in soil, and reducing the risk of N loss. It is essential to find ways to reduce environmental impacts in order to meet increasing consumer demands and sustainability goals. Considering the negative effects of conventional irrigation and fertilization methods, the combined application of organic and inorganic fertilizers with controlled irrigation was useful not only for improving rice yield, but also for promoting sustainable agricultural practices.

Compared to regular irrigation and fertilization methods, we found that controlled irrigation and the use of a combination of organic and inorganic fertilization had several advantages. While controlled irrigation and organic and inorganic fertilization showed potential for improving the efficiency of N use and the resulting grain yield, our results suggest that other factors, such as crop establishment, plant density, and pest management, are limiting yields, which must be understood and addressed before considering methods for improving N efficiency and crop yields.

Conflict of Interest

The authors declare no conflict of interest.

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