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Soil Nitrogen Distribution Affects Nitrogen Utilization and Yield of Drip-Irrigated Rice

Juanjuan Li [1,2,†], Changnan Yang [1,2,†], Xuezhi Zhang [1,2], Shengbiao Wu [1], Hailong Chi [1], Xinjiang Zhang [1,2,*] and Changzhou Wei [1,2]

1 Department of Agricultural Resources and Environment, College of Agriculture, Shihezi University, North 4th Street No. 221, Shihezi 832003, China; ljj6741@126.com (J.L.); changnanyang@126.com (C.Y.); czwei@shzu.edu.cn (C.W.)
2 Key Lab of Oasis Ecology Agriculture of Xinjiang Production and Construction Group, Shihezi University, North 4th Street No. 221, Shihezi 832003, China
* Correspondence: zhangxj@shzu.edu.cn; Tel.: +86-181-1926-8389
† These authors contributed equally to this work.

Abstract: The cultivation of drip-irrigated rice has resulted in lower yields. However, the decrease in rice yield under drip irrigation and its relationship with the existing water and N regime have not been fully explained. Research and development of optimized water and N-management techniques are crucial for increasing rice yield under drip irrigation. In this study, two irrigation treatments were set: conventional drip irrigation (DIO) and drip irrigation with water stress (DIS). Each irrigation treatment contained four N rates: urea N 240 kg ha^{-1} (LN), urea N 300 kg ha^{-1} (MN), urea N 360 kg ha^{-1} (HN), and ammonium sulfate N 300 kg ha^{-1} (AN). The soil's ammonium and nitrate contents were measured on the 2nd and 28th days after N application at panicle initiation stage. At anthesis, the aboveground and root biomass of rice were measured. In heading and maturity stage the N content of aboveground was measured and the yield, yield components, and NPFP were assessed at maturity stage. The results showed the following: (1) On the second day after N application, the contents of soil NO_3^--N and NH_4^+-N in the 0–10 cm soil layer were highest for both the DIO and DIS. On the 28th day after N application, the soil NO_3^--N content was highest at the 20–40 cm depth, while the soil NH_4^+-N content was still highest at the 0–10 cm depth. (2) The aboveground and root biomass in DIO treatment were significantly higher than in DIS. Furthermore, the root biomass at the 0–10 cm depth was significantly greater than at the 10–50 cm depth for both the DIO and DIS treatments. In the DIO treatment, the root biomass at the 10–50 cm depth was significantly higher with the HN and AN treatments compared to MN. However, in the DIS treatment, the root biomass at the 10–50 cm depth did not show significant differences between the MN, HN, and AN. (3) N accumulation in rice was significantly higher for the DIO treatment compared to the DIS treatment. Under the same irrigation treatment, the N accumulation in rice was highest in the AN and lowest in the LN. The PrNTA and PrNTC in DIS were significantly higher than in DIO, while the PoNAA and PoNAC were significantly lower in DIS. (4) The number of panicles, spikelets per panicle, seed-setting rate, 1000-grain weight, and grain yield were significantly lower in DIS. Under the DIS, these parameters were not significantly different among the MN, HN, and AN. In the DIO, the seed-setting rate, 1000-grain weight, and yield were not significantly different between the HN and AN, but were significantly higher than in the MN and LN. (5) NPFP was significantly higher in the DIO compared to the DIS. Among the different N rates, NPFP was highest with the AN treatment and lowest with the LN. In summary, under drip irrigation, there was a mismatch between soil mineral N and the distribution of rice roots, leading to reduced N accumulation and utilization in rice, ultimately impacting yield formation. Increasing N application and soil ammonium nutrition can improve rice yield under drip irrigation. However, optimizing N fertilizer management may not increase rice yield further when irrigation is further limited.

Keywords: rice cultivation; nitrogen absorption; root distribution; soil mineral nitrogen

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1. Introduction

Rice (*Oryza sativa* L.) is one of the world's major staple crops [1], and also one of the most water-dependent crops, accounting for over 43% of the total agricultural water usage for irrigation [2,3]. The global population growth, climate change, and severe shortage of available arable land and irrigation water pose significant threats to agricultural production systems [4]. To address the global freshwater shortage issue, it is essential to enhance water productivity and to conserve water resources via water-saving technologies [5]. Drip irrigation, as an effective method of water-saving irrigation in crop production, has been widely adopted in water-scarce regions [6,7]. Drip-irrigated rice cultivation has steadily developed and is considered a crucial agronomic technology for addressing food security and water conservation in arid regions min Xinjiang, China [5]. Specifically, compared with traditional flooded rice production, drip irrigation can save 65% of water and increase fertilizer utilization by 10% [8,9]. However, the yield of drip-irrigated rice (5.9–8.7 $t \cdot ha^{-1}$) has fallen far below the expected target (10.9–12.05 $t \cdot ha^{-1}$) recently [10]. The reason for this discrepancy is the occurrence of rice spikelet degeneration in drip-irrigated rice [11], yet the mechanism behind this phenomenon has not been well explained. In addition, it is very important that optimized irrigation and N application to improve the yield of drip-irrigated rice are explored further.

Water and N application are crucial for maintaining crop productivity [12]. In dryland soils, nitrification results in the predominance of nitrate in N forms, while in anaerobic flooded soils, ammonium is prevalent. During the process of cultivating drip irrigation, the soil is under suboptimal irrigation conditions, and the primary form of nitrogen in the soil is inorganic nitrate nitrogen. Irrigation significantly enhances the migration rate of soil nitrate nitrogen compared to ammonium nitrogen. [13]. Rice requires a significantly higher amount of water for growth compared to other crops; thus, the amount of irrigation water and frequency for drip-irrigated rice production is much higher than that for other locally drip-irrigated crops (the irrigation frequency for drip-irrigated rice is usually every 3 days, and the irrigation water volume is generally two to three times that of conventional drip-irrigated cotton and maize). The high-frequency and high-volume irrigation pattern may lead to a mismatch between the distribution of soil mineral nitrogen and nitrogen uptake by rice roots, and this may further impact rice yield formation. Currently, there has not been sufficient research. N accumulation, distribution, and transportation in various organs is closely related to plant yield formation [14]. Proper N application can promote root development, enhance water and N absorption, and can ultimately increase grain yield [15]. The absorption and utilization of N in rice are influenced by different N forms, N-application rates, timing, and methods. Studies have found that rice prefers ammonium nitrogen to nitrate; ammonium application can improve the rice's ability to adapt to water stress [16]. Different forms of N supply also affect plant N absorption, assimilation, and transportation [17]. Research has shown that compared to the sole supply of either ammonium or nitrate, simultaneous external supply of NH_4^+-N and NO_3^--N can promote biomass and grain yield in rice [18,19]. Irrigation and N application significantly influence post-anthesis N absorption and transportation, N use efficiency, and grain yield [20]. Reasonable nitrogen application can promote the nitrogen transportation from pre- and post-anthesis organs to the grain [21], increase the vertical distribution gradient of nitrogen among canopy leaves, and enhance the nitrogen transportation and contribution to the grain, ultimately resulting in a higher grain yield. [22]. Additionally, it has been found that with increased irrigation volume and frequency, crop N uptake significantly increases pre- and post-anthesis but is also accompanied by an increase in NO_3^--N leaching [23,24]. Whether the irrigation and nitrogen application strategy of drip irrigation in rice cultivation can maximize nitrogen uptake efficiency, and whether optimizing the irrigation and nitrogen application strategy can further improve rice yield, still needs further exploration. In this study, a two-year field experiment with two different irrigation treatments and four nitrogen levels was conducted on drip-irrigated rice. The main hypothesis of this research is that the current irrigation system for rice might not be conducive to nitrogen absorption and root growth, and that optimizing the irrigation method and nitrogen application system may increase the yield of drip-irrigated rice. The main purpose of this study is to elucidate the correlations between different drip irrigation methods, nitrogen application levels, rice root growth, soil nitrogen distribution, nitrogen uptake and transport, as well as their relationship with yield formation. This study can provide theoretical basis and technical references for achieving more efficient rice cultivation techniques in arid regions.

2. Materials and Methods

2.1. Experimental Site Description and Rice Growth Conditions

The field experiments were conducted at the Agricultural Experiment Station of Shihezi University, located in Shihezi City, Xinjiang Uygur Autonomous Region, China, in 2022 and 2023. The coordinates are 44°19′9″ N latitude and 86°0′39″ E longitude. The annual average relative humidity is 60.13% and average wind speed is 1.45 m/s, with an altitude of 412 m. The soil type is meadow soil and the climate is characterized by a temperate continental climate, the average temperature is18.5 °C, and an annual sunshine duration of 2721 to 2818 h. The basic physical and chemical properties of the soil are presented in Table 1.

Table 1. Physical and chemical properties of soil at 0–40 cm depth in experimental site.

Year	Organic Matter ($g \cdot kg^{-1}$)	Alkali Hydrolyzable N ($mg \cdot kg^{-1}$)	Olsen-P ($mg \cdot kg^{-1}$)	Available K ($mg \cdot kg^{-1}$)	Bulk Density ($g \cdot cm^{-3}$)	Filed Water Capacity (w%)
2022	20.4	51.2	9.7	315.5	1.30	23.1
2023	19.3	54.3	10.5	321.3	1.37	24.7

2.2. Experimental Design

The design included a two-factor completely randomized experiment of irrigation management (Irrigation: I) and different N-management practices (N fertilization: N), with three replicates for each treatment. The irrigation management consisted of the following: (1) drip irrigation throughout the entire rice growth period (DIO, from dry-seed sowing to seedling emergence and growth to the three-leaf stage until physiological maturity, with soil moisture controlled at 90–100% of field water holding capacity); (2) drip irrigation with water stress throughout the entire rice growth period (DIS, from dry-seed sowing to seedling emergence and growth to the three-leaf stage until physiological maturity, with soil moisture controlled at 80–100% of field water holding capacity). Under each irrigation management, four N-fertilization treatments were implemented: urea N 240 kg ha^{-1} (LN), urea N 300 kg ha^{-1} (MN), urea N 360 kg ha^{-1} (HN), and ammonium sulfate N 300 kg ha^{-1} (AN). The N application rate of 300 kg ha^{-1} is the conventional N application rate for drip-irrigated rice in arid areas of Xinjiang. LN and HN represent a 20% reduction and increase, respectively, from the conventional N application rate. The AN treatment employed ammonium sulfate + DMPP, with the amount of DMPP added at 1% of the N application rate. In total, there were eight treatments, each with three replicates, and each plot measured 7 m × 2 m.

A planting pattern of 1 film, 2 tubes, and 4 rows was adopted in the experiment. The sowing range was 1.25 m, the plant spacing was 10 cm, and the row spacing was 10 cm + 26 cm + 10 cm, as shown in Figure 1. With a sowing depth of 2–3 cm, a spacing of 10 cm between plants, and a row spacing of 26 cm. Manual direct seeding was performed with 6–8 seeds per hill, with a sowing density of 3.0×10^5 hills per hectare. After emergence, the rice was thinned to 6 plants per hill at the three-leaf stage. The rice cultivar "Liangxiang 3" was planted (*Oryza sativa* L.). on April 30th in both 2022 and 2023, with harvesting on September 30th in 2022 and October 15th in 2023. During the entire growth period, the rice was fertilized with P_2O_5 at 110 $kg \cdot ha^{-1}$, K_2O at 70 $kg \cdot ha^{-1}$, water-soluble silicon fertilizer at a rate of 30 $kg \cdot ha^{-1}$, boron fertilizer at a rate of 7.5 $kg \cdot ha^{-1}$, and zinc fertilizer at a rate of

6 kg·ha^{-1}. The N fertilizer used was urea (containing 46% N), the phosphorus fertilizer used was ammonium phosphate (containing ≥ 50% P_2O_5), and the potassium fertilizer used was potassium sulfate (containing ≥ 52% K_2O). The amounts of phosphorus and potassium fertilizer were consistent across all treatments. All fertilizers were applied in three split applications: at seedling emergence to tillering, at tillering to panicle initiation, and at panicle initiation to maturity, with a N fertilizer ratio of 4:3:3. Other field management measures were similar to local conventional management methods.

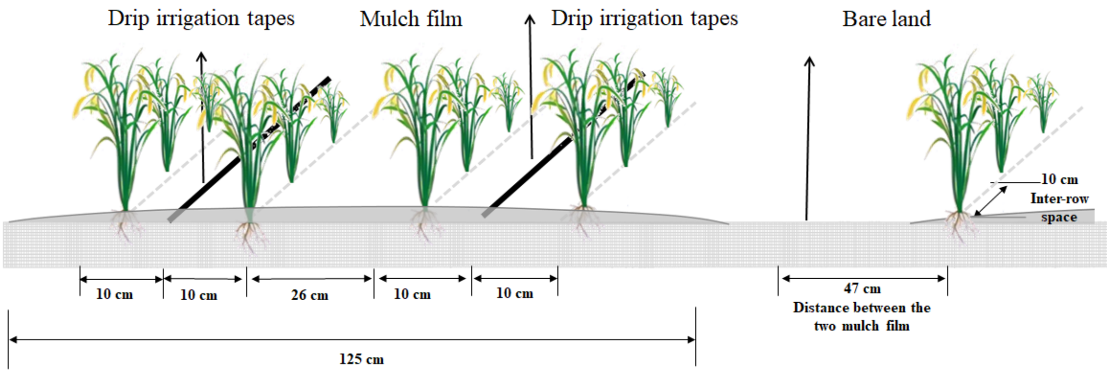

Figure 1. Planting mode for drip irrigation under plastic-film mulching.

Time domain reflectometer (TDR) technology (TRIME-TDR, IMKO, Germany) was used to monitor soil moisture content for irrigation management. During the experiment, soil moisture content at different depths (0–20 cm, 20–40 cm, 40–60 cm) was monitored at a fixed time each day (09:00 a.m.). When the soil moisture content (0–20 cm) fell below the predetermined irrigation threshold for each treatment, irrigation was initiated to replenish the moisture. Water meters and fertilizer tanks were installed in each plot to record irrigation and fertilization volumes.

The changes in soil moisture content under different water treatments and local precipitation statistics during the experiment are shown in Figure 2.

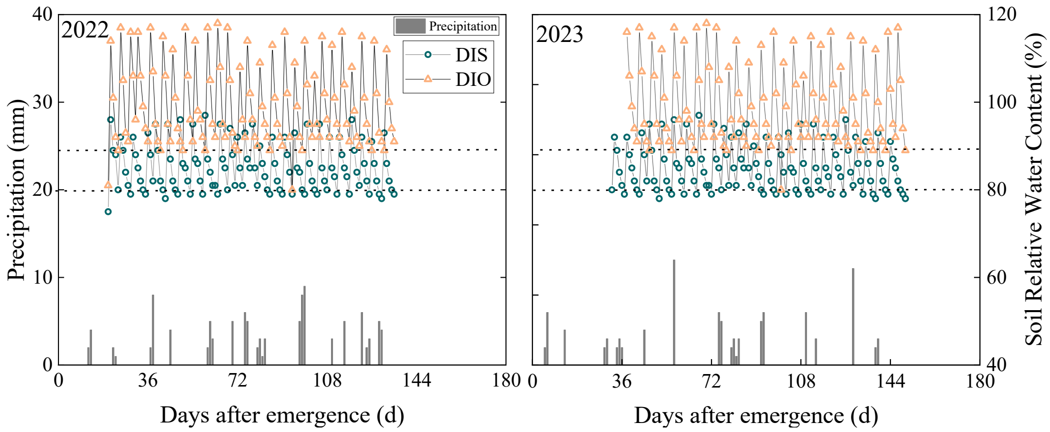

Figure 2. The dynamic changes in soil moisture content under different irrigation managements (from seedling emergence to harvest) and the local precipitation during the rice growing season (data obtained from the local meteorological station in 2022 and 2023) were analyzed. Here, DIO and DIS, respectively, refer to full-season drip irrigation (maintaining soil moisture at 90–100% of field capacity throughout the entire rice growth period, from rice seedling emergence to the three-leaf stage) and full-season drip irrigation water stress (maintaining soil moisture at 80–100% of field capacity throughout the entire rice growth period, from rice seedling emergence to the three-leaf stage).

2.3. Sampling and Measurement Methods

2.3.1. Soil NO_3^--N and NH_4^+-N Content

The 2nd and 28th day after N application at the panicle initiation stage (during the second fertilization, the N application rate was 30% of the total N application rate), soil NO_3^--N and NH_4^+-N contents were determined. Soil samples were collected by coring to a depth of 0–40 cm and were stored in a round aluminum sample box [25]. After removing the crop roots, the soil samples were thoroughly mixed, then immediately transferred to centrifuge tubes and stored at −20 °C. These frozen soil samples were later thawed and mixed in the laboratory, followed by determination of mineral N contents. Subsequently, 5 g of mixed soil sample was treated with 25 mL of 0.01 mol L^{-1} KCl solution, shaken for 0.5 h, and then filtered. A spectrophotometer was utilized to determine the mineral N contents in the soil-extract solution (Shimazu, UV-2600, Shanghai Spectrometer Instrument Co., Ltd., Shanghai, China, 722 visible light spectrophotometer), the mineral N contents of fresh soil samples were calculated based on the soil water contents to circumvent potential errors stemming from soil-moisture fluctuation [26,27].

2.3.2. Rice Biomass and Root Distribution

At the flowering stage (78 days after seedling emergence), three rice plants were randomly selected from each plot. The area around the plants was cleared of debris, and the aboveground portion of the plants was removed from the base of the stem. Subsequently, a root auger (diameter × depth: 7 cm × 10 cm) was used to collect roots from five different soil layers, with each layer being 10 cm deep, at the base of the stem. The collected roots were gently washed with running water to remove soil and debris from the root surface, then labeled and transferred to the laboratory. The aboveground and roots were then fixed at 105 °C for 30 min, dried at 80 °C to constant weight, and stored in a dry and ventilated place for biomass determination. Roots located in the 0–10 cm depth were defined as shallow roots, while roots in the 10–50 cm depth were defined as deep roots.

2.3.3. Nitrogen Content and Nitrogen Transport Efficiency in Different Organs of Rice

Two adjacent rows with a length of 100 cm were selected as the sampling area in the plots. The aboveground parts of wheat in the sampling area were cut off at anthesis and maturity, respectively. The plant samples were divided into different organs at anthesis (stem +sheath, leaf, and spike) and maturity (stem + sheath, leaf, and spike), respectively. The organs were dried to constant weight at 75 °C. The N concentration of the dried samples was determined using the micro-Kjeldahl method. The N accumulation and translocation of rice was calculated according to the method described by Wang et al. [26,27]:

N accumulation amount of an organ (kg ha $^{-1}$) = N concentration of the organ × dry weight of the organ

Pre-anthesis N translocation amount (PrNTA, kg ha $^{-1}$) = N accumulation amount of vegetative organs at anthesis − N accumulation amount of vegetative organs at maturity

Pre-anthesis N translocation rate (PrNTR, %) = Pre-anthesis N translocation amount/N accumulation amount of vegetative organs at anthesis × 100

Contribution rate of pre-anthesis N translocation amount to grain (PrNTC, %) = Pre-anthesis N translocation amount/N accumulation amount in grain at maturity × 100

Post-anthesis N accumulation amount (PoNAA, kg ha $^{-1}$) = N accumulation amount of plant at maturity − N accumulation amount of plant at anthesis

Contribution rate of post-anthesis N accumulation amount to grain (PoNAC, %) = PoNAA/N accumulation amount in grain at maturity × 100

2.3.4. Rice Yield, Yield Components, and N Partial Factor Productivity (NPFP)

During the maturity of rice, three 1 m^2 areas were selected in each plot to estimate grain yield (taking care to exclude marginal effects). Then, 15 rice plants were sampled from each plot to determine yield components, including the number of panicles per hectare, spikelets per panicle, grain setting rate, and 1000-grain weight.

The formula for calculating the NPFP is as follows:

$$\text{NPFP} = \text{Y/N} \times 100\%$$

where NPFP represents the partial factor productivity (kg·kg $^{-1}$), Y is the yield (t·ha^{-1}), and N is the N application rate (kg·ha^{-1}).

2.4. Statistical Analysis

All original data were analyzed using Excel 2016. Figures were plotted in Excel 2016 and Origin Pro 22.0 software (Origin Lab Corporation, Northampton, MA, USA). Analysis of variance (ANOVA) was used to evaluate the differences in mineral N; N accumulation and translocation, grain yield components, grain N concentration (GNC), and related parameters. The least significant difference (LSD TEST) test was used to compare the differences between the means of these parameters at $p < 0.05$. Statistical analyses were performed using SPSS Version 19.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. Nitrate (NO_3^--N) and Ammonium (NH_4^+-N) Content in the 0–40 cm Soil Layers

On the second day after N application during the panicle initiation stage, the NO_3^--N content in 0–10 cm soil layer under both irrigation treatments was significantly higher than that in 10–20 cm and 20–40 cm soil layers (Figure 3A,B). On the 28th after nitrogen application the panicle initiation stage, NO_3^--N content in soil at different depths of the two irrigation treatments was significantly different. Compared with 0–10 cm soil layer under DIS treatment, the NO_3^--N content in 10–20 cm soil layer increased by 38.56%, and that in 20–40 cm soil layer increased by 88.95%. Under DIO treatment, compared with the NO_3^--N content in 0–10 cm soil layer, the NO_3^--N content in 10–20 cm soil layer increased by 43.24%, and the NO_3^--N content in 20–40 cm soil layer increased by 94.04% (Figure 3C,D).

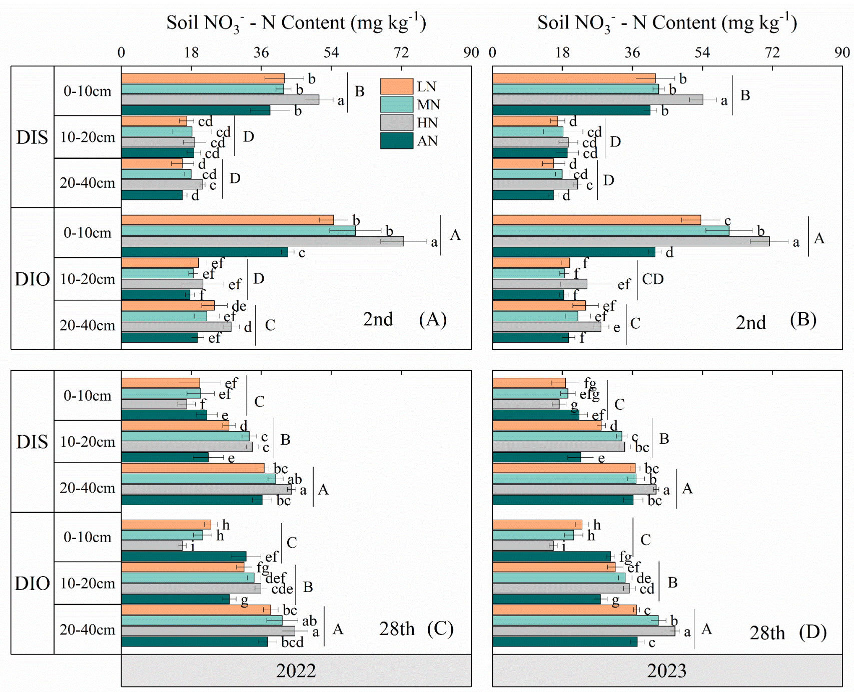

Figure 3. Soil NO_3^--N content in the 0–40 cm soil layers on the second day after N application and before the next round of N application during the panicle initiation stage. Note: (**A**,**B**) represent soil NO_3^--N content on the second day after N application during the panicle initiation stage in 2022 and 2023, respectively; (**C**,**D**) represent soil NO_3^--N content on the 28th day after N application

during the panicle initiation stage in 2022 and 2023, respectively. Different lowercase letters on top of the bars indicate significant differences ($p < 0.05$. LSD tset) among different soil depths within the same irrigation treatment; uppercase letters indicate significant differences ($p < 0.05$, LSD test) among different soil layers under different irrigation and N management. DIS and DIO represent, respectively, normal drip irrigation cultivation mode (soil relative moisture content maintained at 80–100%) and drip irrigation water stress cultivation mode (soil relative moisture content maintained at 90–100%), LN, MN, HN, and AN represent urea N at 240 kg ha^{-1}, urea N at 300 kg ha^{-1}, urea N at 360 kg ha^{-1}, and ammonium sulfate N at 300 kg ha^{-1}. Horizontal bars represent the standard error. Mean values ± SE are from three replicates.

The NH_4^+-N content in 0–10 cm soil layer was significantly higher than that in 10–20 cm soil layer and 20–40 cm soil layer on the second day after nitrogen application at the panicle initiation stage. On the 28th day after nitrogen application at the panicle initiation stage, the NH_4^+-N content in the soil layers of the two irrigation treatments showed the same trend, and the NH_4^+-N content in the 0–10 cm soil layer was significantly lower than that in the 10–20 cm and 20–40 cm soil layers. Under DIS treatment, the NH_4^+-N content in 10–20 cm soil layer decreased by 69.75% and that in 20–40 cm soil layer decreased by 68.23% compared with that in 0–10 cm soil layer. Under DIO treatment, compared with the NH_4^+-N content in 0–10 cm soil layer, the NH_4^+-N content in 10–20 cm soil layer decreased by 73.13%, and that in 20–40 cm soil layer decreased by 73.12% (Figure 4).

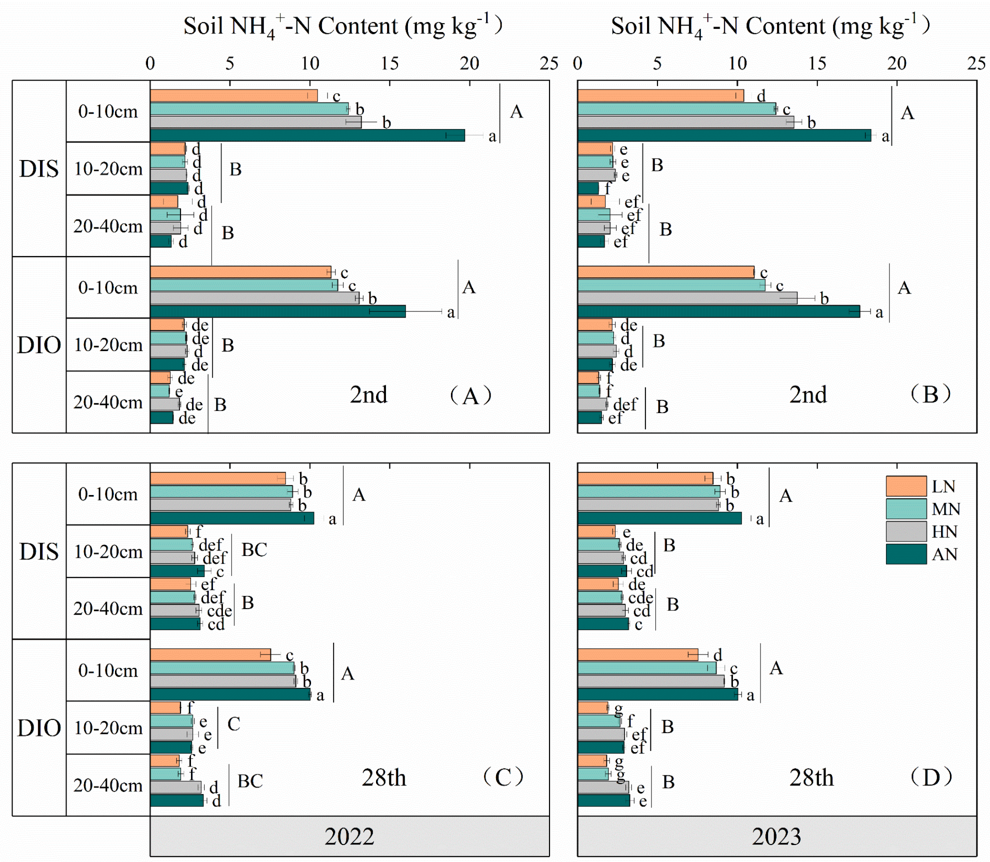

Figure 4. Soil NH_4^+-N content in the 0–40 cm soil layers on the second day after N application and before the next round of N application during the panicle initiation stage. Note: (**A**,**B**) represent soil NH_4^+-N content on the second day after N application during the panicle initiation stage in 2022 and 2023, respectively; (**C**,**D**) represent soil NH_4^+-N content on the 28th day after N application during the panicle initiation stage in 2022 and 2023, respectively. Different lowercase letters on top of the bars indicate significant differences ($p < 0.05$, LSD test) among different soil depths within the same irrigation treatment; uppercase letters indicate significant differences ($p < 0.05$, LSD test) among

different soil layers under different irrigation and N management. DIS and DIO represent, respectively, normal drip irrigation cultivation mode (soil relative moisture content maintained at 80–100%) and drip irrigation water stress cultivation mode (soil relative moisture content maintained at 90–100%), LN, MN, HN, and AN represent urea N at 240 kg ha^{-1}, urea N at 300 kg ha^{-1}, urea N at 360 kg ha^{-1}, and ammonium sulfate N at 300 kg ha^{-1}. Horizontal bars represent the standard error. Mean values ± SE are from three replicates.

3.2. Biomass of Aboveground and Root Distribution of Drip-Irrigated Rice

Both irrigation management and N regines significantly influenced the aboveground biomass and root biomass at different soil depths of rice during the flowing stage. The aboveground biomass and shallow and deep root biomass in the DIO treatment were significantly higher than those in the DIS (Figure 5). The aboveground biomass of rice and root biomass at different soil depths were the lowest in the LN treatment under both irrigation treatments. Under the DIO treatment, the aboveground biomass of rice and shallow and deep root biomass were significantly higher in the HN and AN compared to the MN. However, under the DIS treatment, there were no significant differences in the aboveground biomass of rice and shallow and deep root biomass among the MN, HN, and AN treatments (Figure 5).

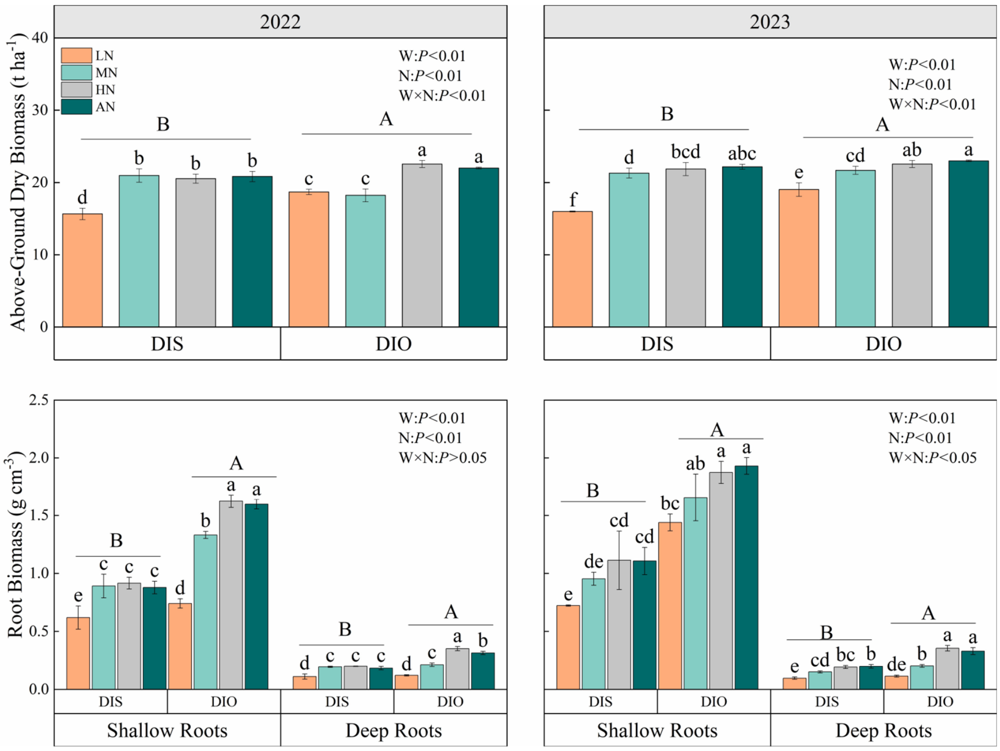

Figure 5. Effects of different irrigation and N regimes on aboveground biomass and root biomass at different depths in drip-irrigated rice for 2022–2023. Different lowercase letters on the bars indicate significant differences among different irrigation and N application treatments (p < 0.05. LSD test). Different uppercase letters on the bars indicate significant differences among different irrigation treatments (p < 0.05, LSD test). DIS and DIO represent the drip irrigation water stress cultivation mode (soil relative moisture content maintained at 80–100%) and the normal drip irrigation cultivation mode (soil relative moisture content maintained at 90–100%), respectively; LN, MN, HN, and AN represent urea N at 240 kg ha^{-1}, urea N at 300 kg ha^{-1}, urea N at 360 kg ha^{-1}, and ammonium sulfate N at 300 kg ha^{-1}. The root system at the 0–10 cm depth is defined as the shallow root system, and the root system at the 10–50 cm depth is defined as the deep root system.

Under the same water treatment, compared with MN, the shallow root biomass increased by 12.32% by increasing nitrogen fertilizer (HN), the deep root biomass decreased by 19.06% by reducing nitrogen fertilizer (LN), and the deep root biomass increased by 14.08% by increasing ammonium nitrogen. Compared with MN, the application of nitrogen fertilizer (HN) increased the deep root biomass by 37.69%, the application of nitrogen fertilizer (LN) decreased the deep root biomass by 69.56%, and the application of ammonium nitrogen increased the deep root biomass by 34.65% (Figure 5).

3.3. Nitrogen Accumulation and Translocation in Drip-Irrigated Rice

As can be seen from Table 2, irrigation methods and nitrogen application methods have significant effects on nitrogen accumulation in each organ of rice and total nitrogen accumulation in plants. At anthesis, the difference in plant nitrogen accumulation under MN, HN, and AN treatments decreased, and the grain nitrogen accumulation under HN treatment was only 19.34% higher than that under MN treatment. The grain nitrogen accumulation under AN treatment was only 33.61% higher than that under MN treatment. Nitrogen accumulation of plants under DIS treatment was 20.90% lower than that under DIO treatment (Table 2). At maturity, under the same water treatment, the grain nitrogen accumulation under HN treatment was only 17.02% higher than that under MN treatment. The grain nitrogen accumulation under AN treatment was only 27.43% higher than that under MN treatment (Table 2).

The irrigation mode had no impact on PrNTA, while N regimes significantly influences PrNTA. Under the same irrigation treatment, PrNTA showed significant differences under N regimes, with the overall trend being AN > HN > MN > LN. Both PrNTR and PrNTC were significantly higher under DIS compared to DIO. Under both DIS and DIO treatments, PrNTR showed no significant difference under different N regimes. Under DIS treatment, there was no significant difference in PrNTC under different N regimes, while under DIO treatment, PrNTC followed an overall trend of AN > HN > MN > LN (Table 3).

PoNAA and PoNAC were both significantly lower under DIS than DIO. Under DIS treatment, PoNAA showed the trend of AN > HN > MN > LN under different N regimes, while under DIO treatment, PoNAA showed the trend of HN > MN > LN > AN under different N regimes. Under DIS treatment, PoNAC showed the trend of LN > AN > HN > MN under different N management, while under DIO treatment, PoNAC showed the trend of LN > N > HN > AN under different N regimes (Table 3).

Table 2. Nitrogen distribution in different organs at anthesis and maturity in rice plants with different irrigation and nitrogen regimes.

Year	Irrigation Modes	Nitrogen Management	Nitrogen Accumulation Amount at Anthesis (kg ha^{-1})			Nitrogen Accumulation Amount at Maturity (kg ha^{-1})		
			Stem + Sheath + Leaf	Spike	Plant	Stem + Sheath +Leaf + Spike Axis + Husk	Grain	Plant
2022	DIS	LN	35.28 ± 2.37 f	1.45 ± 0.60 d	36.73 ± 1.93 e	1.23 ± 0.84 e	50.87 ± 2.22 d	54.25 ± 3.82 f
		MN	66.16 ± 13.20 de	2.73 ± 0.17 cd	68.88 ± 13.05 cd	1.51 ± 0.63 de	80.83 ± 14.91 c	86.13 ± 15.11 e
		HN	82.64 ± 6.39 cd	3.11 ± 1.02 c	85.74 ± 7.34 c	5.98 ± 2.00 cde	94.23 ± 8.74 bc	107.61 ± 6.20 cde
		AN	105.57 ± 3.28 ab	3.91 ± 0.64 bc	109.47 ± 3.11 ab	7.74 ± 0.76 bcd	114.10 ± 10.89 ab	136.18 ± 7.38 abc
		Average	72.41 ± 29.56 B	2.80 ± 1.02 B	75.21 ± 30.58 B	4.12 ± 3.25 B	85.01 ± 26.55 B	96.04 ± 34.59 B
	DIO	LN	60.68 ± 8.39 e	2.48 ± 0.13 cd	63.16 ± 8.48 d	11.68 ± 3.95 bc	88.80 ± 11.82 bc	106.17 ± 17.78 de
		MN	82.29 ± 5.66 cd	2.74 ± 0.37 cd	85.02 ± 5.49 c	11.49 ± 1.17 bc	108.19 ± 10.65 ab	130.29 ± 9.98 bcd
		HN	99.65 ± 5.24 bc	6.05 ± 0.46 a	105.70 ± 4.78 b	13.47 ± 2.78 b	125.25 ± 11.61 a	153.05 ± 12.31 ab
		AN	122.64 ± 3.02 a	4.86 ± 0.95 ab	127.50 ± 3.96 a	19.77 ± 3.67 a	124.92 ± 2.06 a	161.88 ± 7.46 a
		Average	91.31 ± 26.27 A	4.03 ± 1.72 A	95.35 ± 27.59 A	14.10 ± 3.88 A	111.79 ± 17.27 A	137.85 ± 24.97 A
2023	DIS	LN	35.34 ± 2.80 d	1.62 ± 0.27 d	36.96 ± 1.91 d	3.88 ± 2.10 e	51.70 ± 0.85 d	55.58 ± 2.93 e
		MN	62.46 ± 8.40 c	2.72 ± 1.58 cd	65.18 ± 8.41 c	4.48 ± 0.17 e	82.10 ± 15.01 c	86.58 ± 14.90 d
		HN	75.72 ± 15.50 bc	4.61 ± 1.93 bc	80.33 ± 15.79 bc	12.69 ± 2.85 de	95.55 ± 7.31 bc	108.25 ± 5.45 cd
		AN	90.17 ± 7.24 ab	5.65 ± 1.11 ab	95.82 ± 7.54 ab	21.04 ± 1.84 bcd	114.10 ± 10.89 ab	135.14 ± 9.13 bc
		Average	65.92 ± 23.32 B	3.65 ± 1.81 B	69.57 ± 25.08 B	10.52 ± 8.08 B	85.86 ± 26.28 B	96.39 ± 33.69 B
	DIO	LN	56.36 ± 11.08 cd	1.85 ± 0.70 cd	58.21 ± 10.68 cd	17.47 ± 6.13 cd	88.80 ± 11.82 bc	106.26 ± 17.80 cd
		MN	74.99 ± 7.69 bc	3.88 ± 0.88 bcd	78.87 ± 8.39 bc	22.42 ± 3.32 bc	108.19 ± 10.65 abc	130.61 ± 10.02 bc
		HN	91.34 ± 3.70 ab	6.30 ± 1.31 ab	97.64 ± 4.35 ab	28.40 ± 1.21 b	125.25 ± 11.61 a	153.65 ± 12.43 ab
		AN	108.11 ± 8.04 a	7.95 ± 1.31 a	116.06 ± 6.86 a	39.36 ± 4.66 a	124.92 ± 2.06 a	164.29 ± 6.72 a
		Average	82.70 ± 22.16 A	5.00 ± 2.68 A	87.69 ± 24.84 A	26.91 ± 9.43 A	111.79 ± 17.27 A	138.70 ± 25.79 A
	Two-way ANOVA							
2022	I (Irrigation)		19.01 **	24.85 **	46.61 **	98.37 **	38.85 **	79.65 **
	N (Nitrogen)		34.70 **	26.36 **	96.91 **	11.77 **	25.38 **	40.03 **
	I × N		0.2 ^{ns}	6.14 **	0.56 ^{ns}	0.87 ^{ns}	1.79 ^{ns}	1.44 ^{ns}
2023	I (Irrigation)		41.44 **	8.58 *	22.59 **	128.90 **	37.55 **	81.64 **
	N (Nitrogen)		90.13 **	24.03 **	42.66 **	36.42 **	25.93 **	40.06 **
	I × N		0.55 ^{ns}	0.92 ^{ns}	0.20 ^{ns}	0.58 ^{ns}	1.71 ^{ns}	0.97 ^{ns}

Different lowercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among treatments. Different uppercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among different irrigation treatments. DIS and DIO, respectively, represent normal drip irrigation cultivation mode (soil relative moisture content maintained at 80–100%) and drip irrigation water stress cultivation mode (soil relative moisture content maintained at 90–100%); LN, MN, HN, and AN represent urea N at 240 kg ha^{-1}, urea N at 300 kg ha^{-1}, urea N at 360 kg ha^{-1}, and ammonium sulfate N at 300 kg ha^{-1}. I, irrigation amount; N, N fertilization rate; ns, not significant ($p > 0.05$); *, $p < 0.05$ significant levels; **, $p < 0.01$ significant level.

Table 3. The contribution of the translocation from pre-anthesis accumulation in vegetative organs and the post-anthesis assimilation to grain nitrogen of rice with different irrigation and nitrogen regimes.

Year	Irrigation Modes	Nitrogen Management	PrNTA (kg ha^{-1})	PrNTR (%)	PrNTC (%)	PoNAA (kg ha^{-1})	PoNAC (%)
2022	DIS	LN	32.98 ± 1.20 f	93.6 ± 6.2 ab	64.9 ± 3.0 abcd	17.52 ± 0.81 f	34.2 ± 9.40 abc
		MN	63.58 ± 2.66 d	98.0 ± 14.1 a	80.1 ± 11.7 a	17.25 ± 1.11 f	21.3 ± 6.63 c
		HN	72.37 ± 1.71 c	87.8 ± 6.1 abc	77.3 ± 8.1 ab	21.87 ± 1.95 e	23.4 ± 3.30 c
		AN	87.40 ± 1.30 a	82.9 ± 1.1 abc	77.0 ± 6.5 ab	26.70 ± 3.23 d	23.3 ± 3.76 c
		Average	64.08 ± 22.95 A	90.6 ± 6.6 A	74.8 ± 6.8 A	20.84 ± 4.45 B	25.5 ± 5.85 B
	DIO	LN	46.13 ± 4.53 e	76.3 ± 5.8 bc	52.1 ± 1.9 d	43.00 ± 1.91 b	47.8 ± 8.24 a
		MN	62.93 ± 2.78 d	76.7 ± 6.2 bc	58.4 ± 4.1 cd	45.26 ± 2.23 ab	41.7 ± 2.21 ab
		HN	77.90 ± 3.62 b	78.3 ± 5.5 bc	62.4 ± 3.0 bcd	47.35 ± 1.80 a	37.4 ± 6.70 abc
		AN	90.54 ± 1.28 a	73.8 ± 0.2 c	72.5 ± 2.1 abc	34.05 ± 0.68 c	27.5 ± 5.38 bc
		Average	69.38 ± 19.17 A	76.3 ± 1.9 B	61.4 ± 8.5 B	42.42 ± 5.86 A	38.6 ± 8.57 A
2023	DIS	LN	33.21 ± 1.04 e	94.0 ± 3.1 a	64.2 ± 1.2 abc	18.61 ± 4.84 e	36.0 ± 1.43 de
		MN	61.20 ± 1.06 cd	98.0 ± 3.9 a	76.3 ± 14.4 a	21.40 ± 3.92 e	26.6 ± 4.38 f
		HN	67.95 ± 2.19 bc	90.5 ± 1.2 ab	71.3 ± 4.6 ab	27.92 ± 3.24 d	29.3 ± 2.45 ef
		AN	75.32 ± 2.02 ab	83.5 ± 1.0 bc	66.5 ± 7.3 ab	39.32 ± 4.33 c	34.6 ± 2.37 def
		Average	59.42 ± 18.40 A	91.5 ± 6.2 A	69.6 ± 5.4 A	26.81 ± 9.21 B	31.6 ± 4.44 B
	DIO	LN	40.91 ± 4.29 e	72.6 ± 3.6 d	46.7 ± 7.6 c	47.39 ± 2.05 b	54.5 ± 4.32 a
		MN	56.87 ± 3.80 d	75.9 ± 4.8 cd	52.7 ± 1.8 bc	51.74 ± 2.56 ab	47.7 ± 4.20 ab
		HN	69.81 ± 2.92 b	76.6 ± 4.8 cd	56.2 ± 6.7 bc	56.01 ± 2.40 a	44.5 ± 2.96 bc
		AN	78.57 ± 4.93 a	72.7 ± 1.6 d	62.9 ± 3.1 abc	48.23 ± 0.54 b	38.6 ± 0.85 cd
		Average	61.54 ± 16.39 A	74.4 ± 2.1 B	54.6 ± 6.8 B	50.84 ± 3.92 A	46.4 ± 6.62 A
	Two-way ANOVA				F-valued		
2022	I (Irrigation)		1.54 ^{ns}	26.02 **	27.07 **	706.24 **	24.92 **
	N (Nitrogen)		14.89 **	1.85 ^{ns}	7.01 **	6.30 **	6.20 **
	I × N		9.59 **	1.15 ^{ns}	1.87 ^{ns}	34.69 **	1.63 ^{ns}
2023	I (Irrigation)		2.60 ^{ns}	139.56 **	24.13 **	309.02 **	117.06 **
	N (Nitrogen)		172.18 **	6.36 **	2.12 ^{ns}	13.09 **	9.45 **
	I × N		3.57 *	3.69 *	1.89 ^{ns}	13.72 **	7.69 **

Different lowercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among treatments. Different uppercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among different irrigation treatments. DIS and DIO, respectively, represent normal drip irrigation cultivation mode (soil relative water content maintained at 80–100%) and drip irrigation water stress cultivation mode (soil relative water content maintained at 90–100%). LN, MN, HN, and AN, respectively, represent urea N 240 kg ha^{-1}, urea N 300 kg ha^{-1}, urea N 360 kg ha^{-1}, and ammonium sulfate N 300 kg ha^{-1}. PrNTA, Pre-anthesis N translocation amount; PrNTR, Pre-anthesis N translocation rate; PrNTC, Contribution rate of pre-anthesis N translocation amount to grain; PoNAA, Post-anthesis N accumulation amount; PoNAC, Contribution rate of post-anthesis N accumulation amount to grain. I, irrigation amount; N, N fertilization rate; ns, not significant ($p > 0.05$); *, $p < 0.05$ significant levels; **, $p < 0.01$ significant levels.

3.4. Drip Irrigation Rice Yield, Yield Components, and NPFP

Irrigation methods and nitrogen application methods significantly affected the yield composition and yield of rice (Table 4). The data showed that compared with DIO, the number of panicles per unit area, grains per panicle, seed setting rate, 1000-grain weight, and yield of DIS treatment were significantly reduced. Under the same irrigation method, the panicle number per unit area, kernel number per panicle, seed setting rate, 1000-grain weight, and yield of LN treatment were lower than those of other nitrogen management treatments. Under DIS treatment, MN, HN, and AN treatments had no significant difference in panicle number per unit area, grain number per panicle, seed setting rate, 1000-grain weight, and yield. Compared with DIO, DIS reduced the yield by 36.42% (Table 4). Under the same irrigation amount, the yield of drip irrigation rice was increased by increasing nitrogen application amount and changing nitrogen form. Under the same water treatment, MN, HN, and AN treatments increased yield by 68.36%, 65.38%, and 52.75%, respectively, compared with LN treatment (Table 4).

Table 4. Effects of different irrigation and nitrogen regimes on rice yield composition.

Years	Irrigation Modes	Nitrogen Management	Panicle Number $\times 10^6$ ha^{-1}	Spikelets per Panicle	Seed Setting Rate (%)	1000-Grain Weight (g)	Yield (kg ha^{-1})
2022	DIS	LN	3.6 ± 0.2 c	71.8 ± 0.7 c	52.1 ± 1.5 e	20.0 ± 0.2 d	2.7 ± 0.1 d
		MN	3.9 ± 0.2 bc	83.0 ± 0.3 b	65.2 ± 1.5 d	22.9 ± 0.3 c	4.5 ± 0.2 c
		HN	4.1 ± 0.0 ab	80.9 ± 1.1 b	66.9 ± 1.6 cd	23.1 ± 0.6 c	5.1 ± 0.3 c
		AN	3.9 ± 0.1 b	81.4 ± 1.5 b	69.6 ± 0.5 c	23.1 ± 0.6 c	5.3 ± 0.9 c
		Average	3.9 ± 0.2 B	79.3 ± 5.1 B	63.5 ± 7.8 B	22.3 ± 1.5 B	4.4 ± 1.2 B
	DIO	LN	4.1 ± 0.1 ab	73.1 ± 3.5 c	66.3 ± 2.3 d	21.9 ± 0.9 cd	4.3 ± 0.3 cd
		MN	4.3 ± 0.1 a	83.9 ± 0.3 ab	74.4 ± 0.3 b	26.8 ± 0.5 b	7.1 ± 0.7 b
		HN	4.3 ± 0.1 a	88.4 ± 3.2 a	82.6 ± 2.0 a	29.8 ± 1.3 a	9.4 ± 0.8 a
		AN	4.3 ± 0.1 a	88.5 ± 3.2 a	79.7 ± 0.2 a	29.8 ± 1.3 a	8.9 ± 1.0 a
		Average	4.2 ± 0.1 A	83.5 ± 7.3 A	75.8 ± 7.1 A	27.0 ± 3.7 A	7.4 ± 2.3 A
2023	DIS	LN	3.5 ± 0.1 e	80.1 ± 0.5 c	53.5 ± 1.0 d	22.2 ± 1.6 e	3.4 ± 0.2 f
		MN	3.9 ± 0.1 d	84.4 ± 4.2 bc	66.0 ± 1.8 c	24.4 ± 0.7 d	5.3 ± 0.2 e
		HN	4.0 ± 0.1 bcd	85.9 ± 1.3 bc	69.1 ± 0.4 c	25.8 ± 0.8 d	6.1 ± 0.2 d
		AN	3.9 ± 0.1 cd	85.4 ± 3.8 bc	69.7 ± 1.0 c	25.3 ± 0.2 d	5.9 ± 0.4 d
		Average	3.8 ± 0.2 B	84.0 ± 2.6 B	64.6 ± 7.6 B	24.4 ± 1.6 B	5.2 ± 1.3 B
	DIO	LN	3.9 ± 0.2 d	86.1 ± 1.5 bc	69.6 ± 0.1 c	27.5 ± 0.4 c	6.4 ± 0.3 d
		MN	4.1 ± 0.1 abc	90.1 ± 2.7 ab	74.8 ± 0.6 b	29.2 ± 0.1 b	8.1 ± 0.3 c
		HN	4.2 ± 0.0 ab	95.0 ± 2.6 a	83.8 ± 3.3 a	31.7 ± 0.2 a	10.5 ± 0.4 b
		AN	4.2 ± 0.1 a	98.2 ± 2.1 a	84.6 ± 2.7 a	32.0 ± 0.1 a	11.2 ± 0.4 a
		Average	4.1 ± 0.1 A	92.4 ± 5.3 A	78.2 ± 7.3 A	30.1 ± 2.1 A	9.0 ± 2.2 A
	Two-way ANOVA				F-valued		
2022	I (Irrigation)		53.69 **	13.54 **	310.96 **	120.25 **	131.16 **
	N (Nitrogen)		7.13 **	27.82 **	108.80 **	36.15 **	42.46 **
	I × N		1.31 ^{ns}	2.49 ^{ns}	5.08 *	7.35 **	5.51 *
2023	I (Irrigation)		27.40 **	36.81 **	243.95 **	268.04 **	815.65 **
	N (Nitrogen)		12.42 **	7.74 **	68.66 **	28.45 **	155.71 **
	I × N		0.48 ^{ns}	1.45 ^{ns}	3.49 *	1.39 ^{ns}	17.71 **

Different lowercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among treatments. Different uppercase letters in the same column indicate significant ($p < 0.05$; LSD test) differences among different irrigation treatments. DIS and DIO represent different irrigation modes: normal drip irrigation cultivation mode (soil relative water content maintained at 80–100%) and drip irrigation water stress cultivation mode (soil relative water content maintained at 90–100%), respectively. LN, MN, HN, and AN represent different N fertilization rates: urea N 240 kg ha^{-1}, urea N 300 kg ha^{-1}, urea N 360 kg ha^{-1}, and ammonium sulfate N 300 kg ha^{-1}, respectively. I represents the irrigation amount; N represents the N fertilization rate; ns indicates that the result is not significant ($p > 0.05$); *, ** represent $p < 0.05$, $p < 0.01$, significant levels, respectively.

Irrigation method and nitrogen application rate had significant effects on NPFP of rice (Figure 6). The data showed that the NPFP of rice under DIS treatment was significantly lower than that under DIO treatment, and NPFP was reduced by 43.35% under DIS treatment. Under the two irrigation methods, the NPFP of rice was the highest in ammonium nitrate treatment and the lowest in LN treatment. In 2022, there was no significant difference in NPFP between MN and HN treatments under the two irrigation methods. In 2023, under DIS irrigation, there was no difference in NPFP between MN and HN treatments, but under DIO treatment, the NPFP of HN treatment was significantly higher than that of MN treatment.

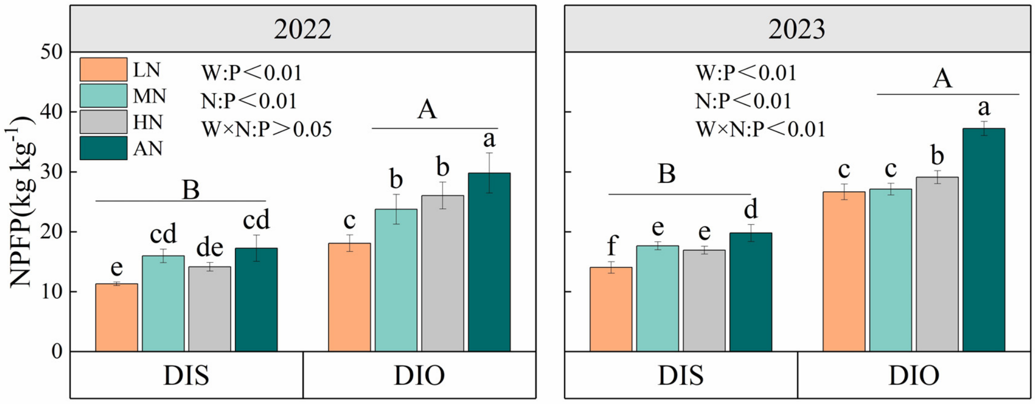

Figure 6. Effects of different irrigation and N regimes on the N partial factor productivity (NPFP) of drip-irrigated rice for 2022–2023. Different lowercase letters on the bars indicate significant differences between the irrigation and N treatment groups (p < 0.05 LSD test), while different uppercase letters represent significant differences between the irrigation treatments (p < 0.05 LSD test). The terms DIS and DIO denote the drip irrigation water stress (maintaining soil relative water content at 80–100%) and normal drip irrigation (maintaining soil relative water content at 90–100%), respectively. Additionally, LN, MN, HN, and AN correspond to urea N 240 kg ha^{-1}, urea N 300 kg ha^{-1}, urea N 360 kg ha^{-1}, and ammonium sulfate N 300 kg ha^{-1}, respectively.

4. Discussion

Cultivation, irrigation, and fertilization all affect soil water and nutrient heterogeneity, as well as root foraging [28,29]. Nitrifying microorganisms are aerophilic microorganisms whose activity is strongly influenced by the partial pressure of oxygen in the soil, which is in turn controlled by the soil moisture content [30]. In general, nitrification in soil is most vigorous at 50–60% of the maximum field water capacity. Our experimental soil relative water content is as follows: DIO (soil relative water content is 90–100%), DIS (soil relative water content is 80–90%); such cultivation conditions are conducive to nitrification process of nitrifying microorganisms. The results of this study indicated that, on the second day after N application in drip-irrigated rice, the soil NO_3^--N and NH_4^+-N content in the 0–10 cm soil layer was significantly higher than in the 10–20 cm and 20–40 cm soil layers for both DIO and DIS treatments. However, on the 28th day after N application, the soil NO_3^--N content was highest at a depth of 20–40 cm soil layer, whereas the soil NH_4^+-N content remained higher in the 0–10 cm compared to the 10–20 cm and 20–40 cm soil layers (see Figures 3 and 4), we attribute these results to two factors: firstly, as previously discussed, the mobility of soil nitrate is significantly higher than that of ammonium due to NH_4^+-N is more easily adsorbed by soil colloids than nitrate NO_3^--N [13]; secondly, in this study, the two soil N samplings were separated by 26 days, during which the soil typically undergoes six to eight irrigation events (see Figure 1). This high-frequency drip irrigation exacerbates the migration of nitrate to the deeper soil layers. Evidence suggested that in drip-irrigated rice under a 3-day irrigation regime, there was a distinct desalination zone within the 0–40 cm soil depth [31], a finding similar to our research results.

Root morphology and spatial distribution directly influence a plant's acquisition of soil resources such as nutrients and water [32,33]. Appropriate water and N management can optimize root architecture and improve root activity to enhance rice's uptake of nutrient resources [34]. In our study, we found that aboveground biomass and shallow and deep root biomass in rice were significantly higher under the DIO compared to the DIS (Figure 5). Correspondingly, the N accumulation of rice, PoNAA, PoNAC, as well as yield were all lower in the DIS compared to DIO (Tables 2–4). These findings are related to the distribution of drip-irrigated rice roots and soil mineral N. The data indicates that both DIS and DIO treatments resulted in a substantial distribution of nitrate in the 20–40 cm depth of the soil (Figures 3 and 4), while approximately 80% of rice roots were distributed in the 0–10 cm soil depth (Figure 5). Previous research has shown a significant positive correlation between root biomass, root length, rice yield, and N use efficiency [35,36]. Well-developed roots play a crucial role in enhancing rice's foraging for soil resources in time and space. Furthermore, we found that under both irrigation quotas, the root biomass of rice in the LN treatment was lower than in other N regimes (Figure 5). Additionally, data shows that in the DIS treatment, different N regimes did not significantly affect the shallow and deep root biomass of rice, whereas under the DIO treatment, the HN and AN treatments had a significant increase in root biomass compared to the MN treatment (Figure 5). Similarly, the maturity stage rice seed-setting rate and yield showed a similar pattern among different N regimes under the DIO treatment, but not under the DIS treatment (Table 4). Research shows that the deep root type for improved N capture in maize consists of architectural, anatomical, and physiological traits that promote rapid exploration of deep soil domains to capture nitrate as it leaches through the rootzone [37]. These results suggest that further limited water irrigation in drip-irrigated rice negatively impacts root growth, N uptake, transport, and yield formation. Meanwhile, many N management strategies for increasing grain yield and NUE in rice production have been developed by researchers and adopted by farmers, such as balanced fertilization, integrated nutrient management, soil testing and formulated fertilization, site-specific nutrient management, deep and side application of N fertilizer, delayed N application at a later growth stage, and integrated water and N management [34,38,39]. Therefore, proper N management can improve rice root growth to attain more N nutrition and subsequently enhance rice yield.

The metabolism, accumulation, and redistribution of N in the vegetative and reproductive organs of rice are important factors determining yield [40–42]. Previous studies have shown that approximately 64% of the N nutrition in rice grains comes from the leaves, with 20% coming from the stems [43]. In this study, we categorize the source of N for the grains into pre-anthesis N transfer amount (PrNTA) and post-anthesis N accumulation total (PoNAA). In most treatments, the PrNTA was higher than the PoNAA in rice (Table 3), consistent with previous research results [44]. This indicates the importance of N in the utilization of vegetative organs and the dominant role of PrNTA in grain N accumulation. Furthermore, our study results reveal that PrNTR and PrNTC were significantly higher under the DIS compared to DIO, while PoNAA and PoNAC were significantly lower under DIS compared to DIO (Table 3). This suggests that drip irrigation poses a form of drought stress for rice growth, with the drought stress experienced by rice under the DIS being stronger than under DIO. Cereal crops often alleviate the negative effects of stress during grain filling by improving the N transport within vegetative organs. [45–47]. Previous studies have shown that N accumulation in crops under stress is positively correlated with nitrate reductase and glutamate synthase activities, which increase C and N remobilization [48]. Under the DIO treatment, the N accumulated in rice is available for its normal growth, ensuring the normal C and N metabolism of rice in the later stage of growth. Therefore, PoNAA and PoNAC under the DIO treatment were significantly higher than under DIS, which is the main reason for the higher N accumulation in mature rice grains under the DIO treatment compared to the DIS. It is evident that further limiting water in drip-irrigated rice leads to a reduction in PoNAA and PoNAC, ultimately affecting the accumulation of N in grains and yield formation (Tables 2 and 3).

Under drought conditions, appropriate replenishment irrigation and optimized N application can promote rice growth and yield formation [49,50]. This study found that both the anthesis stage and the maturity stage of rice showed significantly higher N accumulation in the DIO treatment compared to DIS (Table 2). Under the same irrigation treatment, different N regimes had a promoting effect on rice N accumulation (Table 2). The results of the study indicated that the number of panicles per unit area, spikelets per panicle, seed setting rate, 1000-grain weight, and yield were significantly lower under the DIS treatment compared to DIO, and optimized N management could increase yield, although this promoting effect was not substantial under the DIS treatment. Optimized irrigation can enhance crop N uptake, maximize fertilizer utilization, improve N efficiency, and increase yield [51]. In this study, both soil NO_3^--N and NH_4^+-N content decreased synchronously in the two irrigation treatments and migrated to the deeper soil layers (Figures 3 and 4; Table 4). However, in the DIO treatment, rice deep root biomass showed a certain “root foraging effect” with N-application management, while in the DIS treatment, rice deep root growth did not respond to N regimes (Figure 5). In addition, the data showed that under the DIS treatment, there were no significant differences in the number of panicles per unit area, spikelets per panicle, grain setting rate, 1000-grain weight, and overall yield among the different N treatments (MN, HN, and AN). However, under the DIO, the grain setting rate, 1000-grain weight, and yield of rice were significantly higher in the HN and AN compared to the MN and LN treatments (Table 4). The PoNAA, PoNAC, and PFNP were all lower under the DIS treatment compared to DIO (Table 3, Figure 6). These results indicate that drip-irrigated rice can effectively increase rice N accumulation, PFNP, and yield through increased N application amount and soil ammonium nutrition.

5. Conclusions

A two-year field experiment showed that the mineral N content in 0~10 cm soil layer of drip irrigation showed a decreasing trend in one N-application cycle. This indicated that mineral N in shallow soil was susceptible to the influence of irrigation, and migrates to deep soil, which had an adverse effect on N absorption and yield formation of drip irrigation rice. By increasing the N dose and soil ammonium nutrition, the deep root growth and N absorption of drip irrigation rice could be promoted. However, this approach is limited by irrigation management, and the N dose of drip-irrigated rice threat of does not help to increase rice yield when irrigation was further restricted. Therefore, we should pay more attention to the influence of water management on the yield of drip irrigation rice in the future.

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Abbreviations

PrNTA	Pre-anthesis N translocation amount
PrNTR	Pre-anthesis N translocation rate
PrNTC	Contribution rate of pre-anthesis N translocation amount to grain
PoNAA	Post-anthesis N accumulation amount
PoNAC	Contribution rate of post-anthesis N accumulation amount to grain
NPFP	N partial factor productivity

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