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Effects of Different Irrigation Management and Nitrogen Rate on Sorghum (*Sorghum bicolor* L.) Growth, Yield and Soil Nitrogen Accumulation with Drip Irrigation

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Abstract: Sorghum (*Sorghum bicolor* L.) has emerged as a pivotal global food crop. Consequently, it is imperative to explore sustainable and eco-friendly strategies to achieve sustainable sorghum production with a high yield. This study aimed to reveal the effects of irrigation management and nitrogen rates and their interactions on sorghum growth traits, yield and soil nitrate-N and ammonium-N accumulation to improve irrigation and nitrogen practices under drip irrigation. A 2-year (2021 and 2022) field experiment was conducted on drip-irrigated fertilized sorghum in Heilongjiang Province to investigate the effects of three lower levels of soil moisture (80% (HI), 70% (NI), and 60% (LI) of field capacity) with four nitrogen rates at 225, 150, 75 and 0 kg/ha (designated as HN, NN, LN and WN, respectively) on sorghum growth, yield and soil nitrogen accumulation. The results indicated that irrigation management and nitrogen rate interaction had a significant effect on sorghum growth (plant height, stem diameter, leaf area index (LAI), and SPAD value), yield, aboveground biomass and 0~60 cm soil nitrogen accumulation ($p < 0.05$). The NNHI treatment demonstrated the highest plant height (120.9 and 121.8 cm) and LAI (2.738 and 2.645) in 2021 and 2022, and there was a significant positive correlation between plant height, LAI, and yield ($p < 0.01$). However, the NNNI treatment exhibited the highest yield (7477.41 and 7362.27 kg/ha) in 2021 and 2022, sorghum yield increased and then decreased with an increase in irrigation management and nitrogen rate. In addition, soil nitrate-N and ammonium-N accumulation were significantly affected by the interaction of irrigation management and nitrogen rate ($p < 0.05$) while irrigation management had no significant effect on the accumulation of nitrate-N and ammonium-N. Soil nitrate-N and ammonium-N accumulation increased with the increasing nitrogen rate. Although yield differences between the NNNI and HNNI treatments were not significant, the NNNI treatment with a lower soil moisture limit of 70% field capacity and a nitrogen rate of 150 kg/ha accumulated 10.4% less nitrate-N in soil than the HNNI treatment, reduced risk of nitrate nitrogen leaching. The regression analysis indicated that the optimal irrigation management and nitrogen rate management practices of 71.93% of the soil moisture lower limit and 144.58 kg/ha of nitrogen rate was an optimal strategy for favorable sorghum growth, high-yielding and low soil nitrate-N accumulation of sorghum. This study provides a scientific reference for precise water and fertilizer management in sorghum.

Keywords: sorghum; yield; soil moisture; nitrogen rate; soil nitrate-N and ammonium-N

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1. Introduction

Sorghum (*Sorghum bicolor* L.) stands as a vital food crop among the world's five major cereal crops, spanning Asia, Africa, and America [1–3]. Global sorghum planting area exceeded 4000 × 10^4 ha, for example, the planting area of sorghum in China and the United States in 2022 were 66.20 × 10^4 and 184.94 × 10^4 ha, respectively [4]. Renowned for its adaptability to arid regions, particularly when compared to maize within the C4 plant category, sorghum boasts low water consumption and high water use efficiency [4,5]. Sorghum is widely planted in arid, semi-arid and semi-humid of China, where farmland is often characterized by the seasonal unevenness of rainfall [6]. These areas are prone to over-fertilization by farmers pursuing higher yields [7,8]. Therefore, an exploration of optimal field water and fertilizer management practices for sorghum production is imperative to ensure high and stable yield [9,10].

Irrigation management stands as a pivotal environmental factor influencing sorghum growth, development and yield. The photosynthesis and dry matter accumulation in crops, directly reflected in plant height, stem diameter, leaf area and yield, hinge upon adequate soil water supply. Bonfim et al. [11] reported that yield and SPAD value of sorghum were maximized at 60% field capacity. Wang et al. [12] also reported that plant height, stem diameters, leaf area and seed yield of sorghum in 90% water surface evaporation were significantly higher than the rain-fed treatment. In addition, moderate nitrogen rate increased crop chlorophyll content, promoted photosynthesis, improved light energy utilization efficiency [13], improved dry matter partitioning and foster nutrient accumulation in seed yield [14]. However, excessive nitrogen rates may lead to overgrowth and overcrowding, resulting in tall and slender plants susceptible to lodging and pest infestation. Studies emphasized that crop yields were constrained by a combination of soil moisture and nitrogen, highlighting the intricate interplay between water and nitrogen [15]. This implied that the interaction of water and nitrogen might have a greater impact on crops than the effects of individual factors. Therefore, appropriate soil moisture content and nitrogen rates were crucial for sorghum production, and scientific quantitative research on sorghum growth conditions and yield indexes was needed to reduce water and nitrogen rate inputs and improve farmland ecology while ensuring stable sorghum yields.

Different irrigation management and nitrogen rates had varied effects on nitrogen accumulation in the soil [16]. Ammonium nitrogen accumulated in the soil is easily adsorbed and immobilized by soil agglomerates in the soil, which replenished the soil nitrogen pool for uptake and utilization by the next season's crop [17,18]. However, ammonium-N can be transformed into nitrate-N through nitrification, and the accumulation of nitrogen from fertilizers in the form of nitrate-N residue in the soil will increase the potential risk of nitrogen leaching. Several reports showed that excessive irrigation and nitrogen rate promoted nitrate-N accumulation and leaching from soils, increasing groundwater contamination and greenhouse gas emissions [19–21]. Yan et al. [22] also reported that increasing nitrogen rate increased soil nitrate nitrogen accumulation, while increasing irrigation-decreased soil nitrate nitrogen accumulation. Deep soil nitrate-N showed a gradual increase with increasing irrigation and nitrogen rate, exacerbating the risk of deep soil nitrate-N accumulation and groundwater pollution. Therefore, clarifying the status of soil nitrate-N and ammonium-N accumulation in different water and nitrogen conditions is an important guideline for the safe production of sorghum and the sustainable development of farmland ecology.

Overall, irrigation management and nitrogen rate management constitute vital facets of sorghum production, which not only affects crop growth and development but also inevitably influences the nitrate-N and ammonium-N content of the soil [23]. Crop growth and soil nitrogen accumulation are closely related to the safe production of sorghum. Therefore, it is necessary to find more rational irrigation management and nitrogen rate management models to maximize the crop yield while considering the sustainable use of agricultural soils. Currently, there are not many reports considering the response of sorghum growth, yield and soil nitrogen accumulation to irrigation management and nitrogen application and their interactions. Heilongjiang Province belongs to the northeast sorghum-producing region, one of the main sorghum-producing regions in China [24,25]. The average annual total sorghum production is nearly 400,000 tons, accounting for about one-tenth of the country. In addition, drip irrigation has become one of the most commonly used modes during sorghum cultivation because of its water- and fertilizer-saving characteristics.

We conducted a field experiment in 2021 and 2022 to investigate the effects of different irrigation management and nitrogen rate on sorghum growth, yield and soil nitrogen accumulation with drip irrigation, aiming to (1) reveal effects of different irrigation management, nitrogen rates and their interactions on sorghum plant height, stem diameters, LAI, SPAD, aboveground biomass and yield, (2) explore the effects of different irrigation management and nitrogen rates and their interaction on soil nitrate-N and ammonium-N accumulation in sorghum fields. The results of this study will provide theoretical basis and technical reference for producing high sorghum yields and synergistic use of irrigation management and nitrogen rate in sorghum planting.

2. Materials and Methods

2.1. Experimental Site Description

The study was conducted at the experimental site in Harbin, Heilongjiang, China (126°44′ E, 45°44′ N) during the sorghum growing season in 2021 and 2022. The local climate is the moderate temperate monsoon climate, with an average annual temperature of 3.1 °C, an effective cumulative temperature of 2700 °C and an average crop evaporation of 796 mm. The frost-free period is 130~140 d, and rainfall is mostly between 400 and 650 mm with most of the precipitation concentrating in the months of July–September, which accounts for about 70% of the year. Precipitation and temperature data during the experiment period were measured by an automatic weather station at the experiment station (Figure 1). Soil (0~60 cm) was collected in each plot with a 200 cm^3 cutting ring and taken to the laboratory. Soil physical properties including particle size distribution, bulk density, field capacity and wilting point were determined by the soil-cutting ring method [26]. The experiment soil was loamy soil, a total N content of 0.27 g/kg, a soil organic matter content of 32.2 g/kg, a total P content of 1.07 g/kg, an available phosphorus content of 24.81 mg/kg, an available potassium content of 262.22 mg/kg, and a pH of 7.12. The physical properties of different soil layers were shown in Table 1.

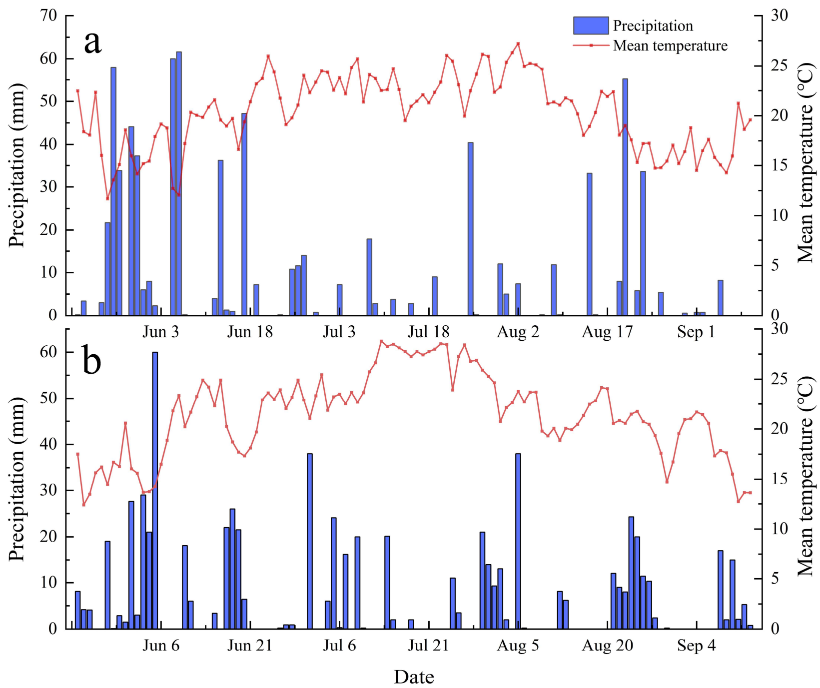

Figure 1. Daily precipitation and daily mean temperature in 2021 (**a**) and 2022 (**b**) during the sorghum growing season.

Table 1. Physical properties of different layers of soil.

Soil Depth (cm)	Particle Size Distribution (%)			Soil Type	Bulk Density (g/cm^3)	Field Capacity (%)	Wilting Point (%)
	Clay	Silt	Sand				
0~20	36.8	47.2	16	Clay loam	1.29	25.6	11.4
20~40	35.2	46.4	18.4	Clay loam	1.26	26.5	11.1
40~60	33.4	47.8	18.8	Clay loam	1.14	27.2	11.2

2.2. Experimental Design

The in situ experiment was conducted in 2021 and 2022. The experimental treatments consisted of 3 irrigation management levels and 4 nitrogen rates. Irrigation management was set to 3 lower levels of soil moisture: high irrigation (HI), normal irrigation (NI) and low irrigation (LI) at 80%, 70% and 60% of field capacity, respectively. The upper level of the soil moisture content is 100% of field water holding capacity for each treatment. Nitrogen rate was set at 4 levels at 225, 150, 75 and 0 kg/ha (designated as HN, NN, LN and WN, respectively), with treatments at 150%, 100%, 50% and 0% of the local fertilization rate, respectively. A total of 12 treatments were conducted in the experiment. The experimental sorghum variety for both years was Long Hybrid 22, which was sown on 19 May 2021 and harvested on 15 September 2021 and sown on 20 May 2022 and harvested on 19 September 2022, respectively.

The experimental plots were randomly distributed with 3 replications, each plot was 3.25 m wide and 5.25 m long. Each plot was equipped with a water meter and fertilizer tank to control the amount of irrigation water and nitrogen fertilizer. To prevent water and fertilizer movement between adjacent plots, a 1.0 m wide buffer zone was set up between each plot. P_2O_5 75 kg/ha and K_2O 150 kg/ha were applied as seed fertilizer in each experimental plot, and the fertilizer was kept at a distance of 3~5 cm from the seeds when applying it. One-third of the nitrogen fertilizer was applied with the seed fertilizer, and the remaining two-thirds of the nitrogen fertilizer was applied at the jointing and heading stage, and the fertilizer was applied by drip irrigation, in which the fertilizer was dripped in with the irrigation water. The drip irrigation tape was patch type drip irrigation belt. Soil water content was measured by soil auger method every 7 days. The irrigation amount for different treatments was calculated using the following equation:

$$I = 10 \times \theta \times H \times \left(\beta_i - \beta_j\right) \quad (1)$$

where I is the irrigation amount, kg/m^2; θ is the average soil bulk density in the planned wetting layer, g/cm^3; H is the depth in the planned wetting layer (0~60 cm soil layer), cm; β_i is the average value of the target soil water content in the 0~60 cm soil layer, %; and β_j is the average soil water content in the 0~60 cm soil layer, %.

2.3. Measurement of Sorghum Growth Traits

Plant height, stem diameter, leaf area and SPAD value were measured at the jointing, heading, filling and maturity stages of sorghum. Each time, ten representative plants were selected from each plot when measuring the plant height with a tape measure and stem diameters with vernier calipers. Sorghum's inverted second leaves were selected and after removing dust from the leaf surface, the average SPAD value readings at 10 points on each leaf were recorded using a chlorophyll meter (SPAD-502, Minolta Co Ltd., Osaka, Japan). Leaf area of the fully expanded leaves of the plants was determined. The leaf area of each leaf was measured by a leaf area meter (LI-3100, LI-COR, Lincoln, NE, USA). The leaf area index (LAI) was then calculated as follows:

$$\text{LAI} = \rho \frac{\sum_{j=1}^{m} \sum_{i=1}^{n} S_{ij}}{m} \quad (2)$$

where S_{ij} is the leaf area of the i-th leaf of the j-th plant measured with a leaf area meter, m^2; n is the total number of leaves of the j-th plant; m is the number of plants measured, and ρ is the planting density, plants/m^2.

2.4. Aboveground Biomass and Seed Yield

At the maturity stage, the aboveground biomass of each plot was taken as a sample using the five-point sampling method, and the sampled plants were placed in a nylon mesh bag, firstly dry-blanched in an oven at 110 °C for 1 h, then dried at 80 °C until constant mass, and finally naturally cooled in a dryer to determine the weight of aboveground biomass of each plant. At harvest, 4 m^2 of uniformly growing sorghum plants were selected for harvest in the middle of each plot. Additional spikes were taken for drying and stripping, and the seed yield of each plot was calculated.

2.5. Nitrate-N and Ammonium-N Accumulation in Soil

Soil samples were collected using the soil auger method after harvest [27]. The samples were taken from the middle of the drip irrigation zone of each plot, perpendicular to the drip irrigation laterals at a distance of 10 cm. The soil samples from each sampling point were divided into 0~10 cm, 10~20 cm, 20~30 cm, 30~40 cm, 40~50 cm and 50~60 cm depth intervals. Soil nitrate-N and ammonium-N contents were determined using an automated analyzer by extraction with 2 mol/L potassium chloride solution [28]. Nitrate-N and ammonium-N accumulation (N_n and N_a) in different soil layers were calculated according to the following formula:

$$N_n \ or \ N_a = 0.1D \times P_b \times C \quad (3)$$

where N_n and N_a is the accumulated amount of soil nitrate-N and ammonium-N, kg/ha; D the thickness of the soil layer, cm; P_b is the soil bulk weight, g/cm^3; C is the mass ratio of inorganic nitrogen in a given soil layer, mg/kg.

2.6. Data Analysis

Analysis of variance (ANOVA) was performed using the SPSS Statistics 18.0. ANOVAs were used to analyze the data on plant height, stem diameter, LAI, SPAD value, seed yield, and soil nitrate-N and ammonia-N accumulation. Duncan's test, regression and Pearson correlation analysis for two years data was conducted by the correlation procedure in the SPSS 17.0. (version 23, IBM Corp., Chicago, IL, USA). All figures were created using OriginPro 2016 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Plant Height, Stem Diameter, LAI and SPAD Value

Sorghum plant height in the 2021 and 2022 increased gradually with the growth stage and was the highest at the filling stage and maturity stage, as shown in Figure 2. Irrigation management had a significant effect on plant height at the heading stage and filling stage, the nitrogen rate had a significant effect on plant height at the heading stage, and the interaction of irrigation management and nitrogen rate had a significant effect on plant height at the heading stage, filling stage, and maturity stage in 2021 and 2022 (Table 2). Plant height was highest in the HNNI treatment at the 2021 heading stage and in the NNHI treatment at the 2022 filling stage. The NNHI treatment had the highest plant height at the filling and maturity stages.

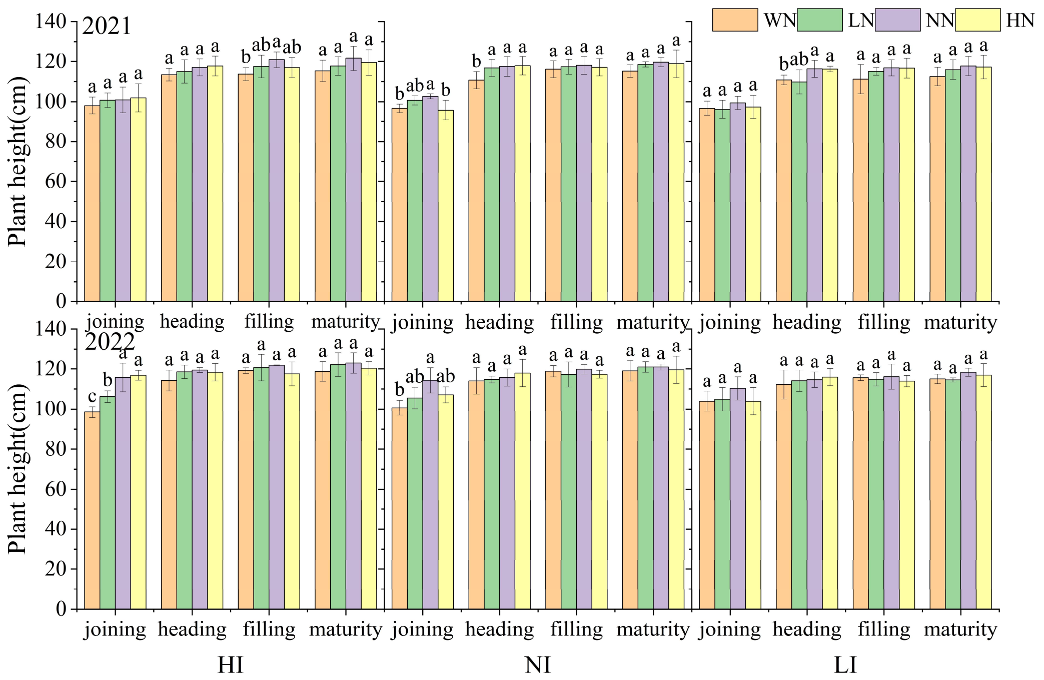

Figure 2. Sorghum plant height at each growth stage in different treatments. Note: LI, NI, and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively. HN, NN, LN, WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively. Different lowercase letters within columns indicate significant differences in nitrogen rates at the same stage and under the same irrigation management indicated by Duncan's test at $p < 0.05$.

Table 2. Significance level of the effects of irrigation management and nitrogen rate on plant height, stem diameter, leaf area and SPAD value of sorghum.

Factors	Growth Stages	Plant Height		Stem Diameter		LAI		SPAD	
		2021	2022	2021	2022	2021	2022	2021	2022
Irrigation management	Jointing Stage	ns	ns	ns	ns	ns	ns	*	ns
	Heading Stage	*	*	*	**	ns	ns	*	*
	Filling Stage	*	*	*	*	*	*	*	ns
	Maturity Stage	ns	*	ns	*	ns	ns	*	ns
Nitrogen rate	Jointing Stage	ns	*	ns	*	*	*	ns	*
	heading Stage	**	*	ns	ns	*	*	*	*
	Filling Stage	ns	ns	*	ns	ns	*	*	*
	Maturity Stage	*	ns	ns	ns	*	*	ns	*
Irrigation management × Fertilization rate	Jointing Stage	ns	*	ns	*	*	*	**	*
	Heading Stage	**	**	*	**	*	*	**	*
	Filling Stage	*	*	*	*	*	**	**	**
	Maturity Stage	*	*	ns	*	*	*	**	*

Note: ns, * and ** mean no significant difference, significant difference at $p < 0.05$ and significant difference at $p < 0.01$, respectively.

Stem diameters in the 2021 and 2022 showed a decreasing trend as sorghum grew (Figure 3). Irrigation management had a significant effect on stem diameters at the heading stage and filling stages in the 2-year experiment, the nitrogen rate had no significant effect on sorghum stem diameters at all stages, and the interaction of irrigation management and nitrogen rate had a significant effect on stem diameters at the heading and filling stages (Table 2). Under the different nitrogen rate treatment, the stem diameters of HI treatments were larger than those of the NI and LI treatments by 0.54~2.36 mm at heading stage and 0.78~2.36 mm at filling stage in 2021 and 2022. Stem diameter was largest in the NNNI treatment at heading stage in 2021 and in the HNHI treatment at heading stage in 2022. The NNHI treatment had the largest stem diameters at the filling stage in 2021, while the HNHI treatment had the largest stem diameters at the filling stage in 2022.

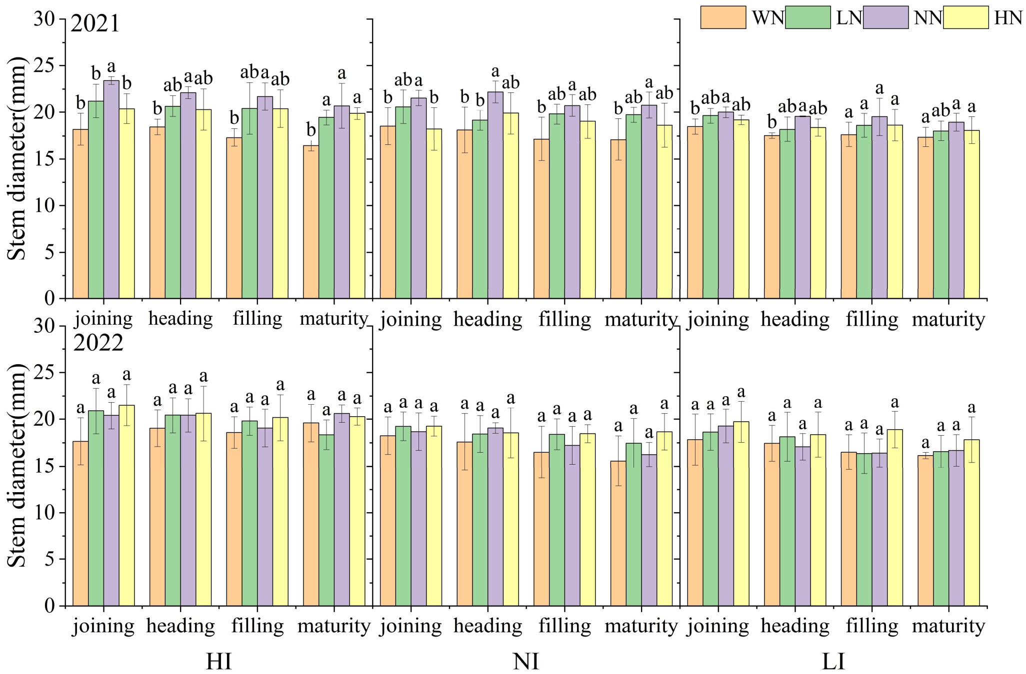

Figure 3. Sorghum stem diameter at each growth stage in different treatments. Note: LI, NI and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively. HN, NN, LN and WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively. Different lowercase letters within columns indicate significant differences in nitrogen rates at the same stage and under the same irrigation management indicated by Duncan's test at $p < 0.05$.

The LAI of sorghum showed an increasing and then decreasing trend with the growth of sorghum and reached the highest at the heading stage, as shown in Figure 4. Irrigation management had no significant effect on LAI at the all growth stages in 2021 and 2022, nitrogen rate had a significant effect on sorghum plant height at joining, heading and filling stages, and interaction of irrigation management and nitrogen rate had a significant effect on stem diameters at all growth stages (Table 2). Under HI treatments, the LAI of NN treatment at the heading stage was significantly higher than that of HN treatment, while the differences between NN and HN treatments were not significant at other stages in 2021 and 2022. Under NI treatments, the LAI of NN and HN treatments at the heading stage were significantly higher than those of LN and WN treatments in 2021 and 2022. Under LI treatments, the LAI of HN treatment were the highest in each growth stage in 2021 and 2022.

The SPAD values of sorghum leaves increased and then decreased with the growth of sorghum and were the highest at the filling stage, as shown in Figure 5. Irrigation management significantly affected SPAD values at the filling stage in the 2-year experiment, the nitrogen rate significantly affected SPAD values at the jointing, heading and filling stages, and the interaction of irrigation management and nitrogen rate had a significant effect on SPAD at all stages of sorghum, and a highly significant effect on SPAD values at the filling stage. Under HI treatments, the SPAD value of HN treatment was the highest at the heading, filling and maturity stages in 2021 and 2022. Under the NI and LI treatments, there were no significant difference between the SPAD value of different nitrogen rate treatments at the jointing and heading stages, and the SPAD value of the HN treatment was significantly higher than that of the WN treatment at the filling stage.

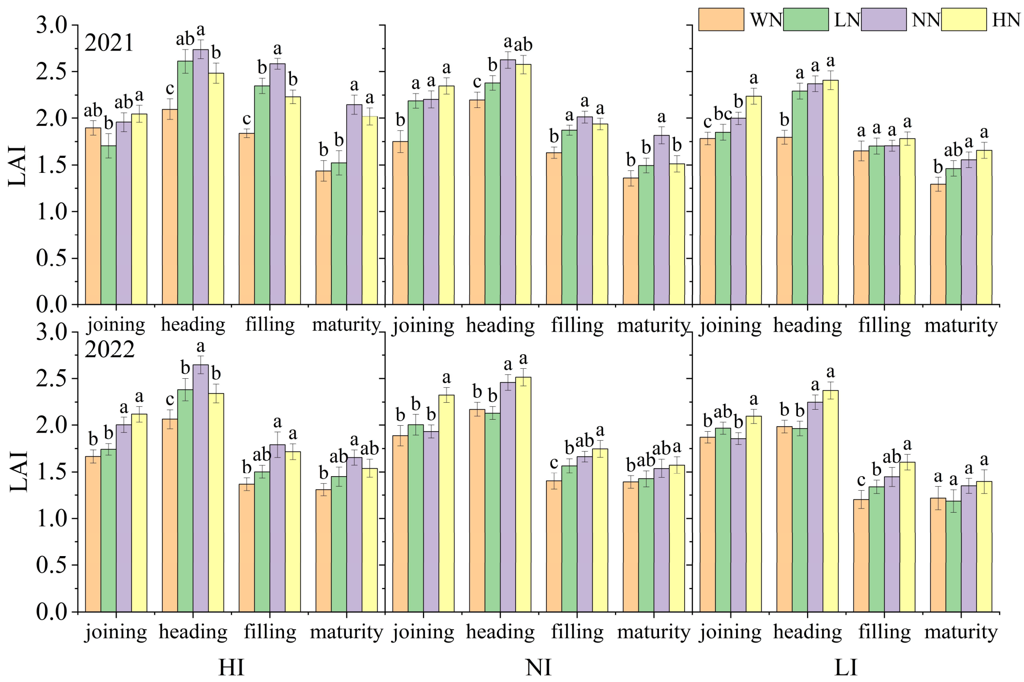

Figure 4. Sorghum LAI at each growth stage in different treatments. Note: LI, NI, and HI refer to lower levels of soil moisture at 80%, 70% and 60%, respectively. HN, NN, LN and WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively. Different lowercase letters within columns indicate significant differences in nitrogen rates at the same stage and under the same irrigation management indicated by Duncan's test at $p < 0.05$.

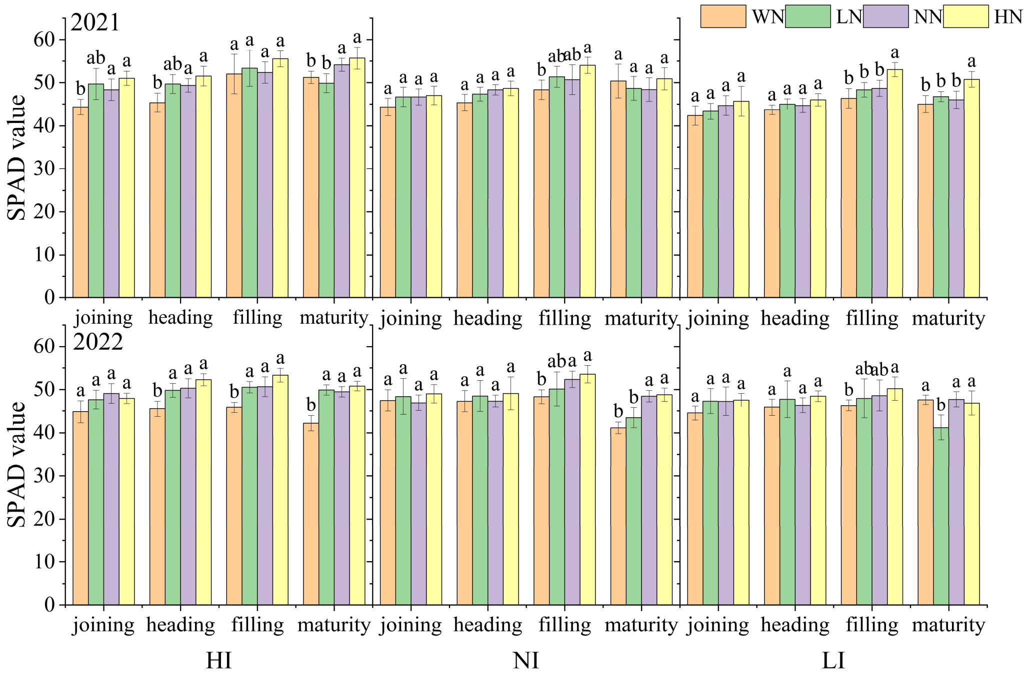

Figure 5. Sorghum SPAD values at each growth stage in different treatments. Note: LI, NI and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively. HN, NN, LN and WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively. Different lowercase letters within columns indicate significant differences in nitrogen rates at the same stage and under the same irrigation management indicated by Duncan's test at $p < 0.05$.

3.2. Yield and Aboveground Biomass

In 2021 and 2022, irrigation management, nitrogen rate, as well as the interaction between irrigation management and nitrogen rate exhibited significant effects on yield and aboveground biomass ($p < 0.05$) (Table 3). Irrigation management and the interaction of irrigation management and nitrogen rate significantly affected aboveground biomass ($p < 0.01$).

Table 3. Effect of irrigation management and nitrogen rate treatments on Sorghum yield, aboveground biomass and soil Nitrate-N and Nitrate-N accumulation.

Treatments	Yield (kg/ha)		Aboveground Biomass (kg/ha)		Nitrate-N Accumulation (kg/ha)		Ammonium-N Accumulation (kg/ha)	
	2021	2022	2021	2022	2021	2022	2021	2022
HI	6538.01 a	6536.54 ab	12,594.09 a	14,713.89 a	75.3 a	76.21 a	33.17 a	30.87 a
NI	6474.63 a	6877.72 a	14,213.00 a	12,825.15 ab	78.77 a	77.77 a	32.66 a	31.61 a
LI	6143.90 b	6295.24 b	11,352.56 b	11,031.75 b	79.79 a	77.2 a	34.7 a	34.08 a
HN	6204.87 b	6791.09 a	12,991.15 ab	13,904.35 a	93.88 a	92.53 a	43.08 a	38.23 a
NN	7039.15 a	6846.28 a	14,848.72 a	13,298.82 a	82.22 b	83.55 b	43.08 b	34.06 ab
LN	6350.67 b	6422.43 ab	11,705.62 b	13,089.13 a	77.82 b	78.87 b	43.08 c	34.07 b
WN	5947.35 b	6219.54 b	11,334.07 b	11,135.53 b	77.82 c	58.79 c	43.08 d	34.07 c
Irrigation management	*	*	**	**	ns	ns	ns	ns
Fertilization rate	**	*	*	*	**	**	**	**
Irrigation management × Fertilization rate	*	*	**	**	**	**	**	**

Note: Different lowercase letters within columns indicate significant differences indicated by Duncan's test at $p < 0.05$. ns, * and ** mean no significant difference, significant difference at $p < 0.05$ and significant difference at $p < 0.01$, respectively.

The regression analysis between soil moisture and nitrogen rate was shown in the below equation:

$$Z = -11,354.72 + 66.2268Y + 51.6749Y - 0.0348XY - 0.0518X^2 - 0.0613Y^2 (R^2 = 0.79, p < 0.01) \quad (4)$$

where Z was the yield (kg/ha), X was lower levels of soil moisture (%), and Y was the nitrogen rate (kg/ha).

The yield achieved its maximum of 6962.40 kg/ha after computing the partial derivative of the regression equation, which indicated the optimal lower levels of soil moisture to be 71.93% and the optimal nitrogen rate to be 144.58 kg/ha (Figure 6).

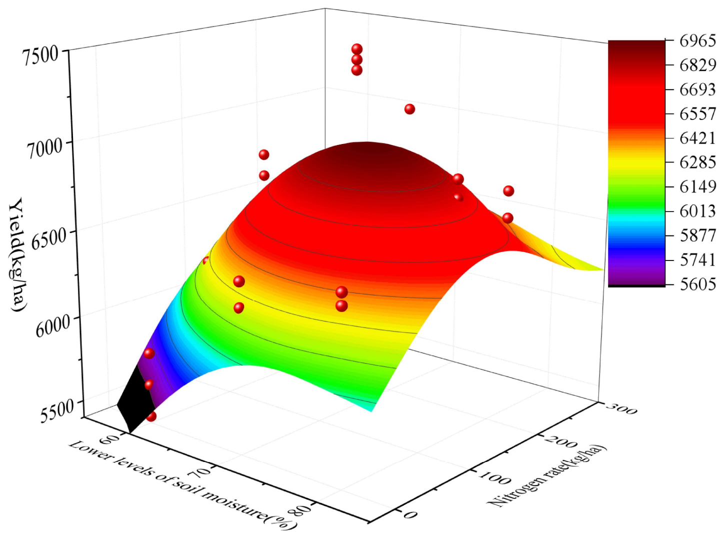

Figure 6. Sorghum yield under different irrigation management and nitrogen rate.

In 2021 and 2022, the yield of NNNI treatment was the highest (Figure 7). The yield of NNNI treatment was significantly higher than those of all other treatments in 2021, while the yield of NNNI treatment was significantly higher than that of all treatments except the HNNI treatment in 2022. Under the HI treatments, the yield of NN treatment was significantly higher than the other nitrogen rate treatments in 2021 and there was no significant difference in yield among different nitrogen rate treatments. Under the LI treatments, the yields of WN treatment were significantly lower than the other nitrogen rate treatments in 2021 and 2022.

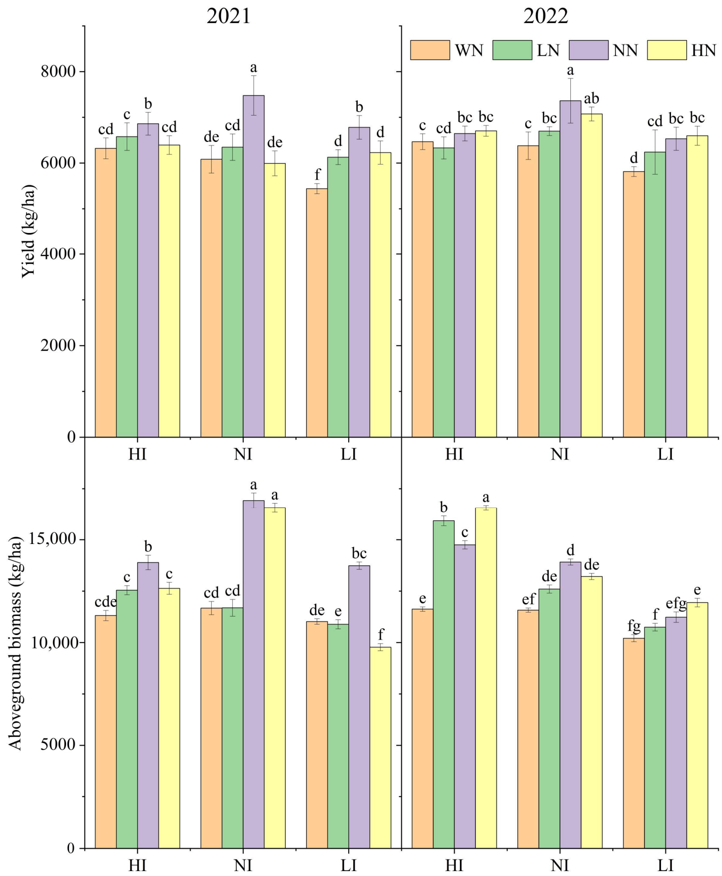

Figure 7. Sorghum seed yield and aboveground biomass in different treatments. Note: LI, NI, and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively. HN, NN, LN, WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively. Different lowercase letters within columns indicate significant differences under different irrigation management and nitrogen rates indicated by Duncan's test at $p < 0.05$.

Aboveground biomass was the greatest in the NNNI treatment in 2021 and in the NNHI treatment in 2022 (Figure 7). Under the HI treatments, the aboveground biomass of the NN treatment in 2021 and the HN treatment in 2022 was significantly higher than the other nitrogen rate treatments. Under the NI treatments, the aboveground biomass of the HN and NN treatments were significantly higher than the aboveground biomass of LN and WN treatments in 2021, and the aboveground biomass of NN treatment was significantly higher than the aboveground biomass of WN treatment in 2022. Under the LI treatments, the aboveground biomass of the NN treatment was significantly higher than the other nitrogen rate treatments in 2021, and the aboveground biomass of HN treatment was significantly higher than the aboveground biomass of WN treatment in 2022.

3.3. Soil Nitrate-N and Nitrate-N Accumulation in the 0~60 cm Soil Layer

In 2021 and 2022, nitrate-N accumulation gradually decreased in all treatments with increasing soil depth (Figure 8). Nitrogen rate and the interaction between irrigation management and nitrogen rate significantly affected the accumulation of nitrate-N and ammonium-N in the 0~60 cm soil layer ($p < 0.01$) (Table 3), however, irrigation management did not significantly affect the accumulation of soil nitrate-N and ammonium-N in the 0~60 cm soil layer. The accumulation of nitrate-N in HN treatments were significantly higher than those in NN and LN treatments, while the difference between NN and LN treatments was not significant in 2021 and 2022. Under LI, NI and HI treatments, the accumulation of nitrate-N in NN treatments were 8.02, 6.47, 7.01 kg/ha lower in 2021, and 2.10, 2.55, 4.33 kg/ha lower in 2022 than those in HN treatments. The accumulation of nitrate-N in WN treatments were significantly lower than those in NN and LN treatments. Under LI, NI, and HI treatments, the accumulation of nitrate-N in WN treatments were 8.10, 6.78, 9.71 kg/ha lower in 2021, and 9.41, 12.99, 7.73 kg/ha lower in 2022 than those in LN treatments.

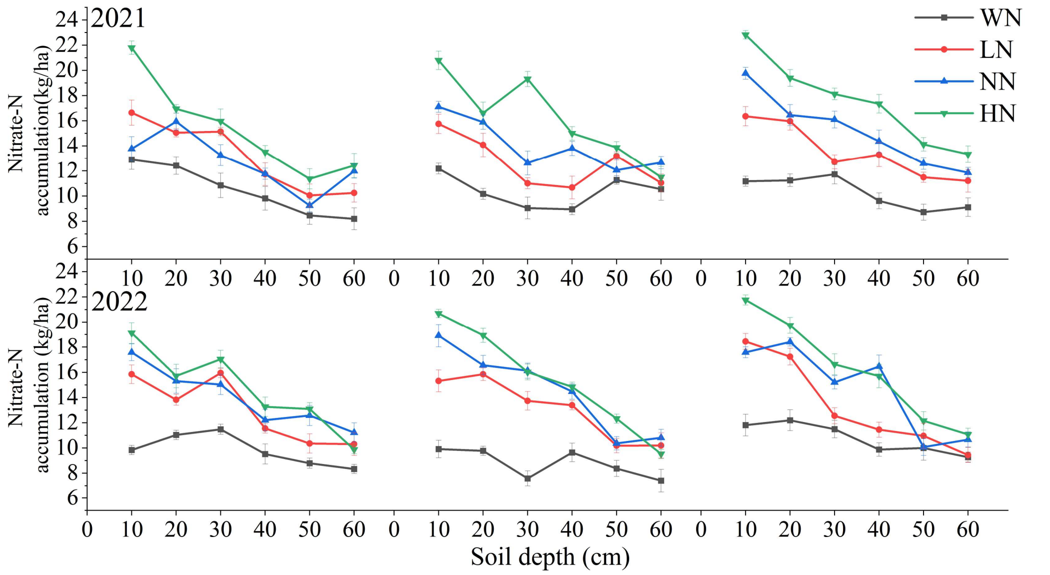

Figure 8. Nitrate-N accumulation in each soil layer in different treatments. Note: LI, NI and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively. HN, NN, LN and WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively.

The effect of different irrigation management and nitrogen rate on ammonium-N accumulation in the 0~60 cm soil layer at sorghum harvest was shown in Figure 9. Ammonium-N accumulation in each soil layer ranged from 2.98 to 9.37 kg/ha in 2021 and from 3.12 to 8.73 kg/ha in 2022, and increased with the increase in nitrogen rate (Figure 9). The accumulation of ammonium-N in HN treatments were significantly higher than that in LN treatments in 2021 and 2022. Under LI, NI and HI treatments, the accumulation of ammonium-N in LN treatments were 11.63, 12.34, 10.57 kg/ha lower in 2021, and 9.41, 12.99, 7.73 kg/ha lower in 2022 than in HN treatments. The accumulation of ammonium-N in WN treatments were significantly lower than in LN treatments. Under LI, NI, and HI treatments, the accumulation of ammonium-N in WN treatments were 5.58, 5.41, 8.18 kg/ha lower in 2021, and 8.27, 5.70, 8.22 kg/ha lower in 2022 than those in LN treatments.

3.4. Pearson's Correlation Coefficients between Sorghum Growth (Plant Height, Stem Diameter, LAI and SPAD Value), Yield, Aboveground Biomass and Soil Nitrogen Accumulation

Sorghum plant height, stem diameters LAI and SPAD value at the filling stage were selected for correlation analysis with yield, aboveground biomass, accumulation of soil nitrate-N and ammonium-N (Figure 10). Yield and aboveground biomass was significantly and positively correlated with plant height at heading stage and maturity stage. Yield was significantly and positively correlated with plant height and leaf area index at the filling stage. Aboveground biomass was significantly positively correlated with plant height, LAI and SPAD value. Soil nitrate-N and ammonium-N accumulation was significantly and positively correlated with leaf area index and SPAD values. Plant height, stem diameters, leaf area index and SPAD values were significantly and positively correlated with each other.

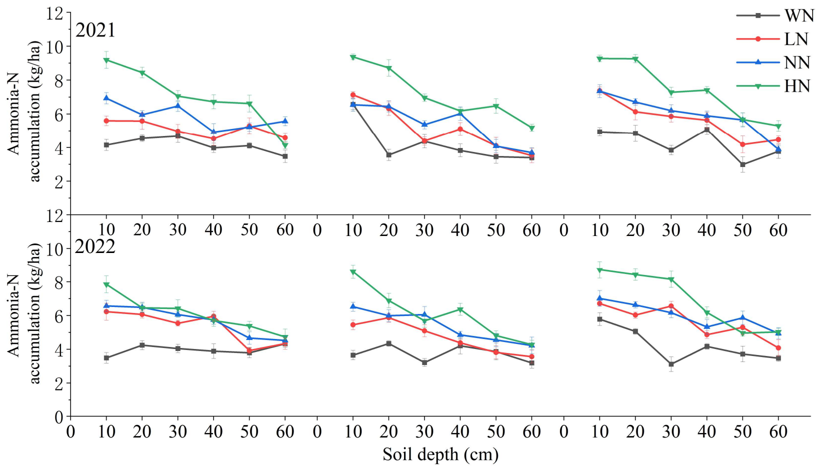

Figure 9. Ammonium-N accumulation in each soil layer in different treatments. Note: LI, NI and HI refer to lower levels of soil moisture at 80%, 70% and 60% of field capacity, respectively; HN, NN, LN and WN refer to nitrogen rate of 225, 150, 75 and 0 kg/ha, respectively.

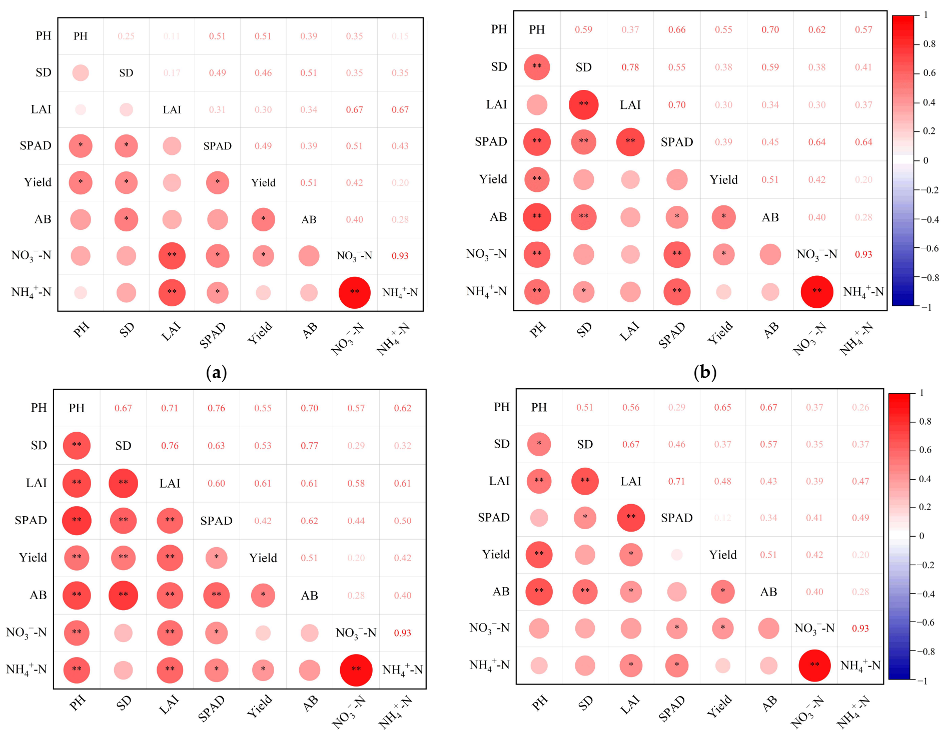

Figure 10. Pearson's correlation coefficients between sorghum growth at (**a**) joining stage, (**b**) heading stage, (**c**) filling stage and (**d**) maturity stage (plant height, stem diameter, leaf area index and SPAD value), yield, aboveground biomass and soil nitrogen accumulation. Note: PH, plant height; SD, stem diameter; LAI, leaf area index; AB, aboveground biomass; NH_4^+-N, ammonium-N accumulation; NO_3^--N, nitrate-N accumulation, respectively. * and ** mean significant difference at $p < 0.05$ and significant difference at $p < 0.01$, respectively.

4. Discussion

4.1. Effects of Irrigation Management and Nitrogen Rate Management on Sorghum Growth

Proper management of irrigation management and nitrogen rates can enhance crop growth, thereby influencing crop yield [29,30]. Our objective was to investigate the impact of irrigation management and nitrogen rate management on sorghum growth and, consequently, yield. In this study, sorghum subjected to the HI treatment exhibited greater plant height, stem diameters and LAI at all growth stages over the 2-year experiment. However, the NI treatment resulted in the highest yield, and the HI treatment did not significantly increase yield. This suggested that the correlation between crop growth status and yield was not always positive [31,32]. Furthermore, excessive irrigation management and nitrogen rates were found to be detrimental to nutrient accumulation in the grain yield [33].

The NNHI treatment maximized both plant height and LAI, highlighting that balanced irrigation management and nitrogen rate management were able to promote the growth of sorghum stems and leaves [34,35]. ANOVA on plant height at each growth stage revealed that irrigation management and nitrogen rate influenced sorghum plant height at heading, filling, and maturity stages, as well as LAI at all growth stages. Increased irrigation management promoted sorghum growth in NN treatments, which was also indicated by the increase in aboveground biomass in response to the increase in irrigation management. However, it was noteworthy that excessive soil moisture did not result in higher yields of sorghum, which might be due to the fact that sound irrigation management and nitrogen rate supply affected the processes of nutrient synthesis transfer and accumulation in crops, allowing more nutrients to accumulate in the sorghum kernels in the NNNI treatment [36,37].

The analysis of the response of sorghum growth parameters to irrigation management and nitrogen rates showed that the interaction affected sorghum growth across more stages compared to the individual effects of irrigation management or nitrogen rate. For instance, the interaction of irrigation management and nitrogen affected LAI and the chlorophyll content of sorghum leaves (SPAD value) at all growth and development stages, impacting yield and nutrient accumulation.

4.2. Effects of Irrigation Management and Nitrogen Rate Management on Sorghum Yield and Aboveground Biomass

Irrigation management and nitrogen were pivotal factors affecting crop yield, and their interaction could contribute to improved yields [38]. Many studies have illustrated the parabolic relationship between irrigation management, fertilizer application and yield. Typically, crop growth and yield reached their peak with a balanced allocation of soil moisture and nitrogen rates [22,39]. Si et al. [40] reported that fertilizer application and water–fertilizer interactions significantly affected the increase in sweet sorghum plant height, stem diameters and yield, and yield increased and then decreased with increasing nitrogen rate and irrigation, with highest yields being achieved with irrigation of 6000 m^3/ha and fertilizer application of 112.5 kg/ha. In our study, the NNNI treatment with drip irrigation resulted in the highest yields in 2021 and 2022, reaching 1156.09 kg/ha and 1439.45 kg/ha, respectively. However, the yield of the HN and HI treatments did not show a significant improvement. This outcome suggested that excessive soil moisture and nitrogen rates did not significantly increase yield, instead, they led to resource wastage [41,42].

4.3. Effects of Irrigation Management and Nitrogen Rate Management on Soil Nitrate-N and Nitrate-N Accumulation

Soil nitrate-N and ammonium-N accumulation, as the main forms of nitrogen absorbed by crops in the soil, were influenced by crop N uptake, irrigation methods and N fertilization rates [43,44]. This study showed that nitrate-N and ammonium-N accumulation in the same soil level showed an increase with the increase in nitrogen rate; both showed the highest nitrate-N content in the 0~20 cm soil layer, and under all treatments, the accumulation of soil nitrate-N and ammonium-N gradually decreased with increasing soil depth. Chen et al. [45] investigated the impact of nitrogen rate on the inorganic nitrogen accumulation of sorghum planting soil and concluded that soil nitrate-N was greatly affected by the amount of nitrogen rate, while ammonium-N was insignificantly affected by the amount of nitrogen rate, and the conclusion about nitrate-Nitrogen in this study was similar to his conclusion. However, the ammonium-N in this study was also more significantly affected by the nitrogen rate, which may be because the pH of the soil in our experiment was 7.12 less than that from Chen et al. The more acidic soil attenuated the nitrification reaction and inhibited the conversion of ammonium-N to nitrate-N [46]. In addition, the interaction of irrigation management and nitrogen rate significantly affected soil nitrogen accumulation, whereas increasing irrigation lowered but did not significantly alter soil nitrogen accumulation. This partly explained the ability of drip irrigation to reduce the leaching effect of gravity water on soil nitrogen accumulation. Previous study indicated that sorghum was a more effective absorber of ammonium-N than nitrate-N [47]. Ammonium-N that accumulated in the soil contributed to soil fertility and provided nutrients for sorghum growth early in the next growing season, while nitrate-N that accumulated in the soil was more soluble in water, increasing the risk of contaminating the environment. This further emphasized the importance of managing nitrogen levels.

In this study, soil nitrate-N accumulation was significantly correlated with nitrogen rate, and the nitrate-N accumulation in the HN treatments was the largest. In 2021, the yields of NN treatments were significantly higher than the yields of WN, LN and HN treatments, and the NNNI treatment had the highest yield of all treatments. In 2022, the yield difference between the HNNI treatment and the NNNI treatment was not significant, and the nitrate-N accumulation from 0 to 60 cm in the NNNI treatment was significantly lower than that in the HNNI treatment by 10.4%. Therefore, the NNNI treatment appeared to be a more appropriate nitrogen application level for achieving high yields and environmentally friendly sorghum production based on the 2-year experiment.

5. Conclusions

Irrigation management and nitrogen rate significantly affected the LAI and SPAD values of sorghum at all growth stages. Aboveground biomass, soil nitrate-N and ammonium-N of sorghum were significantly affected by the interaction of irrigation management and nitrogen rate. Significant correlations were identified between plant height, LAI and yield. The treatment with a lower soil moisture limit of 70% FC and a nitrogen rate of 150 kg/ha achieved maximum sorghum yield (7477.41 and 7362.27 kg/ha in 2021 and 2022, respectively). Integrated water and fertilizer under drip irrigation, as a modern agricultural technology, proved instrumental in enhancing yield and optimizing the efficient utilization of water and nutrients for crop growth. The findings presented in this study offered valuable insights into effective irrigation and nitrogen management strategies for sorghum production, contributing theoretical support for the realization of sustainable agriculture and the scientific cultivation of sorghum in similar soil or climate regions.

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