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Irrigation-Nitrogen Synergies Shaping Fodder Yield, Quality and Water Productivity in Spring Sorghum (*Sorghum bicolor* L.)

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Abstract

Sorghum is known for its drought tolerance and climate resilience grown in water limiting conditions. The cultivation of sorghum in Punjab as low water requiring crop may help in arresting fast declining water table. The nitrogen fertilisation and irrigation management crucial role in the success of any crop. Therefore, this study was carried out to determine the potential effects of irrigation water and nitrogen management on growth, green fodder yield quality of sorghum. The treatments comprised of combinations of four different irrigation levels (I_1-IW/CPE 1.2, I_2-IW/CPE 1.0, I_3-IW/CPE 0.8, I_4-IW/CPE 0.6) and four nitrogen doses (N_1-75 kg N/ha^{-1}, N_2-100 kg N/ha^{-1}, N_3-125 kg N/ha^{-1}, N_4-150 kg N/ha^{-1}) applied in an experiment conducted in split plots design during the years 2024 and 2025. Key findings revealed that irrigation and N application significantly influenced plant height, fodder yield, quality attributes and nutrient uptake. The highest plant height (227.79, 227.20 cm), fodder yield (6.90**,** 6.93 t ha^{-1}), nitrogen uptake (34.37, 34.77 kg ha^{-1}) and Crude protein (14.90, 14.98%) were observed under IW/CPE 1.2 in the year of 2024 and 2025 respectively. In nitrogen management scenario highest growth, yield and nitrogen uptake was observed under (N_4) 150 kg N/ha^{-1} treatment. While increase the dose of nitrogen (N_4) Crude protein (15.0, 15.20%) and In Vitro Dry Matter Digestibility (56.78, 56.93%) also increase while NDF (%), ADF (%) and Crude Fibre (%) decrease. Effect of irrigation and nitrogen on most of the soil properties was observed non-significant while application of irrigation on IW/CPE 1.0 base increase the evapotranspiration and decrease the drainage losses of water in field condition. Therefore, an adequate water supply (I_2-IW/CPE 1.0) and normal nitrogen application (125 kg N/ha^{-1}) is recommended for sorghum culture without any significant losses in yield and quality parameters.

Keywords: sorghum, yield, water balance, nitrogen application, fodder quality, water saving.

Introduction

Groundwater depletion has become a critical challenge to the long-term sustainability of agriculture in Punjab, one of India's most intensively cultivated states. The excessive exploitation of groundwater resources is largely attributed to technology- and policy-driven transformations in the agricultural sector, particularly the shift towards paddy-dominated cropping systems, increased dependence on groundwater irrigation, and widespread use of subsidized electricity for pumping (World Bank, 2020). Current estimates indicate that annual groundwater extraction in Punjab exceeds the sustainable recharge limit by approximately 72%, highlighting the severity of the groundwater crisis (Bhatia et al. 2024). As agriculture accounts for the largest share of groundwater consumption, the sector plays a pivotal role in addressing this issue. Among the major crops, paddy is the most water-intensive, requiring substantially higher groundwater inputs than alternative crops (Kishore et al. 2024). Consequently, paddy exhibits a larger groundwater footprint and lower groundwater productivity, raising serious concerns regarding the efficient utilization of water resources and emphasizing the need for crop diversification and improved irrigation management strategies (Singh et al 2022). In view of the escalating groundwater crisis in Punjab, there is an urgent need to promote alternative cropping systems that require less water while ensuring sustainable agricultural productivity. Sorghum (*Sorghum bicolor* L. Moench) has emerged as a promising climate-resilient crop due to its lower water requirement, high water-use efficiency, and ability to withstand drought and high-temperature conditions. Compared with paddy, sorghum consumes substantially less irrigation water and can be successfully cultivated under limited water availability without significant yield penalties ((Kiani et al. 2016)).

In recent years, sorghum cultivation has gained prominence, particularly for fodder across semi-arid tropical environments due to its ability to grow under high temperatures and water-limited conditions where few other crops can survive (Holman et al. 2019). Among the cultivated types, sweet, forage, and grain sorghum are especially important for animal nutrition, although considerable genetic and phenotypic variability exists within and among groups. Compared to maize, sorghum exhibits superior adaptability, high water-use efficiency (WUE), and relatively lower fertiliser requirements (Roby et al. 2017). *Sorghum bicolor* (L.) Moench is regarded as a valuable annual feed crop capable of producing substantial biomass yields. Although global sorghum production has largely stagnated, future productivity will depend on the development of improved varieties suited for silage and fodder applications (Karyoti et al. 2021). Achieving high biomass production requires maintaining optimal plant nutrition

throughout the growing season to ensure efficient nutrient uptake and balanced biochemical processes essential for growth. However, soil fertility decline has become increasingly evident in recent decades due to agricultural intensification and land overexploitation in Punjab, India. Parallel to this, cultivation costs have risen steadily, driven by escalating prices of fossil fuels and synthetic fertilisers (Esar et al. 2023). Consequently, nitrogen fertilizers owing to their well-established role in promoting crop growth and yield, have been applied at increasing rates over the past decade to sustain agricultural productivity. Nitrogen remains a key nutrient for enhancing biomass accumulation and improving yield performance across a wide range of crop species (DePeters et al. 1989).

Proper irrigation scheduling and deficit irrigation are recognised as effective water management strategies to mitigate water scarcity in agriculture (Bhattarai et al. 2020). Deficit irrigation seeks to optimise crop yield, quality, and growth attributes while intentionally supplying water below the full crop evapotranspiration requirement (Jahanzad et al. 2013). Under such conditions, slight reductions in biomass and minimal impacts on final yield may occur when crops are subjected to mild water stress during specific phenological stages or throughout the entire growing season (Roby et al. 2017). In addition, irrigation scheduling can be implemented using two commonly applied approaches: (i) fixed irrigation intervals (frequency-based scheduling) and (ii) maximum allowable depletion (MAD) of soil moisture, which results in variable irrigation intervals. Both approaches enable efficient crop production while conserving water resources (Gheysari et al. 2017). Cultivation practices such as fertiliser application and irrigation are critical for enhancing forage biomass production, nutritional quality, and nutrient-use efficiency. Nitrogen (N) is the most influential nutrient governing plant productivity. Adequate N application enhances the capture and utilisation of solar radiation, thereby promoting photosynthate synthesis and biomass accumulation (Clark et al. 2000). However, the optimal N requirement varies according to crop genotype and regional conditions. Previous studies have reported a wide range of optimal N rates for forage sorghum. For example, Kaplan et al. (2019) identified 90 kg N ha^{-1} as the optimal rate for maximising forage sorghum performance. In contrast, Moosavi et al. (2011) observed the highest dry matter yield (24.6 t ha^{-1}) with 218 kg N ha^{-1}. Despite these benefits, excessive N fertilisation may suppress yield and reduce nitrogen-use efficiency (NUE) (Chen et al. 2018). Most research indicates that appropriate N application significantly increases the crude protein (CP) content of forage sorghum. Sawargaonkar et al. (2013) reported that application of 112.5 kg N ha^{-1} increased CP concentration by 48.8% relative to the untreated control. However, the effects of

N on neutral detergent fiber (NDF), acid detergent fiber (ADF), and crude ash (ASH) remain inconsistent. Some studies have shown that N application can reduce NDF and ADF by up to 6.0% and 5.8%, respectively (Cui et al. 2013), whereas others reported that N fertilisation increases these fiber fractions (Perrin et al. 2014). Additionally, several studies have concluded that ADF, NDF, and ASH contents in sorghum are predominantly controlled by genetic factors rather than N availability (Zhang et al. 2016). Efficient irrigation scheduling based on soil moisture thresholds has become increasingly important in the context of declining groundwater availability, particularly in north-western India, where intensive agricultural practices have led to substantial depletion of groundwater resources. Optimizing irrigation application during the early stages of crop establishment is crucial for enhancing water-use efficiency while maintaining sorghum productivity. Appropriate irrigation timing not only conserves scarce water resources but also supports optimal crop growth and development under water-limited conditions (Gill et al. 1996).

Materials and Methods

Experimental site and soil Properties

The experiment was carried out during the *spring* seasons of 2024 and 2025 at the research farm (32° 04’ 32.02” N, 75° 40’ 75.24” W, and Elevation of 265 m) of Punjab Agricultural University, Regional Station Gurdaspur, Punjab (Fig. 1). The experimental site is characterised as a sub-humid sub-tropical climate with a mean annual precipitation of 700 mm, where the mean maximum temperature reaches as high as 42 °C in May- June while close to freezing temperatures (around 2.9 °C), along with ground frost spells, occur during the months of December-January (Singh et al. 2025). The rainfall during the crop season in the years 2024 and 2025 was 90.5 mm and 192.25 mm, respectively (Fig 2). The mean minimum and maximum temperature and daily rainfall were measured manually at an agrometeorological observatory about 200 m away from the experimental site at Punjab Agricultural University Regional Station, Gurdaspur. The soil was classified as fine silt, hyperthermic Typic Haplustalfs, characterised by a clay loam texture and moderate bulk density 1.30-1.37 Mg m^{-3}, pH 7.33-7.54, and organic carbon 0.59-0.29 % from 0-150 cm soil depth. Similarly, field capacity, permanent wilting, and saturated hydraulic conductivity were 0.24-0.28 m^3 m^{-3}, 0.105-145 m^3 m^{-3}, and 1.26-0.56 cm $h^{-1,}$ respectively (Table1).

Table 1 Soil Profile Characteristics Before Experiment Initiation

Depth	Sand	Silt	Clay	BD	Ks	WHC	FC	PWP	OC	pH	EC	NO_3-N	NH_4-N	Available P	Available K
	(%)			(Mg m^{-3})	(cm h^{-1})	(%)	(m^3 m^{-3})		(%)		(dS m^{-1})	(ppm)		(kg ha^{-1})	
0-15	32.45	36.12	31.43	1.30	1.26	47.74	0.24	0.105	0.59	7.33	0.25	32.93	16.34	27.42	177.9
15-30	41.78	24.63	33.59	1.33	0.96	47.27	0.25	0.107	0.51	7.34	0.22	31.18	12.84	25.73	163.3
30-60	27.34	43.12	29.54	1.33	0.95	51.43	0.25	0.131	0.40	7.38	0.2	27.68	10.39	23.20	156.8
60-90	38.5	28.22	33.28	1.35	0.63	53.45	0.25	0.136	0.38	7.45	0.19	24.18	8.81	20.25	155.2
90-120	23.67	48.21	28.12	1.36	0.60	54.03	0.27	0.142	0.34	7.48	0.18	22.43	8.11	18.14	141.7
120-150	29.88	37.46	32.67	1.37	0.56	56.75	0.28	0.145	0.29	7.54	0.16	20.68	7.06	15.61	134.2

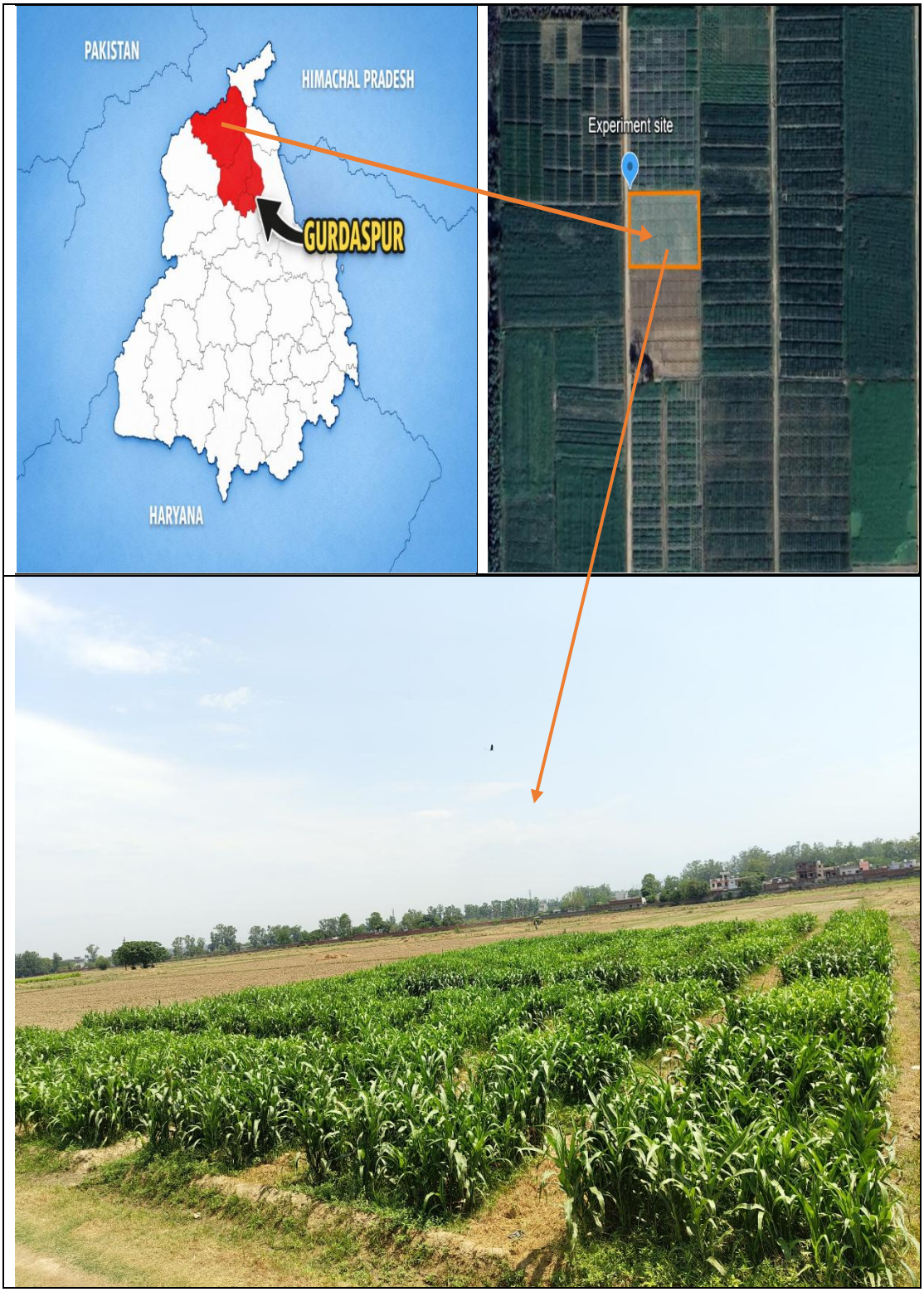


Fig. 1 Experimental site location at RRS Gurdaspur, Punjab, India

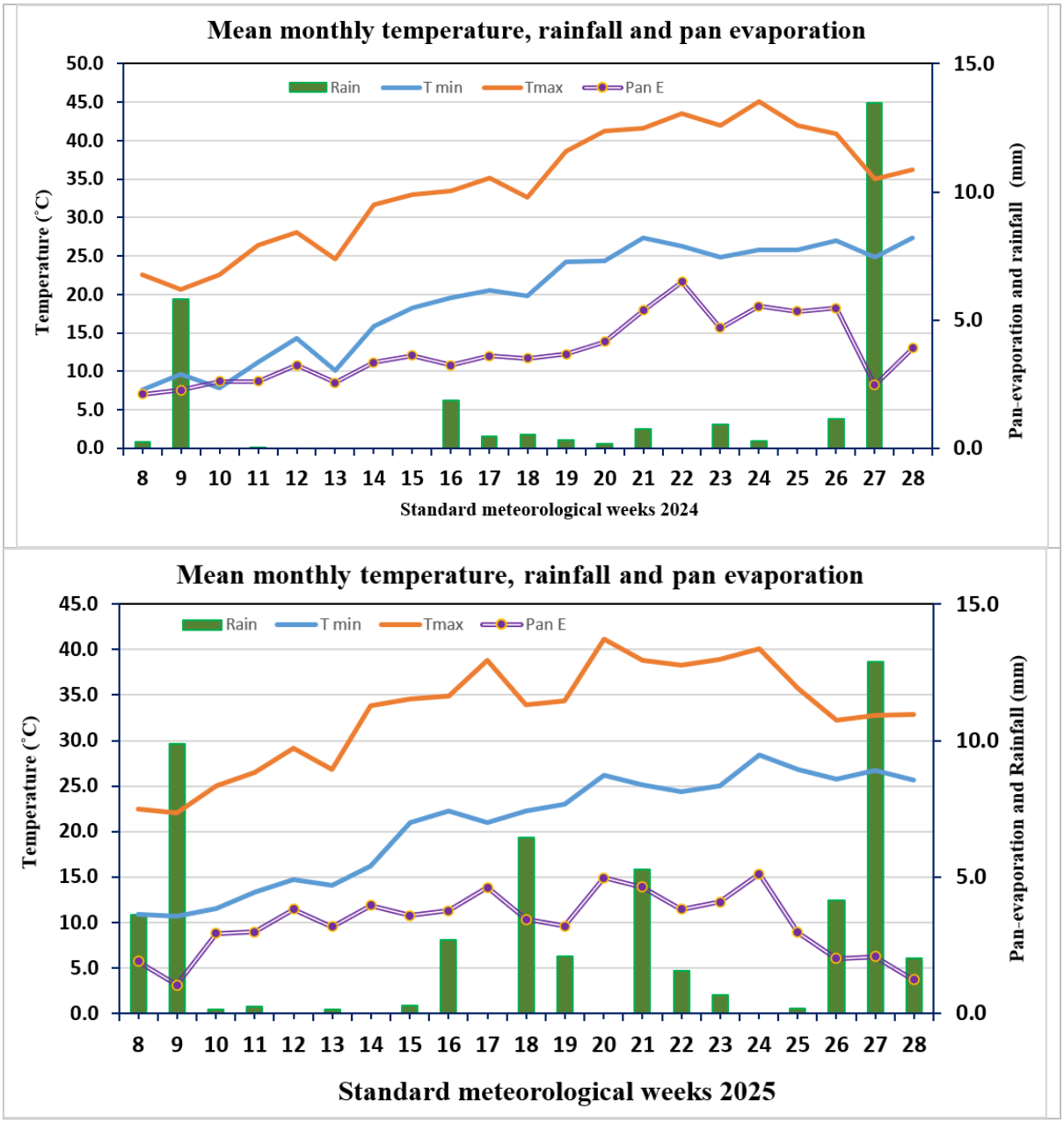


Fig. 2. Standard meteorological weeks showing the Tmax, Tmin, Rainfall and Pan Evaporation during the crop growing season in 2024 (a) and 2025(b) at RRS Gurdaspur.

Experiment details

The experiment was laid out in a blocked split-plot design with 4 irrigation levels (I_1-IW/CPE 1.2, I_2-IW/CPE 1.0, I_3-IW/CPE 0.8, I_4-IW/CPE 0.6) as the main-plot factor and Nitrogen (N_1-75 kg N/ha^{-1}, N_2-100 kg N/ha^{-1}, N_3-125 kg N/ha^{-1}, N_4-150 kg N/ha^{-1}) as a sub-plot factor with three replications. Conventional tillage with a tractor-mounted disk plough was performed to prepare the seedbed. The field was divided into four separate irrigation zones along the length, spaced 1 m apart as a buffer zone. Each irrigation zones were controlled

individually for irrigation applications. There were 48 plots, of which 16 were in each irrigation zone. Each plot was 4 m long and 3 m wide with eight rows spaced 35 cm apart and plant spacing 15 cm. The planting was done on 20th March during both the year 2024 and 2025 using a one-row planter (manual). The pure-live seeding rates used were 12 kg ha^{-1} for sorghum cultivar SPV 1411 (Parbhani Moti) recommended by PDKVV Akola. These cultivars were selected based on their adaptability to sub-humid regions. There were 4 irrigation treatments: (i) I_1– 50 mm, (ii) I_2– 60 mm, (iii) I_3– 75 mm; and (iv) I_4– 100 mm based on pan evaporation. Initially, 60 mm of irrigation (which was applied to all irrigation treatments and later added to their respective total irrigation amount) was aimed to distribute equally for better crop emergence before the start of actual irrigation treatments using the check basin method.

Measurement of soil water content

The volumetric water content (VWC, $m^3\ m^{-3}$) was monitored weekly using a capacitance probe FDR (Frequency Domain Reflectometry) Model: PR2/6 Profile Probe, Delta-T Devices Ltd., UK. Access tubes were manually installed between plant rows in each plot using the manufacturer's augering kit. Measurements were taken at soil depths of 0.1, 0.2, 0.3, 0.4, 0.6, and 1.0 m. The access tubes were installed at 7 DAP in 2024 and 10 DAP in 2025. Soil water depth (mm) at each depth increment was obtained by multiplying VWC by the corresponding depth interval (mm), and the values were summed to determine the total soil water depth (mm) for the 1-m profile (Qi and Helmers, 2010).

Soil Moisture retention

Soil moisture retention characteristics were determined with a pressure plate apparatus at harvesting using applied pressure of 10 kPa to 1500 kPa as described by Gülser et al. (2016).

water holding capacity

The maximum water holding capacity was determined at harvesting by Keen's box as described by Richard (1954).

$$\text{MWHC}\ (\%) = \frac{\text{Wsw} - \text{Wsd} - \text{Wf}}{\text{Wsd} - \text{Wk} - \text{Wg}} \times 100$$

Where, Wsw is the combined weight of the watch glass, Keen's box, filter paper, and saturated soil (g); Wsd is the combined weight of watch glass, Keen's box, filter paper, oven dry soil (g); Wk is the weight of the Keen's box, filter paper (g); Wg is the weight of watch glass in g; Wf is the weight of water absorbed by filter paper (g).

Infiltration rate

Infiltration was measured in-situ by the double-ring infiltrometer method (Reynolds et al. 2008). Water was filled in both the outer and inner rings and the fall of water levels in the inner ring was recorded at different time intervals till the water intake rate became constant.

Saturated hydraulic conductivity

The saturated hydraulic conductivity was determined using the constant head method as described by (Reynolds et al 2008). Undisturbed soil cores (8 cm diameter and 7.5 cm length) were collected from 0 to 7.5 and 7.5–15 cm depths. Samples were saturated in the laboratory. A saturated soil sample along with core was connected with another core and to avoid water leakage, grease was applied in the jointing place on the top of the previous core. A thin layer of water was slowly poured on top of the sample by using siphons connected to a constant head device (Mariotte apparatus). The volume of water that percolates through the sample was measured at definite intervals of time. The hydraulic conductivity was calculated using the following equation:

$$Ks = \left(\frac{Q}{At}\right) \times \{\frac{L}{H + L}\}$$

Where, Ks is saturated hydraulic conductivity (cm h^{-1}), Q is volume of percolate collected (cm^3), L is the length of soil column (cm), A is the cross-sectional area of soil column (cm^2), t is time (h), depth of water above soil (cm).

Crop Growth and green fodder yield

The data for plant parameters, such as plant height, were recorded from the randomly selected five plants from each plot at 30, 60, 90 DAS and at harvesting. The fodder yield at harvesting was recorded from an area of 2 m^2 at maturity and was expressed in t/ha. N uptake (kg ha^{-1}) in fodder was calculated through % N content in fodder multiplied by fodder yield.

Fodder quality attributes

Plant samples collected from each plot at harvest were used for fodder quality analysis. After collection, samples were sun-dried and subsequently oven-dried to a constant weight. The dried material was ground using a Wiley mill and used for laboratory estimations. Crude fiber was determined following the procedure described by A.O.A.C. (2012). Quality attributes, including crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and

in-vitro dry matter digestibility (IVDMD) were determined using Kjeldahl's method (A.O.A.C. 2012), Hogg and Ahlgren (1942), Tilley and Terry (1963), and Dubois et al. (1956), respectively.

Water Balance component and Water productivity

Water Balance components was computed using the water balance equation;

$$\mathrm{ET} = P + I - D \pm \Delta \mathrm{S}$$

(ET_a = Actual evapotranspiration; I = Irrigation water; P = precipitation; D = deep drainage; ΔSW = change in soil water storage between sowing and harvest)

Irrigation water applied to each treatment was measured using a digital flow meter installed at the tube-well outlet and verified at the plot level. Irrigation depth was calculated by dividing the measured discharge volume by the corresponding plot area. A uniform irrigation depth of 6.5 cm was applied during each irrigation level across all treatments. The fixed irrigation depth was maintained to ensure that treatment effects could be attributed specifically to differences in irrigation scheduling, soil moisture thresholds rather than variations in the quantity of water applied per irrigation event. This standardized approach enabled consistent comparison of soil moisture dynamics, water balance components and crop response across treatments under spring sorghum conditions.

Soil moisture storage (mm) in 0-100 cm profile (0-10, 10-20, 20-30, 30-40, 40-60 and 60-100 cm soil depths) was determined before and after each irrigation and after rainfall in crop duration. Soil moisture was measured using Frequency Domain Reflectrometery (FDR) PR2/6 probe (Delta-T Devices Ltd.), which was inserted into access tubes (1 m length) fitted into respective treatments. FDR measures the permittivity (ε) of soil by generating an electromagnetic signal into the soil which provided the respective digital output in % (v/v) and mV (milliVolts) on HH2 meter. The sensor rings were spaced at gap of 10 cm (0-10, 10-20, 20-30 and 30-40 cm), 20 cm (40-60 cm) and 40 cm (60-100 cm) to measure moisture at specific depths. The access tubes were installed unto a depth of 1 m using angering equipment (stabilization plate, auger and an insertion rod).

Runoff losses were assumed to be negligible due to the levelled experimental plots, controlled irrigation application. Deep drainage was considered to be zero if soil profile moisture storage remained less than field capacity and when soil moisture storage exceeded the field capacity storage after irrigation or rainfall, then deep drainage was calculated as difference between the

field capacity storage and soil moisture storage plus irrigation/rainfall. Field capacity of each soil layer was determined using the pressure plate apparatus method (Ogata G and Richard L A 1957).

Plant water-yield relationships are primarily assessed using key indicators such as irrigation and precipitation, which together represent the total water input available for crop production. The irrigation water productivity (Iwp) shows the yield values obtained per unit of water applied to the plant, and the total water productivity (Twp) shows the yield values obtained against the seasonal plant water applied through irrigation and precipitation. These values were calculated from the equations determined by Howell et al. (1990).

$$Iwp = \frac{Fodder\ Yield}{Irrigation}$$

$$Twp = \frac{Fodde\ Yield}{Irrigation + Rain}$$

Statistical analysis

All the collected data were analysed in R version 3.5.1 using Agricolae package version 1.2-8 (de Mendiburu, 2017). The effects of irrigation, nitrogen, and their interaction were analysed using analysis of variance with two error terms: Biomass, quality of fodder and water productivity (WP) were analysed independently for each observation. However, soil Volumatic water content was analysed as a repeated measure considering the DAP as a factor. The mean separation test was done with the least significant difference at 5% significance level. Graphs were prepared using OriginPro software.

Results

Soil Volumetric Water Content

Volumetric soil water content (VWC) for the 1 m soil profile depth among the irrigation treatments and nitrogen is presented in Fig. 3

The initial VWC measured at 15 DAP in both year were not significantly different down to 0.4 m soil profile depth; in all 3 treatments (I_1, I_2, I_3) a significant decrease in VWC value was observed at each depth increment down to 1 m soil profile depth with progressing growing season in all irrigation treatments; however, the decr ease in VWC value was significant only in I_4 treatments with progressing growing season in both years (Fig. 3). These results suggest that the water depletion with depths increase with decrease the numbers of irrigation application. In both years, when comparing the first observation with the last observation, soil water depletion was greater at each depth down to 1 m in I_4 treatment compared to I_2 and I_3;

and this water depletion was the lowest in the I_1 treatment. This suggested that the total soil water depletion amount along the 1 m soil profile decreased with increasing irrigation water supply.

A significant decrease in VWC value was observed among nitrogen plots at each depth down to 1 m with progressing growing season in both years (Fig. 3). N_1 in less volumetric water content observed compared to N_2, N_3 and N_4 because These findings indicate that higher nitrogen availability enhanced sorghum root development, promoting deeper and more vigorous root proliferation and increasing soil water extraction from the profile. Because sorghum exhibits strong root expansion when nitrogen is not limiting, improved nitrogen supply likely accelerated root growth, increased leaf area, and elevated transpiration demand, collectively contributing to greater soil water depletion at deeper soil layers. In contrast, the lowest seasonal reduction in VWC under the N_1 treatment suggests that limited nitrogen availability restricted root biomass formation and suppressed canopy development, thereby reducing plant-driven soil moisture uptake. Overall, VWC declined with depth and time in all treatments, but the depletion magnitude followed the order $N_4 > N_3 > N_2 > N_1$, demonstrating a positive association between nitrogen supply, root expansion, and soil water depletion.

Soil Moisture retention

Soil moisture retention at different suction values in treatment combinations of different irrigation regimes and nitrogen levels after sorghum harvest in 0-15 and 15-30 cm soil layer are defected in figures 4.7 and 4.8. among different treatment effect on soil water retention at different suction was non-significant observed. Field capacity (FC) was not significantly influenced by different irrigation regimes and nitrogen levels (Table 2). Among irrigation regimes, the highest FC (0.248 $m^3\ m^{-3}$) was recorded under I_1 (IW/CPE 1.2), while the lowest value (0.240 $m^3\ m^{-3}$) was observed under I_4 (IW/CPE 0.6). Similarly, among nitrogen levels, FC ranged from 0.231 to 0.252 $m^3\ m^{-3}$, with the maximum value under N_4 (150 kg N ha^{-1}) and the minimum under N_1 (75 kg N ha^{-1}). However, the effects of irrigation regimes, nitrogen levels and their interaction (I × N) on FC were found to be non-significant.

Permanent wilting point (PWP) was also non-significantly affected by irrigation regimes and nitrogen levels (Table 4.2). The highest PWP (0.107 $m^3\ m^{-3}$) was recorded under I_2 (IW/CPE 1.0), whereas the lowest value (0.103 $m^3\ m^{-3}$) was observed under I_3 (IW/CPE 0.8). Among nitrogen levels, PWP varied from 0.097 to 0.111 $m^3\ m^{-3}$, with the highest value under N_4 (150 kg N ha^{-1}) and the lowest under N_1 (75 kg N ha^{-1}). Nevertheless, irrigation regimes, nitrogen levels and their interaction (I × N) did not exert any significant effect on PWP.

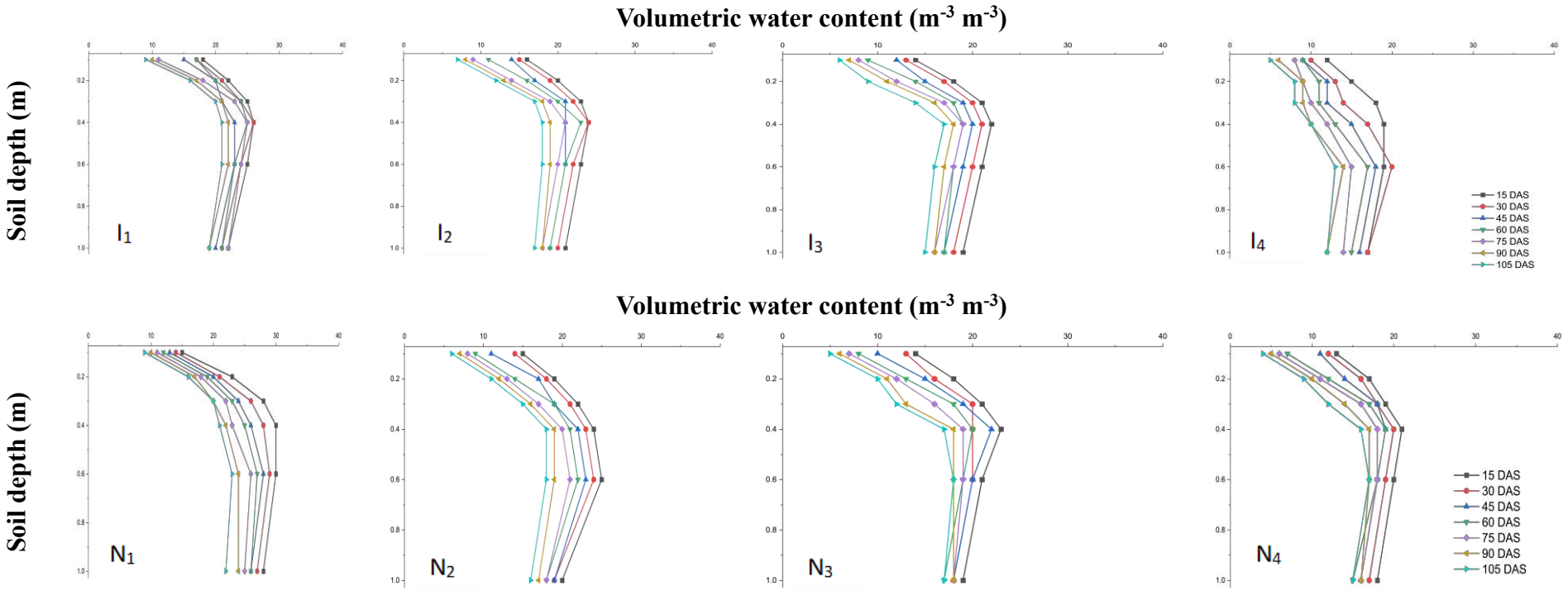
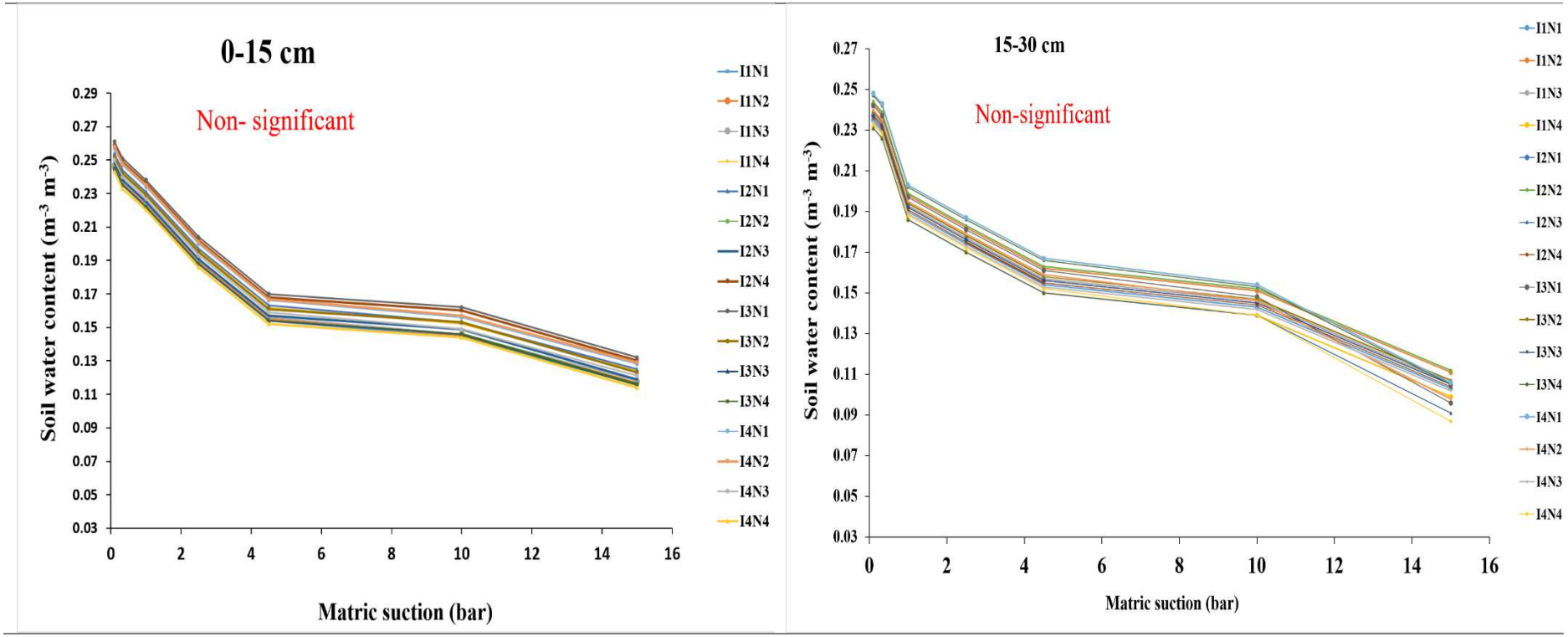


Fig. 3 Soil moisture dynamics under different irrigation and N management along the soil profile at different days after sowing (DAS) pooled data of 2 years of spring sorghum



Figures 4 Soil moisture retention (m^{-3} m^{-3}) after two seasons of spring sorghum as influenced by irrigation regimes and nitrogen (15-30 cm)

Saturated hydraulic conductivity (cm h^{-1})

The data presented in Table 4.2 revealed that soil hydraulic conductivity (SHC) at both 0–7.5 cm and 7.5–15 cm depths were not significantly influenced by irrigation regimes, whereas nitrogen levels exerted a significant effect. At 0–7.5 cm depth, SHC ranged from 0.921 to 0.951 cm h^{-1} under irrigation regimes and from 0.906 to 0.961 cm h^{-1} under nitrogen levels. Similarly, at 7.5–15 cm depth, SHC varied from 0.919 to 0.949 cm h^{-1} among irrigation regimes and from 0.903 to 0.959 cm h^{-1} among nitrogen levels. The highest SHC values at both depths were recorded under N_4 (150 kg N ha^{-1}), whereas the lowest values were observed under N_1 (75 kg N ha^{-1}). Furthermore, the interaction effect of irrigation regimes and nitrogen levels (I × N) was also found to be non-significant at both soil depths.

Water holding capacity (WHC%)

The data presented in Table 2 revealed that water holding capacity (WHC) was not significantly influenced by different irrigation regimes, whereas nitrogen levels exerted a significant effect. Among irrigation regimes, WHC ranged from 48.51 to 49.91%, with the highest value (49.91%) recorded under I_1 and the lowest value (48.51%) under I_4. Among nitrogen levels, WHC varied from 47.72 to 50.68%. The maximum WHC (50.68%) was recorded under N_4, which was significantly higher than N_1 and statistically at par with N_2 (49.12%) and N_3 (49.39%). The minimum value was observed under N_1. However, the interaction effect of irrigation regimes and nitrogen levels (I × N) on WHC was found to be non-significant.

Infiltration rate

The infiltration rate was not significantly influenced by different irrigation regimes and nitrogen (Fig. 5). The infiltration rate was recorded at 1, 3, 5, 10, 15, 30, 60, 120, 180 and 240 minutes time intervals. The infiltration rate (cm min^{-1}) was highest at the initial stage of observation and gradually decreased with the advancement of time and soil depth. After one hour, the infiltration rate was observed to be approximately 1.7 cm h^{-1} on average. Thereafter, the infiltration rate attained a nearly constant rate after three hours, indicating the stabilization of water movement in the soil profile.

The cumulative infiltration rate is deficit in figure 5. the cumulative infiltration rate was non-significant with treatment combination effect, while the rate was increase with time highest cumulative infiltration rate was recorded at 240 minutes.

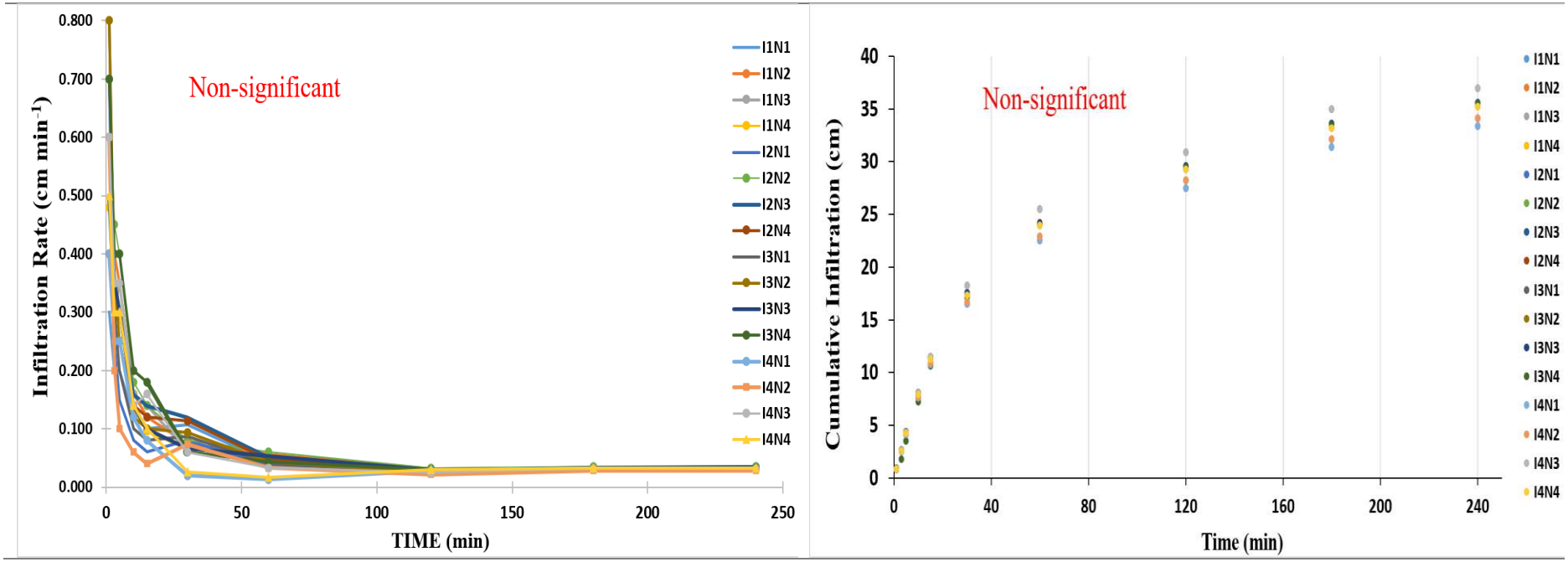


Fig 5 Infiltration and Cumulative infiltration rate (cm min^{-1}) after two seasons of spring sorghum as influenced by irrigation regimes and nitrogen

Table 2 Effect of irrigation regimes and nitrogen levels on soil water retention characteristics and soil hydraulic conductivity in spring sorghum (Pooled two year.)

Treatments		FC (m^{-3} m^{-3})	PWP (m^{-3} m^{-3})	WHC (%)	(SHC 0-7.5 cm)	SHC (7.5-14 cm h^{-1})
Irrigation regimes						
I_1 -IW/CPE 1.2		0.248	0.106	49.91	0.951	0.949
I_2 -IW/CPE 1.0		0.245	0.107	49.21	0.945	0.938
I_3 -IW/CPE 0.8		0.242	0.103	49.30	0.936	0.927
I_4 -IW/CPE 0.6		0.240	0.104	48.51	0.921	0.919
LSD (0.05)		NS	NS	NS	NS	NS
Nitrogen						
N_1 75 kg N/ha^{-1}		0.231	0.097	47.72	0.906	0.903
N_2 100 kg N/ha^{-1}		0.243	0.103	49.12	0.929	0.924
N_3 125 kg N/ha^{-1}		0.250	0.109	49.39	0.947	0.946
N_4 150 kg N/ha^{-1}		0.252	0.111	50.68	0.961	0.959
LSD (0.05)		NS	NS	0.87	0.016	0.015
LSD (0.05) I×N		NS	NS	NS	NS	NS

Growth, yield and water productivity

Irrigation and nitrogen exerted significant and interactive effects on sorghum growth, productivity and water use indices, with clear physiological and agronomic implications (Table 3). Across both seasons, improvement in plant height and biomass production with increased irrigation frequency reflected better canopy establishment and soil moisture-driven physiological activity, whereby I_1 (IW/CPE 1.2) consistently produced the tallest plants (227.79 and 227.20 cm) and the highest fodder yield (6.90 and 6.93 t ha^{-1}) during 2024 and 2025, respectively. Plant height increased rapidly from sowing to 90 DAS and then continued to rise at a slower rate until harvest. In contrast, I_4 (IW/CPE 0.6) exhibited growth suppression due to moisture limitation, resulting in the lowest plant height (209.57-210.91 cm) and fodder yield (5.64-5.65 t ha^{-1}). Increasing nitrogen application improved structural and metabolic functions and thus enhanced above-ground biomass, with N_4 (150 kg N ha^{-1}) consistently achieving the maximum plant height (231.07-230.73 cm), fodder yield (7.00-6.98 t ha^{-1}), and Nitrogen uptake, which indicates how much nitrogen the crop absorbed and stored in its biomass. In this study, nitrogen increased with higher N levels and adequate irrigation, ranging from 24.11-35.41 kg ha^{-1}. Lower uptake under N_1 and I_4 reflects reduced growth and nutrient acquisition. Notably, a further increase to N_4 (150 kg N ha^{-1}) failed to produce significant yield gains as compare to N_3 (125 kg N ha^{-1}), suggesting physiological saturation and diminishing marginal returns typical of luxury N consumption. In contrast to fodder yield trends, irrigation water productivity (I_{WP}) and total water productivity (T_{WP}) responded inversely to irrigation amount, with I_4 producing the highest I_{WP} (31.32-47.12 kg ha^{-1} mm^{-1}) and T_{WP} (12.99-23.49 kg ha^{-1} mm^{-1}) due to reduced irrigation input, demonstrating that water productivity metrics are driven by output-to-input ratios rather than absolute biomass. Similarly, higher N input improved I_{WP} and T_{WP} up to N_4, consistent with enhanced biomass formation per unit water consumed, further highlighting the role of nitrogen in improving intrinsic water-use efficiency through stimulation of leaf photosynthetic capacity, particularly under sub-optimal soil moisture.

Table 3 Effect of irrigation (I) and nitrogen (N) on plant height (cm), fodder yield, nitrogen uptake and water productivity

Experiment (2024)								
	Plant height				Fodder yield (t ha^{-1})	N uptake (kg ha^{-1}) in fodder	I_{WP} (Kg ha^{-1} mm^{-1})	T_{WP} (Kg ha^{-1} mm^{-1})
Irrigation regimes	**30 DAS**	**60 DAS**	**90 DAS**	**At harvesting**				
I_1 -IW/CPE 1.2	88.24	166.42	225.24	227.79	6.90	34.37	15.24	13.33
I_2 -IW/CPE 1.0	86.49	164.37	223.29	224.84	6.40	31.61	23.01	19.17
I_3 -IW/CPE 0.8	85.22	162.68	219.09	219.61	6.25	29.01	26.04	20.84
I_4 -IW/CPE 0.6	81.95	156.14	207.95	209.57	5.64	24.74	31.32	23.49
LSD (0.05)	2.01	4.75	4.51	7.91	0.62	3.41	2.50	2.01
Nitrogen								
N_1 75 kg N/ha^{-1}	81.76	154.54	205.65	206.82	5.50	24.11	21.02	16.87
N_2 100 kg N/ha^{-1}	84.25	161.12	215.79	217.86	6.08	27.23	22.99	18.49
N_3 125 kg N/ha^{-1}	87.42	165.97	225.36	227.06	6.61	32.98	25.09	20.16
N_4 150 kg N/ha^{-1}	88.48	167.99	228.77	231.07	7.00	35.41	26.51	21.31
LSD (0.05)	1.84	4.13	5.38	6.07	0.45	3.09	1.89	1.51
Experiment (2025)								
I_1 -IW/CPE 1.2	88.82	167.20	226.63	227.20	6.93	34.77	17.86	12.99
I_2 -IW/CPE 1.0	86.99	164.77	223.68	225.25	6.43	31.85	28.88	18.48
I_3 -IW/CPE 0.8	85.05	162.33	219.45	220.05	6.27	29.29	34.85	19.91
I_4 -IW/CPE 0.6	82.52	156.25	208.41	210.91	5.65	25.08	47.12	22.18
LSD (0.05)	1.72	2.60	3.98	6.78	0.17	3.77	0.70	0.45
Nitrogen								
N_1 75 kg N/ha^{-1}	82.08	155.04	205.66	207.61	5.56	24.37	28.59	16.27
N_2 100 kg N/ha^{-1}	83.96	161.71	216.70	217.75	6.11	27.57	30.90	17.70
N_3 125 kg N/ha^{-1}	88.17	166.02	225.90	227.32	6.64	33.23	33.78	19.31
N_4 150 kg N/ha^{-1}	89.18	167.77	229.91	230.73	6.98	35.82	35.45	20.28
LSD (0.05)	1.91	3.07	4.91	3.84	0.25	3.09	1.11	0.68
LSD (0.05) I×N	NA	NA	NA	NA	NA	NA	NA	NA

Quality parameters

The fodder quality of spring sorghum was significantly influenced by irrigation regimes and nitrogen application across both years, with notable variation in crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), crude fibre (CF) and in-vitro dry matter digestibility (IVDMD). Higher irrigation supplies improved protein accumulation while reducing fibre fractions. For instance, in 2024 and 2025, respectively, the IW/CPE 1.2 irrigation regime (I_1) recorded the highest CP values of 14.90% and 14.98%, closely followed by I_2, whereas the most restricted irrigation (I_4: IW/CPE 0.6) resulted in the lowest CP (13.35% and 13.48%, respectively). A parallel response was observed with nitrogen, where CP increased progressively up to N4 (150 kg N ha^{-1}), which recorded the maximum CP values of 15.00% in 2024 and 15.20% in 2025, indicating enhanced nitrogen assimilation and protein biosynthesis at moderate-to-high nitrogen supply. Proteins are nutritionally vital because they supply animals with the amino acids required for synthesising body proteins. Since milk contains approximately 3.5% protein, lactating animals require feed with adequate protein levels to sustain production. In the present study, crude protein (CP) content increased with higher irrigation frequency up to an optimum level (Table 4).

For instance, NDF increased under I_4 (51.11% and 51.02% in 2024 and 2025, respectively) and was lowest under I_1, while nitrogen application significantly reduced NDF up to N_4 (48.73% and 48.55% in 2024 and 2025, respectively). ADF followed a similar trend, with maximum values recorded in I_4 (27.43% and 27.25% in 2024 and 2025, respectively) and minimum values under higher nitrogen supply (N_4: 25.60% and 25.30% in 2024 and 2025, respectively). Crude fibre (CF) also declined with increased nitrogen, from 24.60% and 24.48% under N_1 to 22.50% and 22.30% under N_3 in 2024 and 2025, respectively, reflecting enhanced palatability under optimal nutrient status. Correspondingly, digestibility improved under favourable irrigation and nitrogen levels, with IVDMD reaching 56.50% and 56.60% under I_1, and 56.78% and 56.93% under N_4 in 2024 and 2025, respectively, as reduced fibre fractions enhanced enzymatic degradability. Fiber concentration in forage is regulated by several interacting factors such as leaf-to-stem ratio, growth stage, environmental conditions (light availability, temperature and water), and nutrient status (Table 4).

Table 4 Effect of Nitrogen (N) on fodder quality parameters of Spring sorghum under different irrigation regimes (I)

Treatments	Crude protein (%)		NDF (%)		ADF (%)		Crude Fibre (%)		In Vitro Dry Matter Digestibility (%)	
Irrigation regimes	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**	**2024**	**2025**
I_1 -IW/CPE 1.2	14.90	14.98	49.23	49.08	25.98	25.68	22.53	22.35	56.50	56.60
I_2 -IW/CPE 1.0	14.60	14.75	49.68	49.53	26.38	26.18	23.25	23.05	56.05	56.23
I_3 -IW/CPE 0.8	14.30	14.48	50.00	49.88	26.83	26.65	23.75	23.60	55.60	55.70
I_4 -IW/CPE 0.6	13.35	13.48	51.11	51.02	27.43	27.25	24.15	24.00	54.28	54.40
LSD (0.05)	0.52	0.45	0.77	0.59	0.46	0.71	0.67	0.44	1.17	0.99
Nitrogen										
N_1 75 kg N/ha^{-1}	13.28	13.30	51.54	51.49	27.63	27.50	24.60	24.48	54.10	54.28
N_2 100 kg N/ha^{-1}	14.00	14.18	50.73	50.55	27.45	27.30	24.43	24.25	55.10	55.15
N_3 125 kg N/ha^{-1}	14.88	15.00	49.03	48.90	25.93	25.65	22.50	22.30	56.45	56.58
N_4 150 kg N/ha^{-1}	15.00	15.20	48.73	48.55	25.60	25.30	22.15	21.98	56.78	56.93
LSD (0.05)	0.34	0.32	1.04	1.16	0.54	0.49	0.41	0.44	1.15	1.23
LSD (0.05) I×N	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Water balance

The irrigation water applied during the crop season varied according to irrigation levels and ranged from 120 to 360 mm. The highest irrigation (360 mm) was recorded under the treatments I_1N_1, I_1N_2, I_1N_3 and I_1N_4, whereas the lowest irrigation (120 mm) was observed under I_4N_1, I_4N_2, I_4N_3 and I_4N_4. Intermediate irrigation levels of 240 mm and 180 mm were recorded under I_2 and I_3 irrigation levels, respectively. This indicates that irrigation supply increased progressively from I_4 to I_1 irrigation levels. The precipitation received during the cropping season remained uniform across all treatments and was 134 mm. This rainfall contributed significantly to the total water availability for crop growth during the season. Evapotranspiration varied across treatments and ranged from 264 to 381 mm. The maximum ET (381 mm) was recorded under I_1N_3, followed by 373 mm under I_1N_4 and 358 mm under I_1N_2, indicating higher crop water use under higher irrigation supply combined with increased nitrogen application. The minimum ET (264 mm) was observed under I_4N_4, followed by 274 mm under I_4N_1 and I_4N_2, indicating reduced crop water consumption under the lowest irrigation level. In general, evapotranspiration tended to increase with higher irrigation and nitrogen levels. Drainage values varied among treatments and ranged from 29 to 119 mm. The highest drainage (119 mm) was observed under I_1N_1, followed by 116 mm under I_1N_2 and 114 mm under I_1N_4, indicating greater water losses through deep percolation under higher irrigation levels. The lowest drainage (29 mm) was recorded under I_4N_1 and I_4N_2, while slightly higher values (31–34 mm) were observed under other I_4 treatments, suggesting reduced deep percolation losses under limited irrigation. Runoff (R) was absent as sufficient dikes were maintained. The change in soil water storage ranged from −64 to +21 mm. Positive soil moisture storage was recorded under I_1N_1 (21 mm) and I_1N_2 (20 mm), indicating accumulation of soil moisture due to higher irrigation supply. In contrast, negative values were observed under most other treatments, indicating soil moisture depletion during the crop growing period. The highest soil moisture depletion (−64 mm) was recorded under I_4N_3, followed by −49 mm under I_4N_1 and I_4N_2, suggesting greater dependence of the crop on stored soil moisture under lower irrigation levels (Figure 6). Overall, the results indicate that higher irrigation levels increased evapotranspiration and drainage, whereas lower irrigation levels resulted in greater depletion of soil moisture storage.

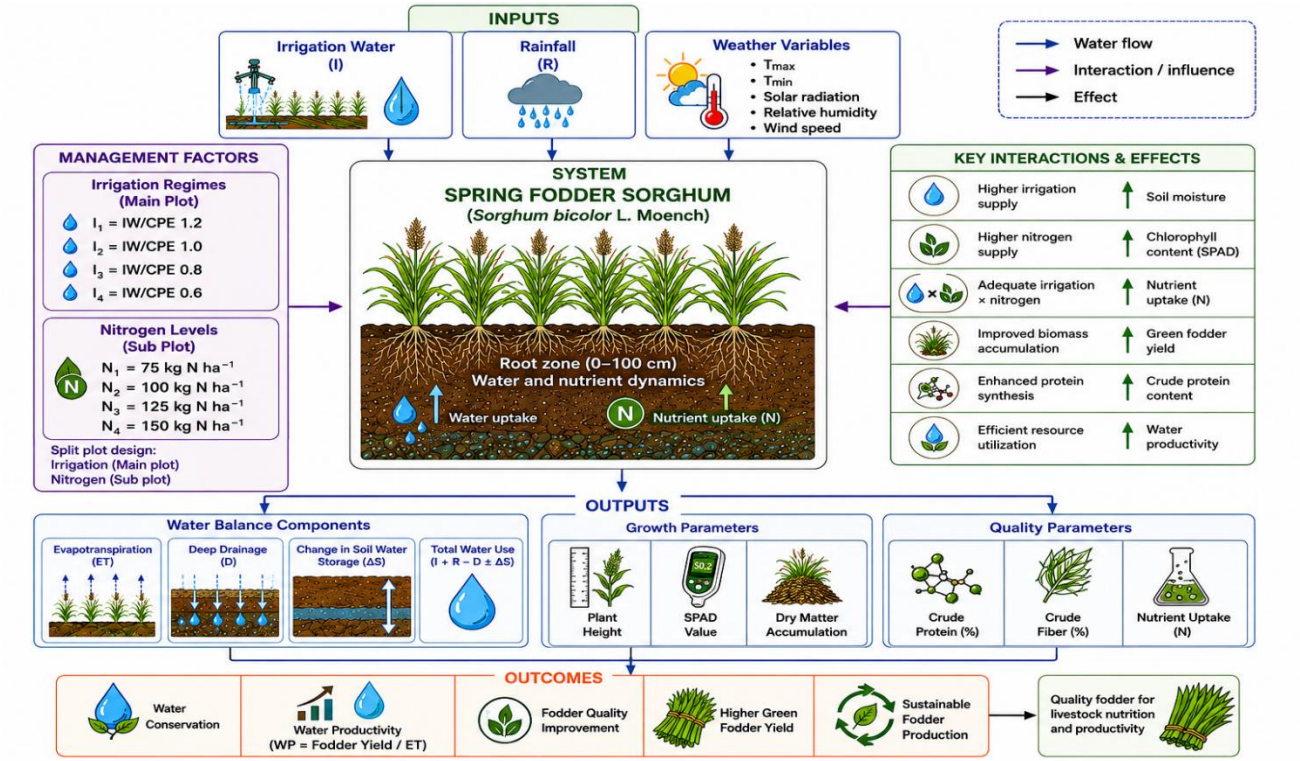


Fig.6 Conceptual model of water and nutrient dynamics governing fodder productivity and quality of spring sorghum under varying irrigation and nitrogen management.

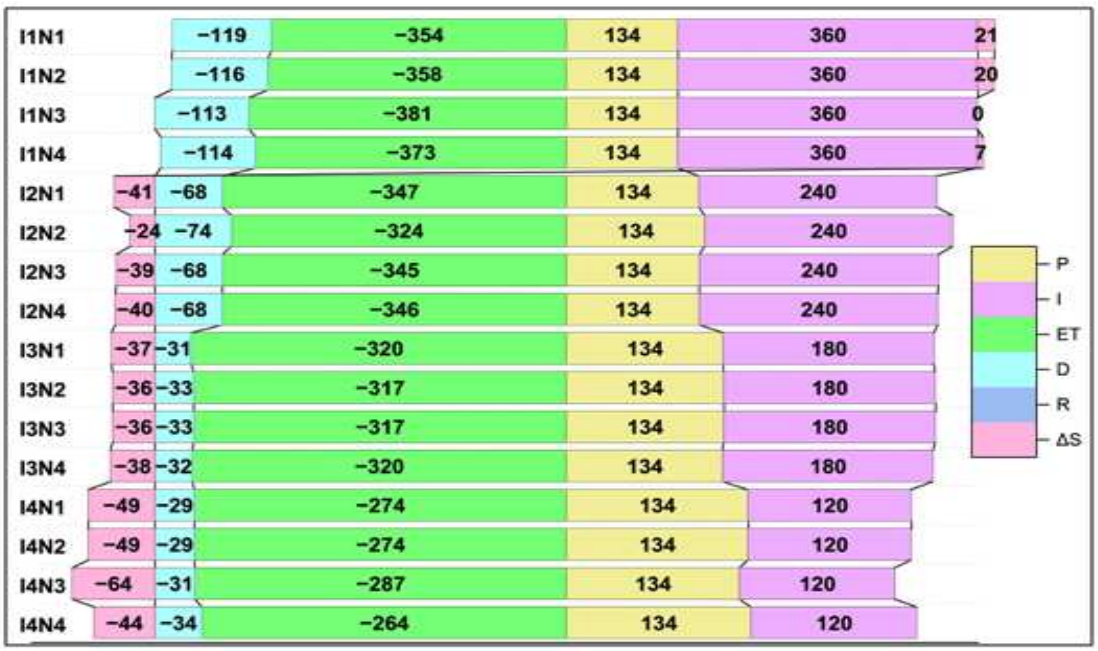


Fig 7 Water balance components of spring sorghum influenced by irrigation regimes and Nitrogen

Discussion

The effects of irrigation regimes and nitrogen management on soil moisture constants, including field capacity (FC), permanent wilting point (PWP), available water capacity (AWC), and maximum water-holding capacity (MWHC), are presented in Table 2. The results indicated that neither irrigation nor nitrogen application exerted a significant influence on FC and PWP across the studied soil depths. Similarly, variations in irrigation and nitrogen levels did not significantly affect AWC and MWHC, irrespective of soil depth. The relative stability of these moisture constants suggests that short-term changes in irrigation scheduling and nitrogen fertilization were insufficient to alter the inherent water-retention characteristics of the soil. These findings are consistent with those reported by Chatterjee et al. (2016), who observed non-significant effects of irrigation, crop residue mulch, and nitrogen management practices on soil moisture-related physical properties.

In contrast, saturated hydraulic conductivity (SHC) was significantly influenced by nitrogen application. The highest SHC values were recorded under the application of 150 kg N ha^{-1}, reaching 0.961 and 0.959 cm h^{-1} at the 0–7.5 cm and 7.5–15 cm soil depths, respectively. The improvement in SHC under higher nitrogen levels may be attributed to enhanced root proliferation, greater root biomass production, and increased organic carbon inputs, which contribute to improved soil aggregation and pore continuity. Additionally, the reduction in soil bulk density observed under higher nitrogen application may have facilitated greater water transmission through the soil profile.

The present findings corroborate the results of Chatterjee et al. (2016), who reported significant increases in saturated hydraulic conductivity with nitrogen application rates of 75 and 150 kg ha^{-1} compared with the control treatment across different soil depths. The enhancement in SHC was primarily associated with improved soil structural properties resulting from increased root growth, higher soil organic carbon content, and lower bulk density. Similar observations were also reported by Lal (1987) and Bandyopadhyay et al. (2010), who highlighted the positive role of organic matter accumulation and root activity in improving soil pore characteristics and hydraulic conductivity. Therefore, the observed increase in SHC under higher nitrogen application indicates the beneficial effect of nitrogen fertilization on soil physical quality and water transmission characteristics.

Crop productivity is strongly influenced by the interaction among soil moisture availability, nutrient supply, and prevailing weather conditions. The higher fodder yield recorded during the second experimental year may be attributed to the relatively warmer temperatures experienced in 2025. As sorghum is a C_4 species with high photosynthetic

efficiency under warm conditions, elevated temperatures likely enhanced biomass accumulation and forage production. The favorable thermal environment may have promoted greater radiation-use efficiency and carbon assimilation, resulting in improved vegetative growth and yield.

The present study demonstrated that restricted irrigation significantly reduced fodder yield and quality parameters. These findings are in agreement with those of Islam et al. (2012), who reported substantial reductions in forage maize yield under drought stress conditions. Likewise, Nematpour et al. (2020) observed a decline in millet forage yield with decreasing irrigation levels. Water deficit adversely affects plant growth by limiting nutrient uptake, reducing stomatal conductance, and suppressing photosynthetic activity, thereby restricting assimilate production and biomass accumulation (Baghdadi et al. 2021; Nematpour et al. 2020). The results further indicated that moderate irrigation (I_2) combined with 125 kg N ha^{-1} (N_3) provided the most favorable conditions for maximizing fodder yield and nitrogen utilization efficiency. In contrast, the lowest irrigation level (I_4) achieved higher water productivity, highlighting the trade-off between biomass production and efficient water use under conditions of water scarcity (Afzal et al. 2012).

Forage quality characteristics were also influenced by irrigation regimes. Lower fiber concentrations are generally preferred because they improve forage intake and digestibility. In the present investigation, crude fiber content increased under water-deficit conditions (IW/CPE 0.6), corroborating the observations of Liu et al. (2011). Under drought stress, plants undergo structural modifications in cell wall composition to maintain tissue integrity under reduced water potential. Increased cross-linking among hemicellulose, lignin, and cellulose components enhances cell wall rigidity and mechanical strength (Ghobadi et al. 2015). Such adaptive responses enable plants to withstand moisture stress but simultaneously increase fiber accumulation and reduce forage quality (Khelil et al. 2013). Consequently, the decline in in vitro dry matter digestibility (IVDMD) observed under limited irrigation may be attributed to its inverse relationship with crude fiber concentration, as previously reported by Yosef et al. (2009).

The observed increase in acid detergent fiber (ADF) and neutral detergent fiber (NDF) under moisture stress is consistent with the findings of Jahanzad et al. (2013), who reported elevated fiber fractions and reduced digestibility in forage sorghum subjected to drought conditions. Variations in forage quality under different irrigation regimes have also been linked to changes in biomass partitioning among leaves, stems, and roots, which directly

influence cell wall composition and digestibility characteristics (Bhattarai et al. 2020; Kaplan et al. 2019; Nematpour et al. 2020).

Nitrogen fertilization played a critical role in enhancing forage productivity and quality. Nitrogen is a key component of chlorophyll, amino acids, and photosynthetic enzymes, making it indispensable for forage crop production (Szulc et al. 2013). In the present study, increasing nitrogen application improved green fodder yield, water-use efficiency, crude protein content, and overall forage quality. However, the beneficial effects of nitrogen were less pronounced under severe moisture stress, indicating that water availability governs the efficiency of nitrogen utilization. Similar observations were reported by Zhao et al. (2005), who found that nitrogen deficiency significantly restricted plant growth, forage yield, and leaf-to-stem ratio. Reduced nitrogen availability limits the activity of essential photosynthetic enzymes such as phosphoenolpyruvate carboxylase (PEPC) and Rubisco, thereby reducing photosynthetic rates and biomass production (Baghdadi et al. 2017; Maranville and Madhavan, 2002; Zhao et al. 2005).

Dry matter digestibility (DMD) decreased under limited irrigation but improved at lower nitrogen levels, which is in agreement with the findings of Kaplan et al. (2019) and Yosef et al. (2009). Adequate water and nitrogen supply enhance photosynthetic efficiency, resulting in greater biomass production and improved forage quality (Baghdadi et al. 2017; Golzardi and Baghdadi, 2017). Increased nitrogen uptake by roots elevates leaf nitrogen concentration, promotes protein synthesis, and contributes to enhanced silage yield and nutritive value (Yan et al. 2011). Furthermore, higher nitrogen application reduced ADF and NDF concentrations while increasing crude protein content, metabolizable energy, digestible organic matter, and gas production, thereby improving overall forage quality (Kaplan et al. 2014). Conversely, nitrogen deficiency reduced crop growth rate, leaf area index, and leaf-to-stem ratio, leading to lower forage yield and nutritional quality (Zhao et al. 2005).

Study limitations and future implications

Although the present study provides detailed field-based insights into the interaction between irrigation scheduling and nitrogen under sorghum crop, the findings are presently limited to two year study and site-specific agroclimatic conditions. Therefore, broader extrapolation of the observed responses requires further validation across diverse environments and multi-location field conditions.

Effect of irrigation or nitrogen on most of the soil properties was found non-significant, This indicates that short-term variations in irrigation scheduling and nitrogen application may

not be sufficient to bring measurable changes in the soil's water-retention and physical behaviour, particularly in clay loam soils.

Conclusion

Irrigation regime and nitrogen application strongly influenced sorghum fodder productivity and quality. The interaction between these factors significantly affected aboveground biomass and crop N uptake. Plant height also showed a strong positive association with fodder yield. The combination of IW/CPE-1.0 and 125 kg N ha^{-1} produced the highest fodder yield. In contrast, excessive moisture (IW/CPE -1.2) and higher N rates (150 kg ha^{-1}) failed to enhance yields, likely due to imbalances in nutrient assimilation, translocation, and storage within the plants. Overall, a balanced irrigation regime with moderate nitrogen input emerged as the most effective approach for achieving high productivity and environmentally sustainable sorghum cultivation over the two-year study. Higher irrigation regimes (I_1 and I_2) resulted in greater evapotranspiration and positive soil water storage (ΔS), reflecting improved soil moisture availability and crop water use compared to deficit irrigation treatments. These findings contribute theoretical support for advancing sustainable agriculture and improving sorghum cultivation practices in regions with comparable soil and climatic conditions.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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