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Response of Sorghum × Sudangrass to Deficit Irrigation and Nitrogen Doses: Implications for Sustainable Forage Production

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ABSTRACT

Sorghum × sudangrass is an important forage crop in semi-arid regions due to its high biomass potential and efficient water use. Improving irrigation and nitrogen management is essential to sustain productivity under increasing water limitations. This study evaluated the effects of different irrigation levels and nitrogen doses on the growth, physiological responses, and forage traits of sorghum × sudangrass. Four irrigation levels (25, 50, 75, and 100% of full irrigation) and three nitrogen doses (50, 100, and 150 kg ha^{-1}) were tested with three replications. Irrigation, nitrogen, and their interaction significantly affected plant performance. Plant height ranged from 227.3 cm under 25% irrigation with 50 kg N ha^{-1} to 313.6 cm under 75% irrigation with 100 kg N ha^{-1}. Fresh forage yield varied between 23.5 and 66.7 t ha^{-1}, while dry biomass ranged from 5.01 to 16.77 t ha^{-1}. Physiological parameters responded positively to increasing inputs; the highest SPAD value (45.36) occurred at 75% irrigation with 100 kg N ha^{-1}. LAI and NDVI reached their maximum under full irrigation with 100–150 kg N ha^{-1}. Forage quality traits also responded to the treatments. ADF and NDF increased slightly with higher inputs, while crude protein yield ranged from 296 to 1191 kg ha^{-1}. Overall, 75% irrigation combined with 100 kg N ha^{-1} produced yields and protein levels comparable to full irrigation with 150 kg N ha^{-1}, indicating a more resource-efficient and sustainable management strategy. Incorporating drought-tolerant and resource-efficient forage species may further improve system resilience under Mediterranean water-limited conditions.

1. INTRODUCTION

Sorghum × sudangrass hybrids (*Sorghum bicolor* × *S. sudanense*) are widely cultivated forage crops valued for their adaptability, high biomass production, and resilience under diverse environments. By combining the robust growth and drought tolerance of sorghum with the rapid regrowth and fine stems of sudangrass, these hybrids achieve a favorable balance of yield, quality, and stress tolerance (Venuto and Kindiger, 2008; Bhat, 2019; Surmen and Kara, 2022). Their versatility has enabled adoption across tropical, subtropical, and temperate regions, and their importance continues to expand in Mediterranean countries such as Türkiye, Italy, and Spain, where they contribute to feed security and livestock resilience. Globally, sorghum ranks among the top five cereals, with over 57 million tonnes of grain produced annually, alongside extensive areas devoted to forage types including sorghum × sudangrass hybrids (FAOSTAT, 2023). Major producers include the United States, India, China, Sudan, and Australia.

A principal agronomic advantage of sorghum × sudangrass hybrids is their superior water use efficiency (WUE) compared with other high-yielding forages such as maize (*Zea mays* L.). Their C4 photosynthetic pathway, high temperature tolerance, and deep root systems allow them to sustain photosynthesis and growth under water stress, producing more biomass per unit of water than maize (Hammer et al., 2010; Behera et al. 2022). These features position sorghum × sudangrass hybrids as strategic forage crops in water-limited regions.

Nitrogen (N) fertilization is equally crucial for maximizing yield and quality. Adequate N enhances chlorophyll formation, leaf expansion, and protein synthesis, thereby increasing dry matter yield, CP content, and digestibility. It also reduces fiber fractions such as NDF and ADF to levels more favorable for ruminant intake (Turgut et al., 2005; Fageria & Baligar, 2005). However, excessive N may lead to nitrate accumulation in tissues, animal health risks, leaching, and nitrous oxide emissions (Raun & Johnson, 1999; Zhang et al., 2015). Conversely, insufficient N reduces growth and forage nutritive value. Sustainable productivity therefore requires careful calibration of N inputs.

Water and nitrogen strongly interact in shaping crop performance. Water deficits limit N uptake and utilization, reducing the benefits of fertilization. Adequate N, on the other hand, can improve osmotic adjustment, root growth, and leaf retention under drought, thereby mitigating some of the negative effects of water stress (Reddy et al., 2010). Recent research has emphasized such interactions, moving from single-factor studies to integrated evaluations (Al-Solaimani et al., 2017; Ghalkhani et al., 2023; Karaer et al., 2024; Wang et al., 2024). Nevertheless, gaps remain, particularly regarding the combined influence of deficit irrigation and N fertilization on both yield and forage quality in Mediterranean climates. Conflicting results persist: some studies report diminishing returns or reduced nutritive value at high N rates (Iptas & Brohi, 2002; Gao et al., 2022). Others emphasize the benefits of split applications and proper timing (Varmazyari et al., 2012; Kohanmoo & Mazaheri, 2003). Similarly, deficit irrigation outcomes vary with severity and method (Varzi & Oad, 2018; Ghalkhani et al., 2023). These inconsistencies hinder the development of precise, resource-efficient management guidelines (Obour et al., 2018).

The Mediterranean basin provides an especially relevant context for these questions. It is characterized by hot, dry summers, irregular rainfall, and high evapotranspiration rates, all of which constrain forage production (Hadebe et al., 2017). Climate change is expected to exacerbate these pressures by lengthening droughts and increasing rainfall variability (IPCC, 2021). At the same time, livestock sectors continue to expand, increasing demand for high-quality feed. Sorghum, with its intrinsic drought tolerance, high biomass potential, and responsiveness to N, is well positioned to become a cornerstone crop for resilient Mediterranean forage systems (Scordia et al., 2021).

These challenges are particularly acute in semi-arid subregions such as the Aydin province of western Türkiye, where prolonged dry summers, high evaporative demand, and limited irrigation water restrict forage production. Low soil organic matter and nitrogen content further constrain productivity, necessitating integrated water–nutrient management. Sorghum × sudangrass hybrids, with their dual advantage of drought tolerance and nutrient responsiveness, are ideally suited to these conditions (Choi et al., 2022; Alhammad et al., 2023). Yet, management recommendations derived from temperate, high-input systems may not translate directly to Mediterranean settings, where optimizing both WUE and N use efficiency is essential (Oresca et al., 2021; Kang et al., 2023).

The present study was therefore conducted to evaluate the combined effects of four deficit irrigation levels (25%, 50%, 75%, and 100% of full irrigation) and three nitrogen application rates (50, 100, and 150 kg ha^{-1}) on the yield and forage quality of sorghum × sudangrass hybrids under Mediterranean climate conditions in Aydin, Türkiye. This full-factorial design provides a comprehensive assessment of both main and interactive effects of water and N management, addressing a critical gap where such integrated studies remain limited. We hypothesized that (i) moderate deficit irrigation (75%) would improve WUE while sustaining acceptable yields, (ii) increasing N rates would enhance biomass and CP content up to an optimum beyond which returns diminish, and (iii) adequate N supply under deficit irrigation would mitigate the negative effects of reduced water availability on both yield and forage quality, particularly by improving CP while reducing NDF and ADF. Findings are expected to inform resource-efficient, climate-resilient forage production strategies for semi-arid and Mediterranean-type environments.

2. MATERIALS AND METHODS

The study was conducted at the experimental site in Aydin Adnan Menderes University Research and Demonstration Farms, Türkiye (37°761 E, 27°758 N) during the sorghum x sudangrass growing season in 2023 and 2024. This site lies within the Büyük Menderes Basin and is characterized by a Mediterranean climate. Prior to the experiment, the field had been under a rotational system involving various legume and grass forage crops, with such practices continuing until 2022. Before the establishment of the experiment, composite soil samples were collected from the 0–30 cm depth of the experimental field and analyzed for their physicochemical properties. The soil was classified as sandy loam, consisting of 63.8% sand, 25.0% silt, and 11.2% clay. The soil reaction was alkaline with a pH of 8.07, and it was non-saline (total soluble salts: 0.017%). Lime content was 4.25%, indicating a calcareous structure, whereas the organic matter content was very low (1.08%). Available macronutrient concentrations showed that phosphorus was at a low level (4.60 ppm), potassium was medium (206 ppm), calcium was high (3233 ppm), and magnesium was medium (142 ppm) (Table 1).

Meteorological data on temperature and precipitation for the experimental site were obtained for two consecutive growing seasons (May–September 2023 and May–September 2024) and compared with long-term averages. Mean air temperature during both seasons closely followed the long-term trend, but with slightly elevated values during the peak summer months. In 2023, temperatures in July and August were marginally above the long-term mean, whereas in 2024 the increase was more pronounced, particularly in June and July. This indicates that the second season experienced a slightly warmer mid-summer period than both the previous year and the climatic average. Precipitation patterns deviated more substantially from the norm. In 2023, rainfall was not only concentrated in May and June but also exceeded the long-term mean during May, June, and July, ensuring relatively favorable moisture availability during early to mid-summer growth stages. By contrast, in 2024, rainfall was comparatively higher only in May, while June, July, and August recorded markedly less precipitation than both the preceding year and the long-term average. Consequently, while the first season (2023) benefited from above-average early-to mid-summer rainfall, the second season (2024) experienced a pronounced rainfall deficit during the critical summer growth period, coinciding with elevated temperatures (Figure 1).

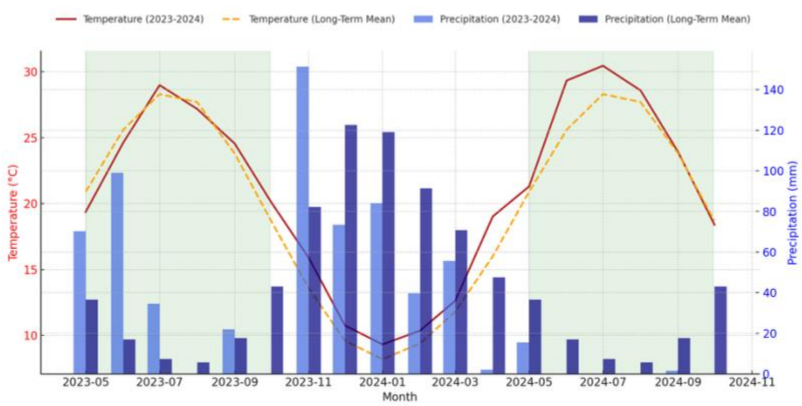

Figure 1. Monthly Temperature and Precipitation Trends (2023-2024) in the experimental area compared to Long-Term Averages (1941-2023).

Experimental Design

The field experiment was conducted during the 2023 and 2024 growing seasons. The experiment was arranged as a two-factor randomized complete block design (RCBD), consisting of four irrigation regimes and three nitrogen application rates. Nitrogen was applied at rates of 50, 100, and 150 kg ha^{-1}. Before planting, a basal fertilization of 15-15-15 was applied to all plots at a rate of 80 kg ha^{-1} P_2O_5 and 80 kg ha^{-1} K_2O. Subsequently, nitrogen was supplied according to the designated levels of the experimental treatments. The experimental crop used in both years was the sorghum-sudangrass hybrid cultivar 'Tonka'. Sowing dates were 20 May 2023 and 22 May 2024, while harvests were conducted on 18 September 2023 and 19 September 2024, respectively.

The experimental plots were randomly distributed with 3 replications; each plot was 3.25 m wide and 5.25 m long. To prevent water and fertilizer movement between adjacent plots, a 1.0 m wide buffer zone was set up between each plot. Irrigation levels were set at 25%, 50%, 75%, and 100% of the soil's field capacity. Irrigation water for the field trial was sourced from a groundwater well located within the experimental site and applied to the plots using a drip irrigation system. Water was extracted with a submersible pump and conveyed through main polyethylene (PE) pipelines with an external diameter of 63 mm. Within each plot, irrigation was delivered to the root zone via PE laterals (16 mm in diameter) fitted with inline emitters, operating at a discharge rate of 2 L h^{-1} and spaced at 25 cm intervals. To facilitate accurate regulation and monitoring of water applications, a 16 mm valve and a flow meter were installed at the inlet of each plot. The available soil water content in the experimental plots was determined using the gravimetric method, and the net irrigation water applied under the 100% irrigation treatment was calculated according to equation (Güngör et al., 2002).

$I = (FC-AW)/100 \times \gamma t \times D$

$V = I \times A \times WL$

In this equation, V denotes the volume of irrigation water and A refers to the plot area (m^2). I represents the irrigation deficit (mm), while WL indicates the irrigation levels (25, 50, 75, and 100%). FC is the field capacity (mm), AW is the available soil water within the 90 cm effective root zone before irrigation (mm), γt is the bulk density (g cm^{-3}), and D represents the effective rooting depth. Based on the measurements, a total of 461.72 mm of irrigation water was applied to the 100% treatment in 2023, and 514.10 mm in 2024. The amounts for the 75%, 50%, and 25% irrigation treatments were calculated proportionally to the 100% irrigation level.

Table 1. Physical properties of the experimental site soils

Soil Depth (cm)	Particle Size Distribution (%)			Soil Type	Bulk Density (g/cm^3)	Field Capacity		Wilting Point	
	Clay	Silt	Sand			(%)	(mm)	(%)	(mm)
0-30	63.80	25.00	11.20	Sandy loam	1.35	23.1	111.5	10.2	40.9
30-60	56.40	30.00	13.60	Sandy loam	1.45	22.9	99.6	9.4	40.8
60-90	68.20	19.20	13.60	Sandy loam	1.52	18.4	83.9	7.3	33.2
	pH	**Salt (%)**	**Lime (%)**	**Organic matter (%)**	**P (ppm)**	**K (ppm)**	**Ca (ppm)**	**Mg (ppm)**	
	8.07	0.017	4.25	1.08	4.60	206	3233	142	

Measurements

Plant height (cm) and leaf number per plant were measured before harvest on 15 randomly selected plants per plot, using a tape measure to extend the uppermost fully expanded leaves. The harvest was conducted at soft dough stage of sorghum × sudangrass. Fresh forage yield (t ha^{-1}) was determined at the harvest of sorghum × sudangrass for each plot. A subsample was oven-dried at 78 °C for 48 h to obtain the dry biomass (t ha^{-1}). Dried samples were ground to pass through a 2 mm screen, and a portion was retained for further analyses. Chlorophyll content (SPAD) was recorded using a SPAD-502 meter (Konica-Minolta Camera Co., Ltd., Japan) at the flowering stage of sorghum × sudangrass (Hoel, 1998). Measurements were taken from the topmost fully expanded leaf during the vegetative stage, and from the flag leaf during the reproductive stages (Rabin and Snapp, 2024). In each plot, SPAD readings were collected from ten randomly selected plants, and the average was used for analysis Normalized difference vegetation index (NDVI) values were measured at the flowering stage using a GreenSeeker™ handheld crop sensor (HCS 100, Trimble Ltd., Sunnyvale, CA, USA). Five readings per plot were taken by holding the sensor 1 m above the crop canopy over a 1 m^2 area, and the mean was used for subsequent analysis (Tagarakis et al., 2017). Leaf area was measured with a portable leaf area meter (LI-3000C, LI-COR, Lincoln, NE, USA) at the flowering stage, using ten representative plants per plot. Leaf area index (LAI) was calculated from the total leaf area per unit ground area according to Allamine et al. (2023) using the equation;

$LAI = (n \times LA) / A$

where n is the number of leaves, LA is the mean leaf area (m^2), and A is the sampled ground area (m^2).

Crude protein content (%) was calculated by multiplying the total nitrogen (N) concentration by 6.25, determined using the Kjeldahl method (AOAC, 2003). Neutral detergent fiber (NDF, %) and acid detergent fiber (ADF, %) were measured with an automated fiber analyzer (ANKOM 2000, ANKOM Technology, NY, USA) following Van Soest et al. (1991). For NDF determination, 0.5 g of ground sample was placed in a fiber filter bag (F57, ANKOM Technology) and digested in a diluted neutral detergent solution containing triethylene glycol (FND20C). ADF was then determined by directly digesting the NDF residue in an acid detergent solution with dry

CTAB powder (FAD20C). Crude protein yield (t ha⁻¹) and relative feed value were calculated according to Horrocks and Vallentine (1999).

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) to evaluate the effects of deficit irrigation and nitrogen fertilization on the measured traits. The experiment was arranged in a two-factor randomized complete block design (RCBD) with three replications, considering irrigation (25%, 50%, 75%, and 100% of full irrigation) and nitrogen doses (50, 100, and 150 kg ha⁻¹) as treatment factors. Significant differences among treatment means were assessed using Duncan's multiple range test (DMRT) at a significance level of $p < 0.05$. Mean comparisons were based on Duncan grouping, where treatments sharing the same letter were not significantly different. These groupings were reported in the tables and reflected in the figures.

All analyses were conducted in R software (v.4.2.2; R Core Team), employing the "agricolae" package (de Mendiburu & de Mendiburu, 2019) for ANOVA and mean separation. Boxplots were generated using the SRplot platform (Tang et al., 2023), which enables advanced statistical annotation and high-quality visualization.

3. RESULTS

The results of the variance analysis and significance levels of the effects of different irrigation regimes and nitrogen doses on the agronomic and quality traits of sorghum × sudangrass are presented in Table 2. The effects of irrigation were found to be highly significant for all examined traits, while nitrogen application significantly influenced most parameters except leaf number and LAI. Furthermore, the interaction between irrigation and nitrogen was significant across all traits, underlining the strong combined influence of water and nutrient management on crop performance.

Table 2. Analysis of variance for sorghum × sudangrass under different irrigation levels and nitrogen doses

		Mean of Squares					
	DF	**PH**	**LN**	**FFY**	**Dry Biomass**	**SPAD**	**LAI**
Year	1	5.013	0.382	0.057	0.028	0.009	0.005
Replication	4	3.263	0.220	6.039	0.434	0.439	0.055
Irrigation	3	9947.8**	345.07**	3805.3**	243.12**	92.79**	53.53**
Y×I	3	60.384**	0.054	2.699	0.039	0.051	0.0080
Nitrogen	2	12109.7**	20.29	2369.0**	206.13**	115.45**	8.903**
Y×N	2	157.5**	0.121	1.964	0.008	0.009	0.013
I×N	6	850.9**	4.968**	215.46**	14.53**	10.12**	0.128**
Y×I×N	6	4.759	0.045	0.827	0.013	0.054	0.022
Error	44	10.930	0.317	4.389	0.203	0.269	0.029
cv		1.23	3.55	2.09	4.05	1.26	3.41
		NDVI	**ADF**	**NDF**	**CPC**	**CPY**	**RFV**
Year	1	0.0033	0.093	0.023	0.00006	98.18	0.002
Replication	4	0.0025	0.197	0.528	0.018	3066.4	0.749
Irrigation	3	0.3850**	25.16**	23.22**	0.716**	1040507.3**	183.79**
Y×I	3	0.0005	0.081	0.133	0.0025	300.82	0.774
Nitrogen	2	0.3683**	8.323**	3.525**	14.59**	1723984.2**	39.988**
Y×N	2	0.00005	0.049	0.124	0.009	12.38	0.658
I×N	6	0.0092**	1.331**	0.860**	0.303**	71962.13**	6.950**
Y×I×N	6	0.0006	0.039	0.140	0.002	118.16	0.610
Error	44	0.0013	0.1471	0.1453	0.0112	1270.4	0.635
cv		4.93	0.99	0.63	1.54	4.61	0.86

** $p < 0.01$, Y: Year; I: Irrigation; N: Nitrogen; DF: different degrees of freedom; PH: plant height; LN: leaf number per plant; FFY: fresh forage yield; LAI: leaf area index; CPC: crude protein content; CPY: crude protein yield; RFV: relative feed value

Plant height and leaf number

Both deficit irrigation and nitrogen fertilization significantly affected plant height (Table 2; Figure 2). Severe water restriction (25%) produced the shortest plants (~227–238 cm), while values increased markedly at 50% irrigation and exceeded 300 cm at 75%. The tallest plants were recorded at 75% irrigation with 100 kg N ha⁻¹

(313.6 cm) and at 100% irrigation with 100 kg N ha⁻¹ (310.6 cm), showing that near-optimal irrigation with moderate nitrogen ensured maximum growth.

The irrigation × nitrogen interaction was evident. At 25% irrigation, nitrogen had little effect, but at 50% irrigation plant height rose sharply from 241.8 cm (50 kg N ha^{-1}) to 288.8 cm (100 kg N ha^{-1}), before declining at 150 kg N ha^{-1} (266.1 cm). At 75% and 100% irrigation, plants remained tallest with 100 kg N ha^{-1} (>310 cm), while 150 kg N ha^{-1} did not add further benefit.

The year × irrigation interaction was also statistically significant, although the overall trend remained consistent between years. In both 2023 and 2024, plant height responded similarly to irrigation treatments, but slight variations were observed, likely due to differences in seasonal temperature and rainfall distribution. The relatively stable averages (266.8 cm in 2023 and 267.3 cm in 2024) indicate that the sorghum × sudangrass hybrid maintained growth performance under comparable irrigation regimes across years, demonstrating its adaptability to inter-annual climatic fluctuations.

On average, 75% and 100% irrigation produced the highest plant heights (285.0 and 283.3 cm), whereas 25% irrigation remained lowest (234.3 cm). Across irrigation regimes, 100 kg N ha^{-1} consistently resulted in the tallest plants (287.8 cm), confirming that moderate nitrogen combined with adequate, but not excessive, irrigation is the most efficient strategy for maximizing sorghum × sudangrass growth.

Deficit irrigation strongly influenced leaf number, while nitrogen had a comparatively weaker effect (Table 3; Figure 2). The lowest values occurred under severe water restriction (25% irrigation), where leaf number remained around 9–10 regardless of nitrogen input. With 50% irrigation, values increased markedly to 14–17, and the highest leaf production was obtained at 75% and 100% irrigation, consistently exceeding 19 leaves per plant. The boxplots confirmed that 75% and 100% irrigation were statistically superior to 25% and 50%, whereas differences between 75% and full irrigation were not significant, indicating a plateau effect.

The irrigation × nitrogen interaction was evident in the intermediate treatments. At 25% irrigation, nitrogen had little impact on leaf number, but at 50% irrigation, leaf production increased from 15.3 (50 kg N ha^{-1}) to 16.5 (100 kg N ha^{-1}) before dropping again to 14.3 at 150 kg N ha^{-1}. At 75% irrigation, maximum values were reached, with 19.8 leaves at 100 kg N ha^{-1} and 20.0 at 150 kg N ha^{-1}. Similarly, under full irrigation, plants produced 19.7 and 20.1 leaves at 100 and 150 kg N ha^{-1}, respectively. These results indicate that optimal canopy development was achieved with adequate irrigation (≥75%) combined with moderate-to-high nitrogen supply.

When averaged across nitrogen doses, 75% irrigation gave the highest mean leaf number (19.15), closely followed by 100% irrigation (18.99), whereas 25% irrigation remained the lowest (9.81). Across irrigation regimes, nitrogen had a limited effect, with averages of 14.8, 16.6, and 16.1 leaves for 50, 100, and 150 kg N ha^{-1}, respectively. Overall, leaf number was primarily determined by irrigation level, while nitrogen contributed to finer adjustments, particularly under moderate-to-high water supply.

The irrigation × nitrogen interaction was evident. At 25% irrigation, nitrogen had little effect, but at 50% irrigation plant height rose sharply from 241.8 cm (50 kg N ha^{-1}) to 288.8 cm (100 kg N ha^{-1}), before declining at 150 kg N ha^{-1} (266.1 cm). At 75% and 100% irrigation, plants remained tallest with 100 kg N ha^{-1} (>310 cm), while 150 kg N ha^{-1} did not add further benefit.

On average, 75% and 100% irrigation produced the highest plant heights (285.0 and 283.3 cm), whereas 25% irrigation remained lowest (234.3 cm). Across irrigation regimes, 100 kg N ha^{-1} consistently resulted in the tallest plants (287.8 cm), confirming that moderate nitrogen combined with adequate, but not excessive, irrigation is the most efficient strategy for maximizing sorghum × sudangrass growth.

Table 3. Mean values of plant height and leaf number of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer dose

	Plant Height (cm)				**Leaf Number**			
2023	266.8				15.91			
2024	267.3				15.76			
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	227.3 f	238.0 e	237.8 e	234.3 c	9.09 g	10.36 f	9.97 f	9.81 c
50%	241.8 e	288.8 b	266.1 c	265.6 b	15.33 d	16.52 c	14.30 e	15.38 b
75%	250.8 d	313.6 a	290.5 b	285.0 a	17.68 b	19.79 a	20.00 a	19.15 a
100%	252.8 d	310.6 a	286.6 b	283.3 a	17.15 b	19.71 a	20.10 a	18.99 a
Mean	243.2 c	287.8 a	270.2 b		14.81	16.60	16.09	

The factors indicated by lettering are significant at P ≤ 0.05, while the same letters denote non-significant differences.

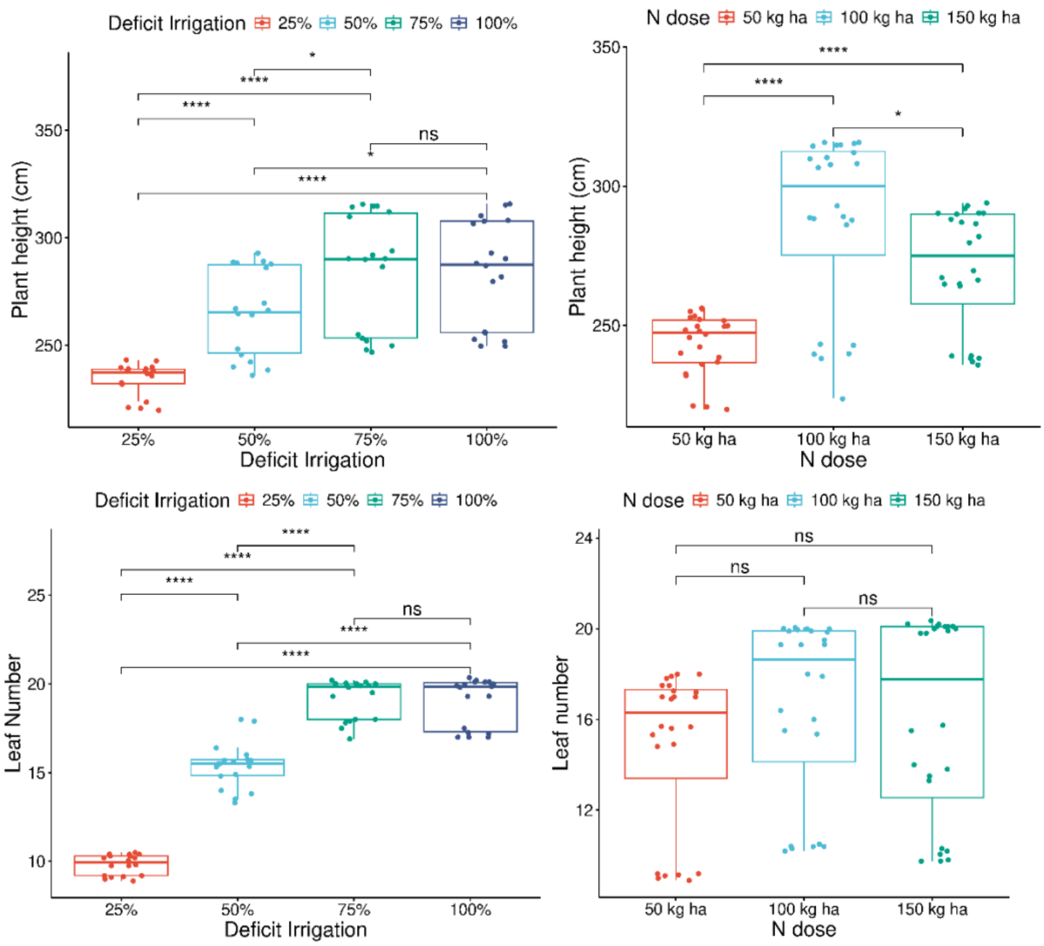

Figure 2. Boxplots of plant height and leaf number per plant of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$.)

Biomass production

Fresh forage yield of sorghum × sudangrass was primarily determined by irrigation levels. The lowest values were recorded under severe water deficit (25% irrigation; 23.5–29.5 t ha^{-1}), clearly indicating strong yield limitation. At 50% irrigation, yields increased markedly, reaching 51.9 t ha^{-1} with 150 kg N ha^{-1}. The highest yields were obtained under 75% and 100% irrigation, where values consistently exceeded 60 t ha^{-1}. Maximum yields were 66.4 t ha^{-1} (75% × 150 kg N) and 66.7 t ha^{-1} (100% × 150 kg N). Statistical comparisons confirmed that 75% and full irrigation were significantly superior to 25% and 50%, while no significant difference was observed between 75% and 100%, suggesting a plateau effect once adequate water supply was achieved (Table 4). Nitrogen application further enhanced yields, though to a lesser extent than irrigation. At 50 kg N ha^{-1}, mean yield was lowest (35.0 t ha^{-1}), whereas increasing nitrogen to 100 kg ha^{-1} significantly improved yield to 50.4 t ha^{-1}. A further increase to 150 kg N ha^{-1} provided only marginal gains (53.6 t ha^{-1}). Boxplot analysis (Figure 3) confirmed that 50 kg N was significantly lower than 100 and 150 kg N, while the difference between the latter two was not statistically significant. This indicates that nitrogen efficiency was maximized at 100 kg N ha^{-1}, with diminishing returns at higher doses.

Dry biomass production was predominantly determined by irrigation regime. The lowest values were observed under 25% irrigation, ranging from 5.0 to 7.2 t ha^{-1} across nitrogen doses, indicating severe yield limitation under water deficit. At 50% irrigation, biomass increased substantially, from 8.1 t ha^{-1} at 50 kg N ha^{-1} to 13.0 t ha^{-1} at 150 kg N ha^{-1}. The highest yields were obtained under 75% and 100% irrigation, consistently exceeding 15 t ha^{-1}. Maximum values were 16.8 t ha^{-1} at 75% × 150 kg N and 16.7 t ha^{-1} at 100% × 150 kg N. Statistical comparisons confirmed that both 75% and 100% irrigation were significantly superior to 25% and 50%, while no significant difference was detected between the two highest irrigation levels, reflecting a plateau effect once water availability was adequate (Table 3; Figure 3). Nitrogen fertilization also exerted a strong influence on biomass accumulation. At 50 kg N ha^{-1}, mean yield was lowest (7.8 t ha^{-1}), whereas increasing nitrogen to 100 kg ha^{-1} significantly enhanced dry biomass to 12.2 t ha⁻¹. A further increase to 150 kg N ha⁻¹ resulted in 13.4 t ha⁻¹, representing only marginal improvement compared with 100 kg N ha⁻¹. Boxplot analysis confirmed that 50 kg N was statistically inferior, while differences between 100 and 150 kg N were not significant. These results suggest that nitrogen efficiency was maximized at 100 kg N ha⁻¹, with diminishing returns at higher doses.

Table 4. Mean values of fresh forage yield and dry biomass of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

	Fresh Forage Yield (t ha^{-1})				Dry Biomass (t ha^{-1})			
2023	46.30				11.16			
2024	46.36				11.12			
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	23.46 h	25.51 h	29.47 g	26.14 c	5.01 j	6.00 ı	7.15 h	6.05 c
50%	36.34 f	47.72 d	51.89 c	45.32 b	8.09 g	11.46 e	12.99 d	10.85 b
75%	39.95 e	62.28 b	66.44 a	56.22 ab	8.91 f	15.19 c	16.77 a	13.62 ab
100%	40.30 e	65.95 a	66.66 a	57.63 a	9.30 f	16.16 b	16.66 a	14.04 a
Mean	35.01 b	50.36 ab	53.61 a		7.83 b	12.20 ab	13.39 a	

The factors indicated by lettering are significant at P ≤ 0.05, while the same letters denote non-significant differences.

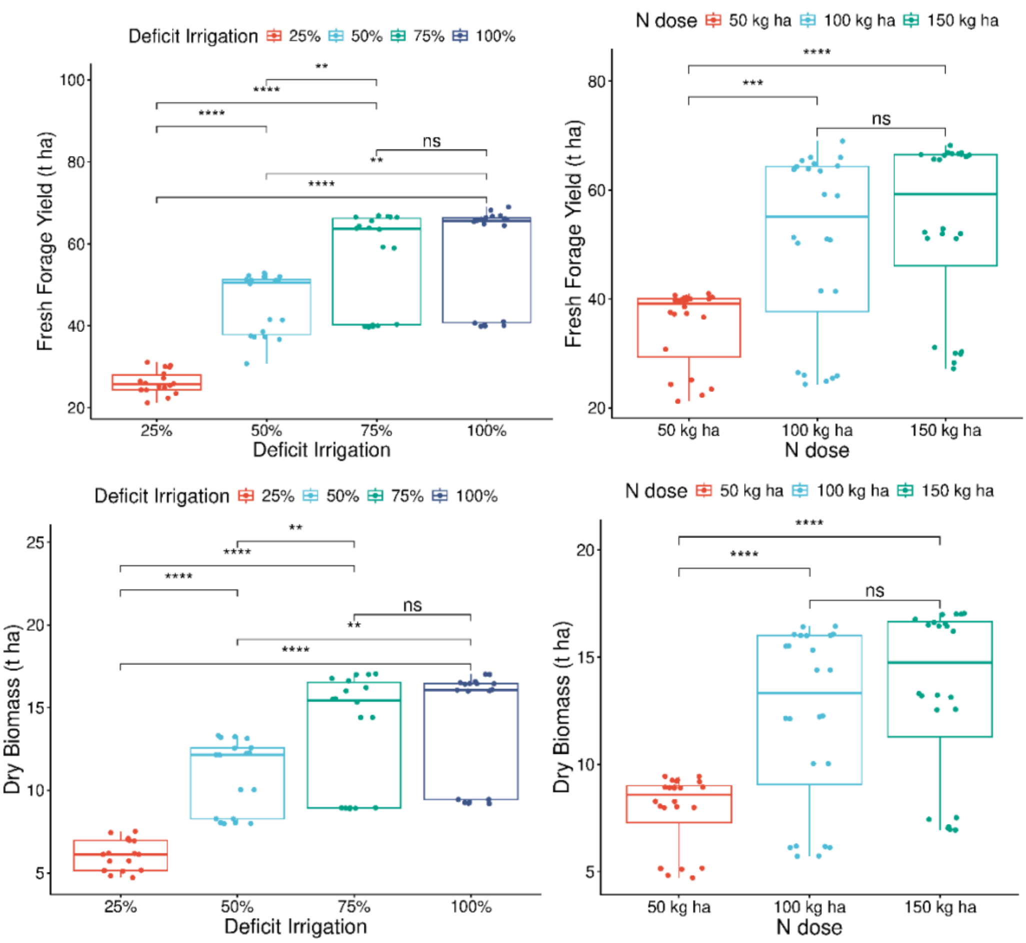

Figure 3. Boxplots of fresh forage yield and dry biomass of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001)

Physiological indicators

Chlorophyll content, expressed as SPAD values, was significantly influenced by both irrigation and nitrogen fertilization, with clear interaction effects (Table 5; Figure 4). Under severe water stress (25% irrigation), SPAD values remained lowest (37.6–38.6) across nitrogen doses, indicating restricted chlorophyll development. At 50% irrigation, values improved substantially, rising from 37.9 at 50 kg N ha⁻¹ to 42.0 at 100 kg N ha⁻¹, before slightly declining at 150 kg N ha⁻¹ (40.9). The highest SPAD readings were observed under 75% and 100% irrigation, where values exceeded 45 with 100 kg N ha⁻¹ and remained above 43 even at 150 kg N ha⁻¹. Boxplots confirmed that 75% and 100% irrigation were statistically superior to 25% and 50%, while no significant difference was detected between 75% and full irrigation, again suggesting a plateau effect.

The irrigation × nitrogen interaction was particularly evident at intermediate water supply. At 25% irrigation, nitrogen addition provided only marginal improvements, while at 50% irrigation SPAD values responded strongly to 100 kg N ha⁻¹ but declined again at higher nitrogen input. At 75% irrigation, the highest SPAD was achieved with 100 kg N ha⁻¹ (45.4), followed closely by 150 kg N ha⁻¹ (43.8). A similar trend was found under full irrigation, with SPAD values of 45.2 and 44.1 at 100 and 150 kg N ha⁻¹, respectively. These findings indicate that nitrogen efficiency was maximized under adequate water availability, particularly at the moderate dose.

When averaged across irrigation levels, SPAD values were lowest under 25% irrigation (38.1), increased at 50% irrigation (40.3), and reached their highest levels under 75% (42.7) and 100% irrigation (43.0). Across irrigation regimes, the highest mean SPAD was obtained with 100 kg N ha⁻¹ (42.7), followed by 150 kg N ha⁻¹ (41.8), while 50 kg N ha⁻¹ produced the lowest average (38.5). Overall, chlorophyll development in sorghum × sudangrass was primarily governed by water availability, but nitrogen, particularly at 100 kg ha⁻¹, further enhanced SPAD under sufficient irrigation.

Canopy development, expressed as leaf area index, responded strongly to irrigation regime and, to a lesser extent, to nitrogen supply (Table 4; Figure 4). Severe water stress (25% irrigation) restricted canopy expansion, with LAI remaining below 3 across nitrogen levels. At 50% irrigation, values increased to about 4–5, indicating a partial recovery of leaf development. The most substantial gains occurred under 75% and 100% irrigation, where LAI values consistently exceeded 6, reaching nearly 7 under higher nitrogen doses. Statistical comparisons confirmed that 75% and full irrigation supported similarly high canopy coverage, both markedly superior to restricted water supply.

Irrigation effects became more apparent when water availability was not limiting. At 25% irrigation, additional nitrogen produced little improvement in LAI. By contrast, at 50% irrigation, values rose from 3.8 under 50 kg N ha⁻¹ to nearly 4.8 with higher nitrogen inputs. Under 75% and 100% irrigation, maximum values were observed with 100–150 kg N ha⁻¹, reflecting enhanced canopy expansion and potential for greater light interception.

Averaged across nitrogen levels, LAI increased from 2.9 at 25% irrigation to 6.4–6.5 under 75–100% irrigation, highlighting the dominant role of water availability in canopy development. Across irrigation regimes, the highest mean LAI was obtained with 150 kg N ha⁻¹ (5.45), closely followed by 100 kg N ha⁻¹ (5.37), while 50 kg N ha⁻¹ remained lowest (4.36). These findings indicate that sorghum × sudangrass canopy growth was primarily governed by water supply, with nitrogen acting as a secondary factor that optimized leaf area expansion under favorable moisture conditions.

Table 5. Mean values of SPAD values and leaf area index of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

	SPAD				Leaf Area Index (cm^2)			
2023	41.00				5.07			
2024	41.02				5.05			
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	37.56 ı	38.21 gh	38.61 fg	38.13 c	2.40 g	3.14 f	3.11 f	2.88 c
50%	37.95 hı	41.96 c	40.88 d	40.26 b	3.75 e	4.81 d	4.83 d	4.46 b
75%	38.90 f	45.36 a	43.75 b	42.67 a	5.63 c	6.65 b	6.88 a	6.39 a
100%	39.69 e	45.16 a	44.06 b	42.97 a	5.65 c	6.88 a	6.97 a	6.50 a
Mean	38.52 c	42.67 a	41.83 ab		4.36 b	5.37 a	5.45 a	

The factors indicated by lettering are significant at P ≤ 0.05, while the same letters denote non-significant differences.

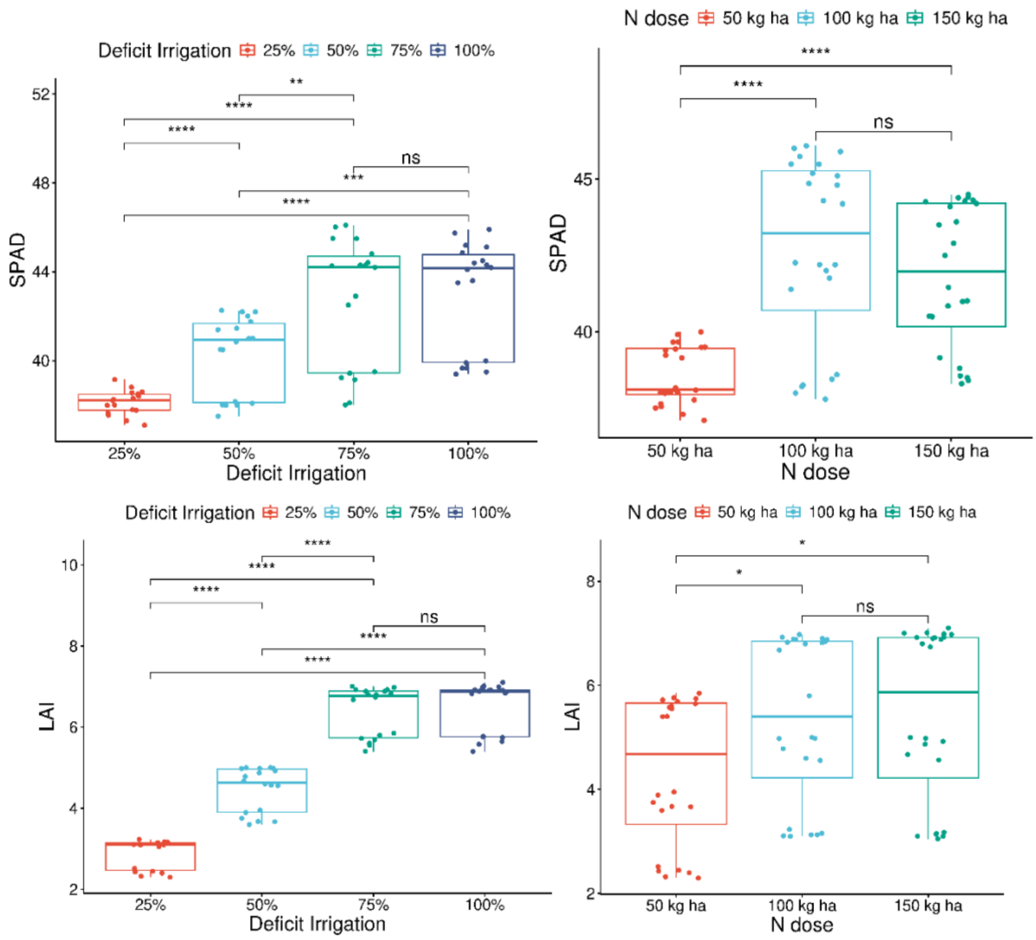

Figure 4. Boxplots of SPAD values and leaf area index of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$)

NDVI, as a physiological indicator of canopy vigor and overall crop performance, was strongly influenced by irrigation regime and nitrogen supply (Table 6; Figure 5). The lowest values were consistently observed under 25% irrigation (0.44–0.64), reflecting reduced leaf area development and limited photosynthetic activity. With increasing water availability, NDVI improved markedly, reaching 0.75 under 50% irrigation and exceeding 0.80 under 75–100% irrigation. Statistical comparisons showed that 75% and full irrigation supported significantly greater NDVI than 25% and 50%, while differences between 75% and 100% were not significant, suggesting that canopy vigor reached a physiological maximum once water availability was adequate.

Nitrogen effects were more evident under moderate to high irrigation levels. At 25% irrigation, nitrogen addition produced only small gains, whereas at 50% irrigation NDVI increased from 0.65 (50 kg N ha^{-1}) to ~0.80 (100–150 kg N ha^{-1}). Under 75% and 100% irrigation, the highest NDVI values were obtained with 100–150 kg N ha^{-1} (0.94–0.96), indicating that nitrogen efficiency was maximized when water was not limiting.

Averaged across nitrogen levels, NDVI increased steadily from 0.55 under 25% irrigation to 0.75 at 50% and peaked at 0.85–0.87 under 75–100% irrigation. Across irrigation regimes, the highest mean NDVI was achieved with 150 kg N ha^{-1} (0.84), closely followed by 100 kg N ha^{-1} (0.82), while 50 kg N ha^{-1} remained lowest (0.61). These results confirm that NDVI was primarily governed by irrigation but further optimized by moderate-to-high nitrogen supply, highlighting its role as a sensitive integrator of water and nutrient effects on crop performance.

Table 6. Mean values of NDVI values of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

		NDVI		
2023		0.761		
2024		0.747		
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	0.440 f	0.571 e	0.636 d	0.549 c
50%	0.646 d	0.800 b	0.803 b	0.750 b
75%	0.668 cd	0.941 a	0.950 a	0.853 a
100%	0.693 c	0.946 a	0.956 a	0.865 a
Mean	0.612 b	0.815 a	0.836 a	

The factors indicated by lettering are significant at P ≤ 0.05, while the same letters denote non-significant differences.

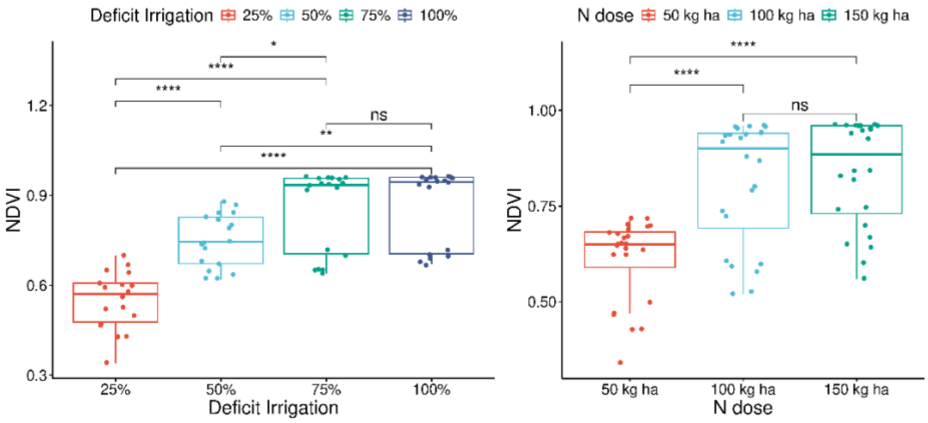

Figure 5. Boxplots of NDVI of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$)

Forage quality parameters

Variation in fiber fractions reflected the combined effects of water and nitrogen supply on cell wall composition, with important implications for forage quality (Table 7; Figure 6). Under severe deficit irrigation (25%), both ADF (37.0%) and NDF (58.2%) remained lowest, indicating reduced structural fiber accumulation but also reflecting limited biomass formation. With increasing irrigation, fiber fractions rose progressively: ADF reached 39.6% and NDF 60.7% under full irrigation, values associated with lower digestibility and restricted forage intake potential. The plateau observed between 75% and 100% irrigation suggests that once leaf expansion and biomass accumulation were maximized, additional water primarily contributed to fiber deposition rather than qualitative improvements.

Nitrogen exerted a smaller but noticeable effect. At 50 kg N ha^{-1}, fiber fractions remained lowest (ADF: 37.8%, NDF: 59.3%), whereas higher nitrogen supply (100–150 kg N ha^{-1}) led to modest increases in both ADF (~38.8%) and NDF (~60.0%). The interaction analysis revealed that nitrogen had little influence under restricted water supply but accentuated fiber concentration under 75–100% irrigation, where maximum values were recorded (39.8% ADF, 61.0% NDF at 150 kg N ha^{-1}).

Taken together, these results demonstrate that fiber accumulation in sorghum × sudangrass was primarily driven by water availability, with nitrogen contributing secondarily under adequate irrigation. Importantly, while improved water and nutrient supply enhanced biomass, they simultaneously increased fiber fractions, underscoring the trade-off between productivity and forage quality.

Table 7. Mean values of ADF and NDF contents of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

	ADF (%)				NDF(%)			
2023	38.47				59.71			
2024	38.40				59.74			
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	36.26 e	37.56 d	37.20 d	37.00 d	58.16 d	58.26 d	58.19 d	58.20 c
50%	36.68 e	38.75 c	38.46 c	37.96 c	58.52 d	59.93 c	60.09 c	59.51 b
75%	38.51 c	39.18 b	39.66 a	39.12 b	60.23 c	60.34 bc	60.92 a	60.49 a
100%	39.56 ab	39.61 a	39.77 a	39.64 a	60.32 bc	60.70 ab	61.04 a	60.68 a
Mean	37.75 b	38.77 a	38.77 a		59.31 b	59.81 ab	60.06 a	

The factors indicated by lettering are significant at $P \leq 0.05$, while the same letters denote non-significant differences.

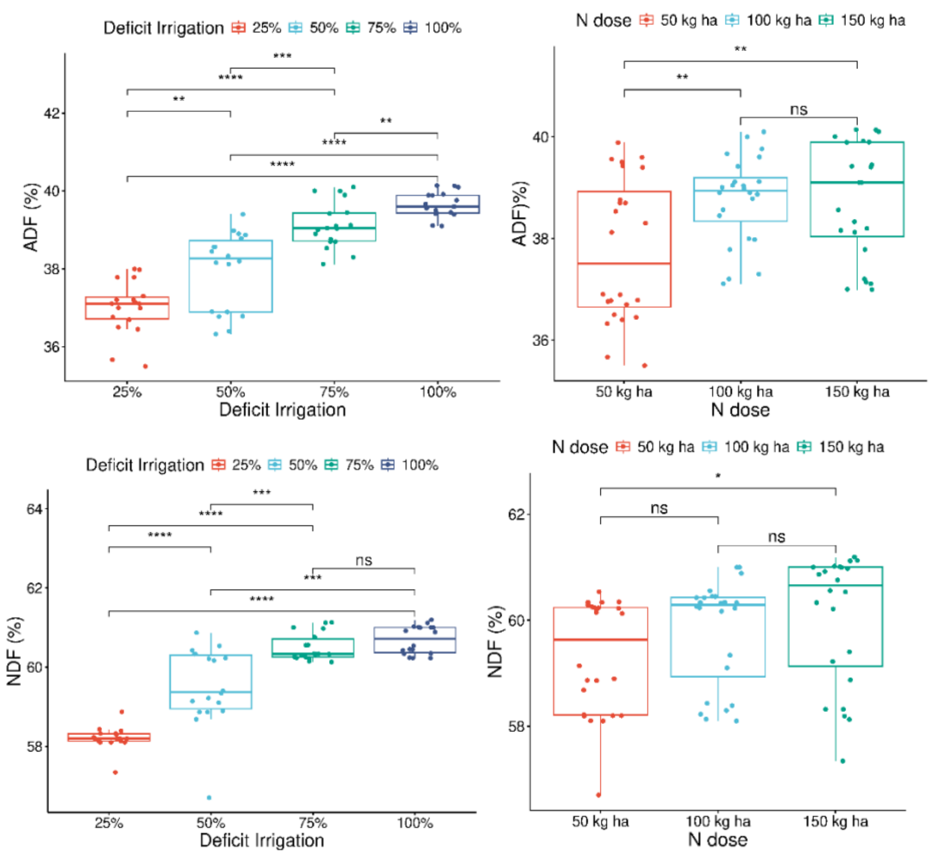

Figure 6. Boxplots of ADF and NDF content of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$)

Crude protein characteristics of sorghum × sudangrass were shaped by nitrogen fertilization to a far greater extent than by irrigation, although yield-related responses reflected the joint contribution of both factors (Table 8; Figure 7).

Crude protein content (CPC) was relatively stable across irrigation regimes, with values ranging from 6.7 to 7.1% under 50–100% irrigation, while slightly higher concentrations were observed under 25% irrigation, reaching up to 7.94% at 150 kg N ha^{-1}. However, statistical analyses indicated that these differences were not significant, confirming that protein concentration was buffered against variation in water supply. In contrast, nitrogen fertilization exerted a pronounced influence. At 50 kg N ha^{-1}, CPC averaged only 5.95%, whereas increasing nitrogen to 100 kg ha^{-1} raised values to 7.26%, and 150 kg N ha^{-1} provided a further but modest increase to 7.33% (Table 7). The boxplots supported this trend, highlighting a clear separation between 50 kg N and the higher nitrogen levels, while no significant difference was detected between 100 and 150 kg N ha^{-1}. These findings suggest that most improvements in protein concentration were achieved at moderate nitrogen input, while additional fertilizer provided diminishing returns (Figure 7).

Crude protein yield (CPY), by contrast, showed strong responsiveness to both irrigation and nitrogen supply, reflecting the combined effects of biomass accumulation and protein concentration. The lowest yields were recorded under 25% irrigation, ranging from 296 kg ha⁻¹ at 50 kg N to 568 kg ha⁻¹ at 150 kg N. With 50% irrigation, CPY rose substantially, from 481 kg ha⁻¹ (50 kg N) to 933 kg ha⁻¹ (150 kg N). The highest values were obtained under 75% and 100% irrigation, where yields exceeded 1000 kg ha⁻¹. Notably, the combinations of 75% × 150 kg N (1191 kg ha⁻¹) and 100% × 150 kg N (1183 kg ha⁻¹) represented the maximum protein yields recorded. Statistical comparisons revealed that 75% and 100% irrigation were significantly superior to 25% and 50%, while differences between the two highest irrigation levels were not significant, pointing to a plateau effect once sufficient water was supplied.

Mean comparisons further illustrate these trends. Averaged across irrigation regimes, CPC values were 5.95%, 7.26%, and 7.33% at 50, 100, and 150 kg N ha⁻¹, respectively, while CPY increased from 467 to 969 kg ha⁻¹ across the same nitrogen levels. Averaged across nitrogen doses, CPC remained nearly unchanged with irrigation (7.1–6.7%), whereas CPY increased sharply from 440 kg ha⁻¹ under 25% irrigation to 749, 938, and 960 kg ha⁻¹ under 50%, 75%, and 100% irrigation, respectively. These results underscore the contrasting behavior of the two traits: while protein concentration was relatively insensitive to irrigation, protein yield responded strongly to the combined effects of water and nitrogen availability (Table 7; Figure 7).

Table 8. Mean values of crude protein content and crude protein yield of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

	Crude Protein Content (%)				**Crude Protein Yield (kg ha^{-1})**			
2023	6.84				772.91			
2024	6.85				770.57			
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	5.90 f	7.59 b	7.94 a	7.14	296.01 h	456.14	568.13 f	440.10 c
50%	5.94 f	7.26 c	7.17 cd	6.79	480.99 g	834.36 e	932.61 d	749.32 b
75%	5.98 f	7.15 ce	7.10 de	6.74	533.96 f	1087.86 c	1191.27 a	937.70 a
100%	5.96 f	7.06 de	7.09 de	6.71	555.13 f	1141.76 b	1182.66 a	959.85 a
Mean	5.95 c	7.26 b	7.33 a		466.53 b	880.04 a	968.67 a	

The factors indicated by lettering are significant at P ≤ 0.05, while the same letters denote non-significant differences.

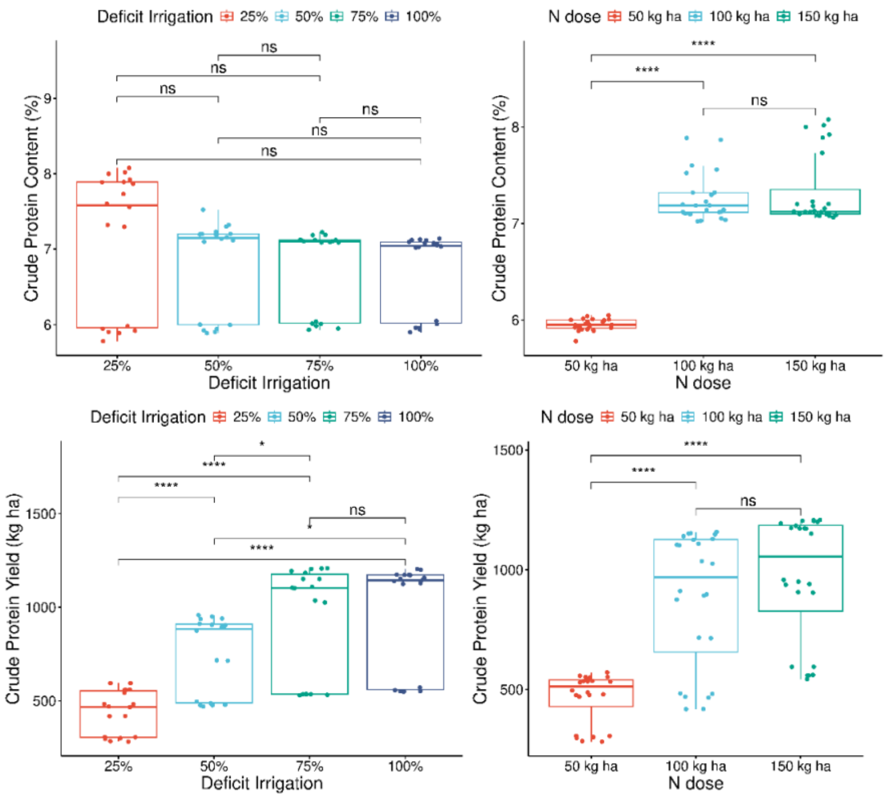

Figure 7. Boxplots of crude protein traits of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$)

Relative feed value, an integrative index of forage quality derived from fiber fractions, was significantly influenced by irrigation and to a lesser extent by nitrogen fertilization (Table 9; Figures 8). Across irrigation regimes, a consistent decline in RFV was observed with increasing water supply. The highest values were recorded under 25% irrigation, averaging 96.0, followed by a progressive reduction to 92.8 at 50%, 89.8 at 75%, and the lowest mean of 88.9 under full irrigation. Statistical comparisons confirmed that all irrigation levels differed significantly, with the exception of 75% versus 100%, indicating that higher water availability promoted greater fiber deposition, thereby reducing forage digestibility and intake potential as reflected in lower RFV.

Nitrogen effects were less pronounced but still evident. At 50 kg N ha^{-1}, RFV was highest (93.4), whereas both 100 and 150 kg N ha^{-1} resulted in slightly lower and statistically similar values (91.3 and 91.0, respectively). The interaction analysis showed that nitrogen had little impact under 25% irrigation, but under higher irrigation regimes it contributed to minor reductions in RFV, paralleling the rise in fiber fractions.

Overall, RFV results demonstrate the trade-off between biomass accumulation and forage quality. While greater water and nutrient availability enhanced yield and protein productivity, they simultaneously reduced relative feed value by increasing cell wall constituents. This highlights the importance of balancing management practices to optimize both quantity and quality in sorghum × sudangrass production systems (Table 8; Figure 8).

Table 9. Mean values of relative feed value of sorghum × sudangrass as affected by different deficit irrigation levels and nitrogen fertilizer doses

		Relative Feed Value		
2023		91.87		
2024		91.88		
Irrig. / N	**50 kg ha^{-1}**	**100 kg ha^{-1}**	**150 kg ha^{-1}**	**Mean**
25%	96.99	95.22	95.78	96.00 a
50%	95.90	91.12	91.24	92.75 b
75%	90.96	89.99	88.56	89.8 c
100%	89.56	88.95	88.26	88.92 d
Mean	93.35 a	91.32 b	90.96 b	

The factors indicated by lettering are significant at $P \leq 0.05$, while the same letters denote non-significant differences.

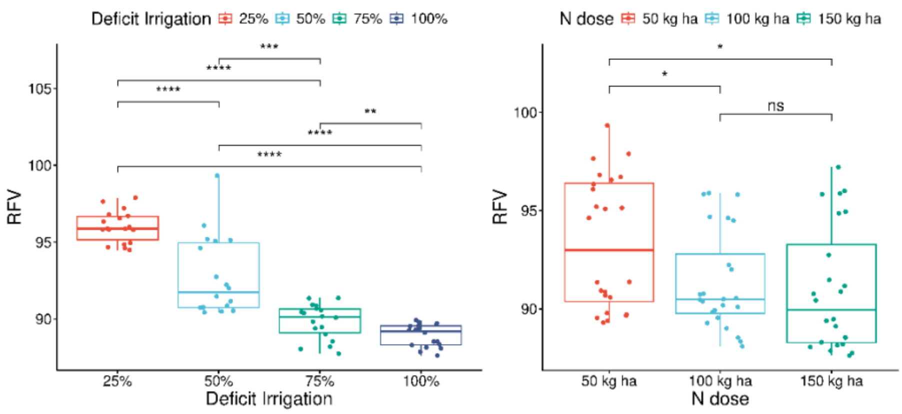

Figure 8. Boxplots of relative feed value of sorghum × sudangrass under different deficit irrigation levels and nitrogen doses. (Plots show median values with variability; significance is indicated as ns, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$.)

4. DISCUSSION

Optimized management of irrigation and nitrogen inputs fosters enhanced crop growth, which consequently contributes to improved yield performance (Comas et al., 2019; Finch, 2020). Our objective was to evaluate the effects of different irrigation levels and nitrogen rates on the growth and yield of sorghum × sudangrass hybrid. Across the two-year experiment, reduced irrigation combined with moderate nitrogen input positively influenced plant height, leaf number, leaf area index (LAI), and SPAD values, NDVI, thereby contributing to greater biomass and crude protein yield. The combination of 75% irrigation and 100 kg N ha^{-1} produced biomass and protein yields comparable to those obtained under full irrigation and higher nitrogen doses, indicating improved resource use efficiency. This outcome highlights an important strategy for sustainable forage production in semi-arid and Mediterranean ecosystems.

In this study, plant height and leaf number were strongly influenced by irrigation levels, with a marked decline observed under the 25% irrigation treatment. This finding is consistent with Blum (2009), who reported that leaf area expansion and vegetative growth are restricted under drought conditions. The absence of significant differences between the 75% and 100% irrigation levels in our experiment parallels the observations of Sinclair and Rufty (2012), who suggested that water-use efficiency reaches a plateau beyond a certain threshold. Conversely, Al-Solaimani et al. (2017) reported that full irrigation resulted in the highest plant height in sudangrass. Such discrepancies may be attributed to differences in cultivar traits, climatic conditions, and irrigation practices

Irrigation practices and nitrogen application are key determinants of crop yield, and their combined effects can significantly enhance productivity (Sun et al., 2009). Numerous studies have demonstrated a curvilinear relationship between water supply, fertilizer input, and yield performance, indicating that optimal growth and yield are typically achieved when soil moisture and nitrogen are supplied in balanced proportions (Yan et al., 2021; Cai et al., 2023). Biomass yield and dry matter production were directly influenced by water limitation. Under the 25% irrigation regime, yields decreased markedly, whereas no significant differences were observed between the 75% and full irrigation treatments. This outcome aligns with the findings of Pereira et al. (2007), who reported that in semi-arid, Mediterranean-type environments, optimized water management can conserve resources without compromising yield. In contrast, Iptas and Brohi (2002) found that full irrigation ensured the highest biomass yields. In the present study, nitrogen fertilization enhanced yield, but increases beyond 100 kg N ha^{-1} were marginal. This is consistent with Cassman et al. (2002) and Ladha et al. (2005), who emphasized that excessive nitrogen inputs offer diminishing yield returns while posing environmental risks. Conversely, Gao et al. (2022) reported that higher nitrogen levels can still enhance yield, highlighting the importance of genotype × environment interactions.

SPAD, LAI, and NDVI values increased with irrigation and nitrogen applications, reaching their maximum levels particularly under 75–100% irrigation combined with 100 kg N ha^{-1}. Nitrogen supports chlorophyll synthesis and thereby enhances photosynthetic capacity (Carpenter et al., 2014; Xiong et al., 2025). In our study, NDVI values of 0.94–0.96 under 75% and 100% irrigation were consistent with the findings of Gitelson et al. (2003), who demonstrated that NDVI is a reliable indicator of nitrogen status and photosynthetic capacity. However, Obour et al. (2018) reported that elevated NDVI and SPAD values do not always directly correlate with yield, suggesting that environmental factors and genotypic differences must be considered when interpreting physiological indicators.

ADF and NDF concentrations increased with higher irrigation and nitrogen inputs, indicating a reduction in forage digestibility. Filho et al. (2018) and Kaplan et al. (2016) reported that elevated fiber fractions decrease digestibility in ruminants, while Wang et al. (2022) noted that rapid growth conditions accelerate lignification. Our findings corroborate these trends. In contrast, Choi et al. (2022) demonstrated that appropriate nitrogen management can sustain high yield while maintaining acceptable forage quality.

In this study, crude protein (CP) content and yield of sorghum × sudangrass were positively influenced by increased nitrogen fertilization, while irrigation played a supportive yet meaningful role. Similar results were reported by Iptas and Brohi (2002), who observed that raising nitrogen to approximately 120 kg N ha^{-1} increased CP content significantly. Moreover, research by Kaplan et al. (2019) demonstrated that combined applications of irrigation and nitrogen enhanced both yield and feed quality in sorghum–sudangrass silage. Notably, CP content plateaued beyond optimal nitrogen levels in our work, aligning with the observation that there are diminishing returns above certain N doses (Mut et al., 2017, in Central Anatolia conditions). Collectively, these findings underscore that a balanced integration of nitrogen and water management can optimize forage protein production while maintaining resource efficiency.

Relative feed value (RFV) was found to be higher under reduced irrigation conditions. Rooney and Blümmel (2009) indicated that increased biomass production typically elevates fiber content, thereby lowering RFV, and our findings are consistent with this trend. Furthermore, Karaer et al. (2024) reported that a combination of 60% irrigation and moderate nitrogen fertilization resulted in a balanced outcome for both yield and forage quality parameters. This suggests that the optimal balance may vary across different ecological conditions and management practices.

5. CONCLUSION

Irrigation emerged as the main determinant of sorghum × sudangrass performance under Mediterranean conditions, while nitrogen acted as a complementary input enhancing growth and nutritive value. Full irrigation and high nitrogen supply increased biomass and protein yield, but also raised fiber fractions and reduced relative feed value, underscoring a trade-off between productivity and quality. Importantly, 75% irrigation combined with 100 kg N ha^{-1} provided yields and protein outputs comparable to the highest-input treatment, while improving water and nitrogen use efficiency. For producers, this indicates that moderate irrigation and fertilization levels can sustain high yield and acceptable quality without the economic and environmental costs of excessive inputs, making sorghum × sudangrass a reliable forage option for resource-limited Mediterranean systems.

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