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Comparison of Growth Responses in Sorghum Genotypes and Corn Grown in Arid Regions Under Different Levels of Water and Nitrogen Supplies

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Abstract

Improving the productivity of cropping systems in terms of irrigation water use and nitrogen (N) fertilizer and exploring the associated effective physiological traits are priorities mostly in water-limited areas. Therefore, this field experiment was conducted on a clay loam soil (thermic family of Typic Haplargids) in central Iran with the three planting dates of 2016 (June 30), early 2017 (June 10), and late 2017 (July 11). Three forage sorghum genotypes including SF002, SF001, and Pegah, three grain sorghum genotypes of MGS5, GS24, GS28, and one common corn hybrid were grown under two irrigation regimes (55% and 85% of the maximum allowable depletion – MAD) as well as two N levels (0 and 112.5 kg N ha^{-1} in the form of urea, 46% N). The results showed considerable genetic variation among the sorghum genotypes in terms of yield. Due to water-limited conditions, the grain and biomass yields of the corn hybrid were decreased more those of sorghum genotypes. However, higher potential sorghum genotypes recorded total dry biomass (shoot biomass and grain yield) values similar to those of corn under both normal and deficit irrigation regimes. On the other hand, the grain share of the total biomass in the corn hybrid was higher in the two irrigation regimes. Under deficit irrigation, the use efficiency values of irrigation water (IWUEb) and N fertilizer (NUEb) for the biomass yield in Pegah and GS24 were higher than those in the corn hybrid. However, IWUEg and NUEg in corn were significantly higher under both irrigation regimes compared to those recorded for even the high-yield potential genotypes of the grain and forage sorghum. The positive effects of N application on the plants declined under water-limited stress, but the negative effects of water deficit stress were reduced with N application, while dry matter and grain yield increased as a consequence of the increase in the maximum leaf area index, chlorophyll *a*, chlorophyll *b*, and carotenoid contents, as well as the enhanced antioxidant activities of catalase, ascorbate peroxidase, and peroxidase enzymes. It can be concluded that the corn-based planting system is superior to sorghum even under low irrigation conditions, and N supply could moderate the negative effects of water shortage stress on plant growth.

Keywords

chlorophyll *a/b* ratio; deficit irrigation; genetic diversity; LAI$_{max}$; nitrogen use efficiency

1. Introduction

Despite severe water scarcity in arid and semiarid regions of the world (Food and Agriculture Organization of the United Nations, 2011), more than 90% of the water resources in these regions are usually consumed by the agricultural sector (FAO, 2017b). However, this sector is losing much of its share of water each year due to increasing drought events, global climate change, and population growth

(Belesky & Malinowski, 2016; FAO, 2017a; Mancosu et al., 2015; Prażak, 2016). These conditions warrant the development of management strategies and practices, including deficit irrigation approaches to improve irrigation water use efficiency (IWUE) (Pang et al., 2018) and to achieve stabilized crop yields (Geerts & Raes, 2009). Accordingly, a number of researchers have investigated the effects of deficit irrigation on crop growth and yield (e.g., Tabib Loghmani et al., 2019; Yousefi et al., 2018). Farré and Faci (2006) studied the yield responses of corn and sorghum to deficit irrigation on a loam soil in northeast Spain and found that while corn yield was higher than that of sorghum under a normal irrigation regime, sorghum outperformed corn under moderate or even severe water-limited stress conditions.

Despite reports indicating improved crop yields and related physiological properties due to the use of nitrogen fertilizer under normal irrigation (Farooq et al., 2009), conflicting results have been reported regarding the effects of nitrogen (N) application under deficit irrigation regimes. Some studies have shown that deficit irrigation reduces the N uptake of plants (Geerts & Raes, 2009; Pandey et al., 2000). For instance, Di Paolo and Rinaldi (2008) found a significant interaction between nitrogen application and irrigation regarding grain yield and water use efficiency (WUE) in corn. Furthermore, Maharjan et al. (2016) evaluated the yield response of corn grown on Hubbard loamy sand in Minnesota, USA, to N management under both full irrigation and water stress conditions. Their results showed that, regardless of the significant differences observed in crop yield, the optimum N application rate was not affected by water management. Rimski-Korsakov et al. (2009) also reported that water-limited stress decreased the aboveground biomass production of corn, independent of the applied N fertilizer levels. In addition, they showed that the N uptake from the fertilizer under water-limited conditions did not depend on the N application rate; rather, it was dependent on the application rate under normal irrigation.

Given the significant relationship between the nutrient level and soil moisture, it has been recommended that a proper balance should be struck between soil moisture and nutrient levels (Farooq et al., 2009; Saravia et al., 2016). This is because the photosynthetic pigment content in leaves is adversely affected by the environmental stress and a lack of nutrients, especially N. Thus, accurate estimation of the leaf photosynthetic pigment content can directly influence stress management and decisions regarding fertilizer application (Shah et al., 2017; Yosefi et al., 2018). Another practice commonly recommended for areas with limited water resources is the use of drought-tolerant plants such as sorghum instead of corn (Farré & Faci, 2006) to supply the forage required for silage preparation in animal farm units. A 5-year study by Amaducci et al. (2016), for example, revealed the superiority of sorghum in terms of yield and water use efficiency over corn, even under well-irrigated conditions. Araya et al. (2016) also showed that, compared to corn, grain sorghum could be a desirable substitute crop for cultivation under water-scarce conditions in Kansas as it would reduce the potential risks to farmer income levels over time. Further, Kisekka et al. (2016) indicated the potential for improving sorghum grain yield under limited irrigation; however, they found that the replacement of sorghum for corn would not be readily welcomed by local users for silage production because of the long storage capacity of corn silage.

Given the priority of improving the productivity of cropping systems in terms of irrigation water use and the level of the most important macronutrient, N, mainly in water-limited areas, the present study was conducted to: (*i*) evaluate the productivity of different cropping systems depending on the field crop, including corn, grain, and forage sorghum, under diverse irrigation regimes and N supplies; and (*ii*) to identify the effective physiological traits of crop performance in each cropping system.

2. Material and Methods

2.1. Site Location and Experimental Conditions

A field experiment was conducted during the growing season, from June to August, in 2016 and 2017 at the Research Farm of Isfahan University of Technology (32°32′ N and 51°23′ E; altitude of 1,630 m above sea level; mean annual temperature of

14.5 °C; mean annual precipitation of 140 mm), located in Lavark, Najaf Abad, Isfahan, Iran. In the first year (2016), sorghum genotypes were planted on June 30, while the planting dates in the second year consisted of June 10 (early 2017) and July 11 (late 2017). The mean air temperatures during the growing seasons were recorded at 25.5 °C in 2016, and 26.6 °C and 24.1 °C on the planting dates of June 10 and July 11, 2017, respectively (Table 1).

Table 1 Monthly mean, minimum, and maximum air temperatures; total rainfall; and evaporation during the growing seasons.

Month	2016				2017			
	T max (°C)	T min (°C)	Rainfall (mm)	Pan evaporation (mm)	T max (°C)	T min (°C)	Rainfall (mm)	Pan evaporation (mm)
June	33.87	18.09	0	375	34.86	19.56	0	380
July	38.17	22.65	0	409	36.01	20.6	0	392
August	34.2	18.58	0	301	34.21	18.75	0	313
September	33.51	17.37	0	285	31.89	15.83	0	248
October	25.8	10.3	0	158	27.01	10.14	0	176

Sowing dates: June 30, 2016; early 2017, June 10; late 2017, July 11.

2.2. Experiment Design and Treatments

The experiment was carried out as a split-split-plot based on a randomized complete block design with three replications. The experimental treatments included the three planting dates of June 30, 2016 (E1), June 10, 2017 (E2), and July 11, 2017 (E3), hereafter referred to as growth environments, two irrigation regimes (normal – NI; deficit irrigation – DI); two N supplies (0 and 112.5 kg N ha^{-1} in the form of urea, 46% N); six sorghum cultivars (three forage sorghum cultivars, including SF002, SF001, and Pegah, as well as three grain sorghum cultivars, including MGS5, GS24, GS28); and one common corn hybrid of Maxima (the mid-maturity groups, FAO 580).

Land preparation was based on deep plowing in the fall, ciclo tiller (power harrow), and leveling operations in the spring. In each sowing date mentioned above, corn hybrid and sorghum genotypes were used as the sub-sub-plots to be planted under two levels of N (0 and 112.5 kg ha^{-1}; N from urea fertilizer; N = 46%) as the sub-plots and two irrigation regimes (55% and 85% of maximum allowable depletion) as the main plots. Each experimental unit (the sub-sub-plot) included four rows (two border lines and two harvest lines), each 4 m in length, at a between-row spacing of 0.70 m. The distance between two consecutive plants in each row was 0.06 m and 0.08 m for sorghum and corn, respectively. In addition, the distance between the main plots was 2 m^2 in each repetition.

In the first year (2016), chemical weed control was performed at the four-leaf stage using dichlorophenoxyacetic acid (Ariashimi, Iran) herbicide at 2 L/ha^{-1}. In the second year (2017), the herbicides Atrazine and Acetochlor 50%, an Emulsifiable Concentrate (EC) formulation (Ariashimi) were used after the first irrigation at doses of 1.5 kg and 2.5 L/ha^{-1}, respectively. In addition, pest control was accomplished in both study years using Imidacloprid (Ariashimi) at a dose of 700 cc per ha.

2.3. Irrigation Regimes

Irrigation levels were determined based on maximum allowable depletion (MAD) from soil water (ASW). This led to the control irrigation of 55% MAD (NI) and the water-limited stress of 85% MAD (DI). From the start of the experiment until the plants were established, both the NI and DI environments were irrigated at the same time to meet their plant irrigation needs. The irrigation regimes were executed after the six–eight-leaf stage.

Daily weather data from the Najaf-Abad Synoptic Station, FAO-Penman-Monteith equation, and sorghum crop coefficient for the different stages of growth (Allen et

al., 1998) were used to determine the soil moisture depletion, based on the sorghum evapotranspiration during the growing season. The experimental plots were irrigated using the MAD threshold values computed for each irrigation treatment using the following equation (Kiani et al., 2016):

$$\theta_{irrig} = \theta_{fc} - (\theta_{fc} - \theta_{pwp}) \times MAD,$$

where θ_{irrig} (m³/m³) is the threshold of soil water content at the irrigation time for the selected MAD; θ_{fc} and θ_{pwp} represent soil water content at field capacity (m³/m³) and at wilting point (m³/m³), respectively; and MAD is the fraction of total available water (TAW; in this study, 55% and 85%) that can be depleted from the root zone. The irrigation depth was estimated based on the soil water content using the following equation (Kiani et al., 2016):

$$D_{irrig} = (\theta_{fc} - \theta_{avg}) \times Z_e,$$

where D_{irrig} (cm) is the irrigation depth, θ_{avg} is the soil water content in the root zone before irrigation (m³/m³), and Ze is the root depth (cm).

Drip irrigation tapes (16 mm in diameter) containing polyethylene drippers were fixed alongside each planting row at 15 cm from each other. The flow rate at each dripper was set to 1.3 L/hr. The irrigation quota was controlled using a ball valve and a volumetric counter in each experimental plot.

The overall quantities of water consumed in 2016 under the normal and deficit irrigation regimes were 5,670 and 4,588 m³ ha⁻¹, respectively. Those consumed in 2017 amounted to 5,546 and 4,663 m³ ha⁻¹, respectively, under the same regimes in E1 (early 2017) and to 5,126 and 4,117 m³ ha⁻¹, respectively, in E2 (late 2017).

2.4. Nitrogen Levels

The soil field was tested prior to N application in both the experimental years of 2016 and 2017. Soil texture was identified as clay loam and its N content in 2016 was measured at 0.03% total N or 105.3 kg ha⁻¹, while that in 2017 was measured at 0.02% total N or 70.2 kg ha⁻¹ of the 0−30 soil depth (Table 2). Accordingly, two N levels of 0 (N_0) and 112.5 (N_1) kg N ha⁻¹ in the form of urea (46% N) were considered. The latter was applied by drip fertigation at the three stages of two to four leaves, stem elongation, and heading growth. Fertilizers containing phosphorus and potash elements were not used because of the appropriate amounts of these elements in the soil (Table 2).

Table 2 Some physicochemical properties of the 0−30 cm soil depth of the study area.

Year	Soil texture	pH	EC (dSm⁻¹)	P (mg kg⁻¹)	K (mg kg⁻¹)	Total N (%)	Organic carbon (%)
2016	Clay loam	7.7	2.16	48.7	325	0.03	0.54
2017	Clay loam	7.3	1.74	67.5	360	0.02	0.61

2.5. Measurement of Traits

Growth responses of the two sorghum genotypes and one corn hybrid of Maxima to normal and deficit irrigation regimes were assessed under different N supplies and the three planting dates. Flag-leaf samples collected at the flowering stage were used to determine changes in the biochemical and agronomic traits, including maximum leaf area, maximum quantum yield of photosystem II, chlorophyll, carotenoid content, antioxidant enzyme activities (i.e., catalase, ascorbate peroxidase, and peroxidase), and both shoot biomass and grain yield irrigation and N use efficiencies, while those of grain and biological yields were measured at maturity. A detailed description of each measurement is provided below.

2.5.1. Maximum Leaf Area Index

The maximum leaf area index (LAI_{max}), defined as the ratio of maximum leaf area (LA_{max}) to the ground area (GA), and was reported as square meters per square meter (Addai & Alimiyawo, 2015).

$$LAI_{max} = \frac{LA_{max}}{GA}.$$

LAI_{max} at the flowering stage in the first year was measured by selecting four plants from each plot using an electronic leaf area meter (WinArea- UT- 11, Iran). In the second year, the leaf area was measured using a nondestructive method, and the data obtained was multiplied by a coefficient of 0.73, which is the standard coefficient calculated for converting leaf area by multiplying length by width relative to the leaf area measured by an electronic leaf area meter based on 20 different leaves.

2.5.2. Maximum Quantum Yield of Photosystem II, Fv/Fm Ratio

The Fv/Fm ratio represents the maximum quantum yield of photosystem II, which is, in turn, highly correlated with the quantum yield of net photosynthesis. The Fv/Fm ratio is measured in a nonfunctional, dark-adapted state (Sayed, 2003). For this purpose, three youngest and fully expanded topper leaves were chosen from each plot and adapted to the dark for approximately 25 min. Chlorophyll fluorescence was measured between 10:00 a.m. and 12:00 p.m. using a portable fluorescence spectrometer (Opti-Sciences, Hudson, NH, USA).

2.5.3. Chlorophyll and Carotenoid Contents

Leaf chlorophyll (Chl) and carotenoid (Car) contents were measured according to Arnon's (1967) method. Briefly, fresh leaf samples (0.3 g) were cut and extracted in 80% acetone at $-4\,°C$. The extract was centrifuged at $10,000 \times g$ for 5 min. The absorbance of the supernatant was read at 645, 663, and 470 nm using a spectrophotometer (model U-1800; Hitachi, Tokyo, Japan). The Chl and Car concentrations were estimated using the following formulae:

$$Chl\ a\ (\text{mg/g FW}) = [(12.7 \times Abs_{663}) - (2.6 \times Abs_{645})] \times \text{mL acetone/mg},$$

$$Chl\ b\ (\text{mg/g FW}) = [(22.9 \times Abs_{645}) - (4.68 \times Abs_{663})] \times \text{mL acetone/mg},$$

$$Total\ Chl\ (\text{mg/g FW}) = [(20.2 \times Abs_{645}) + (8.02 \times Abs_{663})] \times \text{mL acetone/mg},$$

$$Car\ (\text{mg/g FW}) = [(1,000 \times Abs_{470}) - (1.9 \times Abs_{663}) - (63.14 \times Abs_{645})]/214.$$

2.5.4. Antioxidant Enzyme Activities

The catalase (CAT), ascorbate peroxidase (APX), and peroxidase (POX) activities were determined using an extract prepared according to Bradford (1976) with some modifications. Briefly, fresh leaf samples (0.1 g) were homogenized in 1 mL of 50 mM sodium phosphate buffer (pH = 7) containing 2 mM α-dithiothreitol, 0.2% Triton X-100, 2 mM EDTA, 50 mM Tris-HCl, and 2% polyvinyl pyrrolidone, and mixed for 15 min. The homogenate was then centrifuged at $14,000\ g$ for 30 min at 4 °C, and the supernatants were used for enzyme assays.

Catalase Activity. The CAT activity (μmol H_2O_2 min^{-1} mg^{-1} protein) was assayed in 3 mL of 50 mM sodium phosphate buffer (pH = 7) containing 50 μL of the enzyme extract and 4.51 μL of H_2O_2. Enzyme activity was determined according to Aebi (1983) by measuring the decrease in absorbance for 30 s at 240 nm using a spectrophotometer U-1800 (Hitachi).

Ascorbate Peroxidase Activity. The APX (unit mg protein^{-1} min^{-1}) activity was measured as described by Nakano and Asada (1981) using a reaction mixture containing 3 mL of sodium phosphate buffer (pH 7.0), 4.51 μL of H_2O_2, 100 μL of ascorbate, and 50 μL of the enzyme extract. The H_2O_2-dependent oxidation of ascorbate was followed by a decrease in absorbance at 290 nm with an extinction constant of 2.8.

Peroxidase Activity. The POX activity (unit mg protein^{-1} min^{-1}) was determined as described by Herzog and Fahimi (1973). In a total volume, the reaction mixture in contained 3 mL of sodium phosphate buffer (pH 7.0), 4.51 μL of H_2O_2, 3.35 μL of guaiacol, and 50 μL of the enzyme extract. The increase in absorbance due to guaiacol oxidation was measured at 470 nm.

2.5.5. Biomass Irrigation Water Use Efficiency (IWUEb)

The crop WUE of the biomass produced was calculated as the ratio of dry biomass (DBM) at final harvest to water used (WU) by the crop (Tolk & Howell, 2003):

$$IWUEb = \frac{DBM}{WU}.$$

2.5.6. Grain Yield Irrigation Water Use Efficiency of Grain Yields (IWUEg)

The crop WUE for grain yield (IWUEg) was calculated as the ratio of grain yield (GY) at final harvest to the water used by the crop (Tolk & Howell, 2003):

$$IWUEg = \frac{GY}{WU}.$$

2.5.7. Biomass Nitrogen Fertilizer Use Efficiency (NUEb)

Nitrogen fertilizer use efficiency was defined as the ratio of dry biomass (kg) to N (kg) per m^2 (Frasier et al., 2017):

$$NUEb = \frac{DBM}{NU}.$$

2.5.8. Grain Yield Nitrogen Fertilizer Use Efficiency (NUEg)

Grain yield nitrogen use efficiency was defined and calculated as the ratio of grain yield (kg) to N (kg) used per m^2 (Muchow & Sinclair, 1994):

$$NUEg = \frac{GY}{NU}.$$

2.6. Statistical Studies

Analysis of variance (ANOVA) was performed using the GLM procedure in SAS (version 9.1; Cary, North Carolina, USA). The least significant difference test (LSD) was used to assess the significance of differences in treatment means at the 5% probability level. Furthermore, group comparisons of grain and forage sorghum with corn were performed using the SAS software.

3. Results

3.1. Shoot Biomass and Grain Yields

The values obtained for corn shoot biomass and grain yield were significantly different ($p \leq 0.01$) from those recorded for the same traits in grain and forage sorghum genotypes under normal irrigation treatment (Table 3). The shoot biomass yields recorded for corn, grain, and forage sorghum genotypes declined under deficit irrigation treatment. In addition, the grain yields recorded for corn, grain, and forage sorghum genotypes decreased under deficit irrigation treatment (Table 3).

Table 3 Statistical analysis group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) as well as comparisons of means for shoot biomass and grain yields (kg m^{-2}) under the two irrigation regimes.

Irrigation Regimes	Plant types	Hybrid	Shoot biomass yield (kg m^{-2})				Grain yield (kg m^{-2})			
			2016	E-2017	L-2017	Mean	2016	E-2017	L-2017	Mean
Deficit irrigation (DI)	FS	SF001	1.14	1.30	1.02	1.15	0.37	0.41	0.33	0.37
		SF002	1.02	1.35	1.10	1.15	0.43	0.48	0.38	0.43
		Pegah	2.03	2.14	1.47	1.88	0.42	0.47	0.36	0.42
	GS	MGS5	1.07	1.37	1.11	1.18	0.63	0.68	0.54	0.62
		GS24	1.44	2.14	1.41	1.66	0.65	0.89	0.59	0.71
		GS28	0.90	1.22	1.06	1.06	0.58	0.64	0.50	0.57
	C	Maxima	1.47	1.78	1.08	1.45	1.05	1.20	0.82	1.02
	Mean		1.29	1.61	1.18		0.59	0.68	0.50	
Normal irrigation (NI)	FS	SF001	1.88	1.91	1.71	1.83	0.52	0.55	0.45	0.50
		SF002	1.59	1.86	1.72	1.72	0.57	0.61	0.51	0.56
		Pegah	3.44	3.31	2.83	3.19	0.60	0.66	0.51	0.59
	GS	MGS5	1.71	1.95	1.69	1.77	0.79	0.83	0.71	0.78
		GS24	2.42	3.37	2.60	2.80	0.91	1.17	0.85	0.98
		GS28	1.71	2.23	2.03	1.99	0.85	0.89	0.76	0.84
	C	Maxima	2.89	3.09	2.44	2.81	1.54	1.74	1.27	1.52
	Mean		2.23	2.53	2.14		0.83	0.92	0.72	

Statistical analysis for group comparison:

Trait	C vs. S		C vs. FS		C vs. GS		FS vs. GS		C vs. GS vs FS	
	DI	NI	DI	NI	DI	NI	DI	NI	DI	NI
Shoot biomass yield (kg m^{-2})	*	**		**	**	**	**		**	**
Grain yield (kg m^{-2})	**	**	**	**	**	**	**	**	**	**

Significant at * 0.05, ** 0.01 level; ns – nonsignificant. Environments: 2016 (June 30); E-2017 – early 2017 (June 10); L-2017 – late 2017 (July 11). Irrigation regimes: normal irrigation – 55% of the maximum allowable depletion (MAD); deficit irrigation – 85% MAD. Plant types: C – corn hybrid; FS – forage sorghum; GS – grain sorghum.

Significant differences were observed between the two sorghum genotypes in terms of shoot biomass and grain yield under normal and deficit irrigation regimes. Among the grain sorghum genotypes, SG24 had the highest values for shoot biomass and grain yield under both irrigation regimes (Table 3). Among the forage sorghum genotypes, Pegah recorded the highest values for shoot biomass under both irrigation regimes, while it recorded a reduction of 41% in this trait. Finally, both Pegah and SF002 recorded the highest grain yield values under the normal and deficit irrigation regimes, respectively (Table 3).

Under both nitrogen fertilizer treatments, grain and forage sorghum genotypes showed significant differences ($p \leq 0.01$) in the shoot biomass and grain yield values relative to those for the same traits in corn (Table 4). The shoot biomass and grain yields of corn as well as grain and forage sorghum genotypes decreased under the no-fertilizer treatment (Table 4).

Under N supply, corn shoot biomass and grain yield were significantly ($p \leq 0.01$) higher by 20% and 65%, respectively, than the values recorded for grain sorghum genotypes and by 14% and 154%, respectively, for forage genotypes (Table 4).

Significant differences ($p \leq 0.01$) in grain yield were also detected between the two sorghum genotypes under the N fertilizer and no-fertilizer treatments (Table 4).

Table 4 Statistical analysis for group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) as well as comparisons of means for shoot biomass and grain yields (kg m^{-2}) under the two nitrogen fertilizer levels.

Nitrogen levels (kg m^{-2})	Plant types	Plant types	Shoot biomass yield (kg m^{-2})				Grain yield (kg m^{-2})			
			2016	E-2017	L-2017	Mean	2016	E-2017	L-2017	Mean
0 (N$_0$)	FS	SF001	1.26	1.36	1.20	1.28	0.40	0.43	0.36	0.39
		SF002	1.1	1.36	1.24	1.23	0.44	0.48	0.40	0.44
		Pegah	2.38	2.35	1.91	2.21	0.47	0.51	0.40	0.46
	GS	MGS5	1.16	1.38	1.23	1.26	0.64	0.68	0.57	0.63
		GS24	1.67	2.42	1.79	1.96	0.71	0.94	0.67	0.77
		GS28	1.15	1.51	1.39	1.35	0.67	0.71	0.59	0.66
	C	Maxima	1.94	2.12	1.56	1.87	1.21	1.38	0.99	1.20
	Mean		1.52	1.79	1.47		0.65	0.73	0.57	
112.5 (N$_1$)	FS	SF001	1.76	1.84	1.53	1.71	0.49	0.53	0.42	0.48
		SF002	1.51	1.85	1.58	1.64	0.55	0.61	0.49	0.55
		Pegah	3.09	3.10	2.39	2.86	0.55	0.62	0.47	0.55
	GS	MGS5	1.62	1.94	1.57	1.71	0.78	0.84	0.68	0.77
		GS24	2.19	3.09	2.22	2.50	0.85	1.12	0.77	0.91
		GS28	1.47	1.93	1.70	1.70	0.76	0.81	0.67	0.75
	C	Maxima	2.42	2.77	1.96	2.38	1.38	1.56	1.08	1.34
	Mean		2.01	2.36	1.85		0.77	0.87	0.65	

Statistical analysis for group comparison:

Trait	C vs. S		C vs. FS		C vs. GS		FS vs. GS		C vs. GS vs. FS	
	N$_0$	N$_1$	N$_0$	N$_1$	N$_0$	N$_1$	N$_0$	N$_1$	N$_0$	N$_1$
Shoot biomass yield (kg m^{-2})	**	**	**	**	**	**		*	**	**
Grain yield (kg m^{-2})	**	**	**	**	**	**	**	**	**	**

Significant at * 0.05 and ** 0.01 level; ns – nonsignificant. Environments: 2016 (June 30); E-2017 – early 2017 (June 10); L-2017 – late 2017 (July 11). Nitrogen levels: N$_0$ – 0 N ha^{-1}; N$_1$ – 112.5 kg N ha^{-1}. Plant types: C – corn hybrid; FS – forage sorghum; GS – grain sorghum.

3.2. Maximum Leaf Area Index and Fv/Fm Ratio

Significant ($p \leq 0.01$) differences were observed under the normal irrigation regime between the LAI$_{max}$ and Fv/Fm ratios in corn and the values of these traits in grain sorghum genotypes. In deficit irrigation, the differences in these traits between corn and forage sorghum genotypes were significant at the 1% level (Table 5, Table 6).

Under normal irrigation, corn recorded a significantly ($p \leq 0.01$) higher LAI$_{max}$ value than the values (by 14% and 9%, respectively) measured in grain and forage sorghum genotypes (Table 5, Table 6). The two sorghum genotypes tested exhibited significant differences between their values for LAI$_{max}$ and Fv/Fm ratio under normal and deficit irrigation (Table 5, Table 6).

The LAI$_{max}$ and Fv/Fm ratio values recorded for corn were significantly different at the 1% level from the values recorded for grain sorghum genotypes under the two N fertilizer treatments (Table 7, Table 8). The no-fertilizer treatment led to reductions of approximately 17% and 9% in LAI$_{max}$ and Fv/Fm ratio, respectively, in corn, 21% and 10% in grain sorghum, and 22% and 11% in forage sorghum (Table 7, Table 8).

A significant difference ($p \leq 0.01$) was observed between the two sorghum genotypes with respect to LAI$_{max}$ under the two N treatments (Table 7, Table 8). Among the forage and grain sorghum genotypes, SF001 and MGS5 had the highest Fv/Fm ratios under both N treatments and were the most sensitive genotypes, with reductions of 12% and 11%, respectively, in this trait (Table 7, Table 8).

3.3. Photosynthetic Pigments

The Chl *a*, Chl *b*, and Car contents in corn under the deficit irrigation regime exhibited significant ($p \leq 0.01$) differences from the values obtained for these traits in grain sorghum genotypes (Table 5, Table 6). Deficit irrigation reduced the Chl *a*

Table 5 Statistical analysis for group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) as well as comparisons of means for the different traits measured under normal irrigation at 55% of maximum allowable depletion.

Traits	Units	Corn (C)	Forage sorghum (FS)			Grain sorghum (GS)			C vs. S	C vs. GS vs. FS	FS vs. GS	C vs. FS	C vs. GS
			FS1 SF002	FS2 SF001	FS3 Pegah	GS1 MGS5	GS2 28	GS3 24					
LAI		5.37†	4.41	4.46	5.84	4.13	4.63	5.33	**	**	*	**	**
Fv/Fm		0.70	0.70	0.72	0.69	0.72	0.71	0.72		**	**		**
Chl a	mg g^{-1} FW	0.66	0.72	0.74	0.58	0.71	0.67	0.69					
Chl b	mg g^{-1} FW	0.27	0.30	0.32	0.25	0.31	0.29	0.29	*				*
Total Chl	mg g^{-1} FW	0.93	1.02	1.06	0.83	1.03	0.96	0.98					
Chl a/b		2.58	2.44	2.33	2.41	2.35	2.39	2.43					
Car	mg g^{-1} FW	0.27	0.27	0.29	0.24	0.33	0.25	0.27		*	*		
CAT	μmol H_2O_2 min^{-1} mg protein	0.55	0.66	0.62	0.54	0.60	0.54	0.60				*	
POX	μmol H_2O_2 min^{-1} mg protein	1.02	1.05	1.10	1.10	1.20	0.97	1.06					
APX	μmol H_2O_2 min^{-1} mg protein	0.33	0.39	0.35	0.29	0.37	0.35	0.35					
IWUEb	kg m^{-3}	5.14	3.18	3.37	5.85	3.28	3.66	5.14	**	**		**	**
IWUEg	kg m^{-3}	2.77	1.03	0.93	1.08	1.42	1.53	1.80	**	**	**	**	**
NUEb		233.73	143.89	151.45	263.9	147.84	169.26	237.25	**	**	**	**	**
NUEg		131.49	47.51	42.65	50.18	65.57	71.55	84.44	**	**	**	**	**

Significant at * 0.05 and ** 0.01 level; ns – nonsignificant. LAI – leaf area index; Fv/Fm – maximal fluorescence value/variable fluorescence; Chl a – chlorophyll a content; Chl b – chlorophyll b content; Car – carotenoids content; CAT – catalase specific activity; POX – peroxidase specific activity; APX – ascorbate peroxidase specific activity; IWUEb – irrigation water use efficiency of biomass; IWUEg – irrigation water use efficiency of grain yields; NUEb – nitrogen fertilizer use efficiency of biomass; NUEg – nitrogen fertilizer use efficiency of grain yields.

† Each table presents average values of nine data involving three replicates in each planting environment including 2016 (June 30), early 2017 (June 10), and late 2017 (July 11).

Table 6 Statistical analysis for group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) as well as comparisons of means for the different traits measured under the deficit irrigation at 85% of maximum allowable depletion.

Traits	Units	Corn (C)	Forage sorghum (FS)			Grain sorghum (GS)			C vs. S	C vs. GS vs. FS	FS vs. GS	C vs. FS	C vs. GS
			FS1 SF002	FS2 SF001	FS3 Pegah	GS1 MGS5	GS2 28	GS3 24					
LAI		$3.09^†$	3.38	3.19	3.85	3.11	2.85	3.35	*	**	**	**	
Fv/Fm		0.575	0.63	0.64	0.58	0.65	0.59	0.62	**	**		**	**
Chl a	mg g^{-1} FW	0.389	0.52	0.55	0.37	0.53	0.42	0.46	**	**		**	**
Chl b	mg g^{-1} FW	0.144	0.21	0.23	0.15	0.21	0.16	0.18	**	**		**	**
Total Chl	mg g^{-1} FW	0.534	0.73	0.77	0.52	0.74	0.59	0.64	**	**		**	**
Chl a/b		2.795	2.51	2.48	2.61	2.54	2.61	2.58	*			*	
Car	mg g^{-1} FW	0.282	0.3	0.32	0.25	0.36	0.27	0.28	*	**	*	**	**
CAT	µmol H$_2$O$_2$ min^{-1} mg protein	2.26	3.07	2.77	2.31	2.74	2.15	2.53	**	**	**	**	**
POX	µmol H$_2$O$_2$ min^{-1} mg protein	3.018	3.18	3.38	3.28	3.73	2.84	3.23	**	*		**	*
APX	µmol H$_2$O$_2$ min^{-1} mg protein	0.682	0.86	0.8	0.63	0.89	0.75	0.74	**	**		**	**
IWUEb	kg m^{-3}	3.221	2.59	2.58	4.2	2.66	2.39	3.71	*	**	**		**
IWUEg	kg m^{-3}	2.278	0.96	0.83	0.94	1.38	1.28	1.59	**	**	**	**	**
NUEb		125.73	100.3	98.98	161.19	101.94	93.71	145.93	*	**	*	**	**
NUEg		89.24	37.22	32.09	36.44	53.35	50.15	62.35	**	**	**	**	**

Significant at * 0.05 and ** 0.01 level; ns – nonsignificant. LAI – leaf area index; Fv/Fm – maximal fluorescence value/variable fluorescence; Chl a – chlorophyll a content; Chl b – chlorophyll b content; Car – carotenoids content; CAT – catalase specific activity; POX – peroxidase specific activity; APX – ascorbate peroxidase specific activity; IWUEb – irrigation water use efficiency of biomass; IWUEg – irrigation water use efficiency of grain yields; NUEb – nitrogen fertilizer use efficiency of biomass; NUEg – nitrogen fertilizer use efficiency of grain yields.

† Each table presents average values of nine data involving three replicates in each planting environment including 2016 (June 30), early 2017 (June 10), and late 2017 (July 11).

Table 7 Statistical analysis for group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) and comparisons of means for the different traits measured under the nitrogen treatment applied at 112.5 kg ha^{-1}.

Traits	Units	Corn (C)	Forage sorghum (FS)			Grain sorghum (GS)			C vs. S	C vs. GS vs. FS	FS vs. GS	C vs. FS	C vs. GS
			FS1 SF002	FS2 SF001	FS3 Pegah	GS1 MGS5	GS2 28	GS3 24					
LAI		4.64†	4.42	4.35	5.38	4.15	4.09	4.84		**	**		**
Fv/Fm		0.67	0.71	0.72	0.66	0.73	0.68	0.71	**	**		**	**
Chl a	mg g^{-1} FW	0.57	0.69	0.73	0.52	0.70	0.60	0.64	**	**		**	**
Chl b	mg g^{-1} FW	0.23	0.29	0.31	0.22	0.30	0.25	0.27	**	**		**	**
Total Chl	mg g^{-1} FW	0.80	0.98	1.04	0.75	1.01	0.85	0.90	**	**		**	**
Chl a/b		2.55	2.43	2.36	2.45	2.38	2.47	2.43					
Car	mg g^{-1} FW	0.28	0.30	0.33	0.26	0.37	0.27	0.29	*	**	*	**	**
CAT	µmol H$_2$O$_2$ min^{-1} mg protein	1.46	1.98	1.79	1.49	1.76	1.40	1.64	**	**	**	**	*
POX	µmol H$_2$O$_2$ min^{-1} mg protein	2.09	2.23	2.36	2.30	2.60	1.97	2.22	**	**		**	*
APX	µmol H$_2$O$_2$ min^{-1} mg protein	0.52	0.68	0.62	0.49	0.68	0.58	0.58	**	**		**	**
IWUEb	kg m^{-3}	4.66	3.28	3.39	5.64	3.41	3.36	4.94	**	**	*	**	**
IWUEg	kg m^{-3}	2.67	1.10	0.96	1.09	1.54	1.49	1.83	**	**	**	**	**
NUEb		123.03	85.58	88.44	147.57	88.92	88.67	130.3	**	**	*	**	**
NUEg		69.35	28.53	24.89	28.3	39.65	38.74	47.61	**	**	**	**	**

Significant at * 0.05 and ** 0.01 level; ns – nonsignificant. LAI – leaf area index; Fv/Fm – maximal fluorescence value/variable fluorescence; Chl a – chlorophyll a content; Chl b – chlorophyll b content; Car – carotenoids content; CAT – catalase specific activity; POX – peroxidase specific activity; APX – ascorbate peroxidase specific activity; IWUEb – irrigation water use efficiency of biomass; IWUEg – irrigation water use efficiency of grain yields; NUEb – nitrogen fertilizer use efficiency of biomass; NUEg – nitrogen fertilizer use efficiency of grain yields.

† Each table presents average values of nine data involving three replicates in each planting environment including 2016 (June 30), early 2017 (June 10), and late 2017 (July 11).

Table 8 Statistical analysis for group comparisons (among the corn, grain sorghum, and forage sorghum genotypes studied) and comparisons of means for the different traits measured under the no-nitrogen treatment.

Traits	Units	Corn (C)	Forage sorghum (FS)			Grain sorghum (GS)			C vs. S	C vs. GS vs. FS	FS vs. GS	C vs. FS	C vs. GS
			FS1 SF002	FS2 SF001	FS3 Pegah	GS1 MGS5	GS2 28	GS3 24					
LAI		3.82†	3.37	3.29	4.31	3.10	3.39	3.84	**	**	**		**
Fv/Fm		0.61	0.62	0.63	0.60	0.64	0.62	0.64	*	**	*		**
Chl a	mg g^{-1} FW	0.48	0.55	0.56	0.43	0.54	0.50	0.52	*	*		*	*
Chl b	mg g^{-1} FW	0.18	0.22	0.23	0.17	0.22	0.20	0.20	*	*		*	*
Total Chl	mg g^{-1} FW	0.66	0.77	0.79	0.60	0.76	0.70	0.72	**	*		*	**
Chl a/b		2.83	2.52	2.45	2.57	2.51	2.53	2.58	*			*	*
Car	mg g^{-1} FW	0.26	0.26	0.29	0.23	0.32	0.25	0.26		**	**		
CAT	μmol H$_2$O$_2$ min^{-1} mg protein	1.35	1.76	1.60	1.36	1.57	1.29	1.49	**	**	**	**	
POX	μmol H$_2$O$_2$ min^{-1} mg protein	1.95	2.00	2.12	2.08	2.33	1.83	2.06					
APX	μmol H$_2$O$_2$ min^{-1} mg protein	0.48	0.58	0.54	0.43	0.58	0.52	0.51	*	*			**
IWUEb	kg m^{-3}	3.71	2.49	2.56	4.40	2.53	2.69	3.91	**	**		**	**
IWUEg	kg m^{-3}	2.39	0.89	0.79	0.92	1.27	1.31	1.56	**	**	**	**	**
NUEb		236.44	158.62	161.98	277.57	160.86	174.31	252.88	**	**		**	**
NUEg		151.38	56.20	49.84	58.32	79.27	82.96	99.18	**	**	**	**	**

Significant at * 0.05 and ** 0.01 level; ns – nonsignificant. LAI – leaf area index; Fv/Fm – maximal fluorescence value/variable fluorescence; Chl a – chlorophyll a content; Chl b – chlorophyll b content; Car – carotenoids content; CAT – catalase specific activity; POX – peroxidase specific activity; APX – ascorbate peroxidase specific activity; IWUEb – irrigation water use efficiency of biomass; IWUEg – irrigation water use efficiency of grain yields; NUEb – nitrogen fertilizer use efficiency of biomass; NUEg – nitrogen fertilizer use efficiency of grain yields.
† Each table presents average values of nine data involving three replicates in each planting environment including 2016 (June 30), early 2017 (June 10), and late 2017 (July 11).

and Chl *b* contents by approximately 41% and 45% in corn, 32% and 37% in grain sorghum, and 29% and 32% in forage sorghum, respectively. However, the Car content increased by 6%, 7%, and 9% in corn, grain, and forage sorghum genotypes, respectively, due to water shortage (Table 5, Table 6).

Significant differences were detected between the two sorghum genotypes with respect to their Chl *a*, Chl *b*, and Car contents under both normal and deficit irrigation regimes (Table 5, Table 6).

Corn recorded Chl *a* and Chl *b* values that were significantly ($p \leq 0.01$) higher than the values recorded for grain and forage sorghum genotypes under the N fertilizer treatment. Corn under the N supply treatment also attained a Car content significantly ($p \leq 0.01$) higher than the values obtained for grain sorghum genotypes (Table 7, Table 8). In contrast, the no N fertilizer treatment led to reductions of approximately 15%, 20%, and 7% in Chl *a*, Chl *b*, and Car contents in corn, reductions of approximately 19%, 23%, and 11% in grain sorghum, and reductions of 20%, 24%, and 12% in forage sorghum, respectively (Table 7, Table 8). Significant differences in the Chl *a*, Chl *b*, and Car contents were observed between the two sorghum genotypes under both fertilizer treatments (Table 7, Table 8).

3.4. Antioxidant Enzyme Activity

The CAT, APX, and POX enzymes in corn exhibited significantly ($p \leq 0.01$) improved activities under the deficit irrigation regime when compared with the values obtained for these traits in the grain and forage sorghum genotypes (Table 5, Table 6).

Comparisons of the genotypes revealed that the CAT, POX, and APX activities in corn under the deficit irrigation regime were significantly ($p \leq 0.01$) lower than the values measured in grain sorghum genotypes and those measured in forage sorghum genotypes (Table 5, Table 6).

The two sorghum genotypes exhibited significant ($p \leq 0.01$) differences in their antioxidant enzyme activities compared to the corn plant under deficit irrigation regimes (Table 6). Under the N fertilizer treatment, corn exhibited CAT, APX, and POX activities that were significantly different at the 1% level compared to those recorded by the grain and forage sorghum genotypes (Table 5, Table 6). Under the no N fertilizer treatment, these same traits declined in corn, grain sorghum, and forage sorghum (Table 7, Table 8).

The CAT, POX, and APX activities in corn under the N supply treatment were significantly ($p \leq 0.01$) lower by 8%, 7%, and 14%, respectively, compared to the values recorded for these activities in grain sorghum genotypes and by 16%, 8%, and 11%, respectively, in forage sorghum genotypes. Moreover, under the no N fertilizer treatment, the CAT, POX, and APX activities in corn were significantly ($p \leq 0.01$) lower than those of the grain sorghum genotypes and forage sorghum genotypes (Table 7, Table 8). Under N supply treatment, the grain and forage sorghum genotypes showed significant differences in their antioxidant enzyme activities compared to the corn plant (Table 7, Table 8).

3.5. Biomass Irrigation and Grain Yield Irrigation Water Use Efficiency

Under the normal irrigation regime, corn recorded IWUEb and IWUEg values significantly ($p \leq 0.01$) different from the values of grain and forage sorghum genotypes recorded for these traits. Under the deficit irrigation regime, the values of IWUEb and IWUEg recorded by corn were significantly different at the 1% level from the values recorded by grain sorghum genotypes for these traits (Table 5, Table 6). The IWUEb of corn, grain, and forage sorghum genotypes decreased by 37%, 27%, and 24%, respectively, due to the deficit irrigation regime (Table 5, Table 6).

Under the normal irrigation regime, both IWUEb and IWUEg values measured in corn were significantly ($p \leq 0.01$) higher than the values measured for both grain genotypes and forage genotypes (Table 5, Table 6). Corn recorded only IWUEg values significantly higher than those measured for grain and forage sorghum genotypes (Table 5, Table 6).

Significant differences ($p \leq 0.01$) were observed between the two sorghum genotypes with respect to their IWUEb and IWUEg values under both irrigation treatments (Table 5, Table 6). The values of IWUEb and IWUEg measured in grain and forage sorghum genotypes were significantly different at the 1% level from those of corn under both nitrogen fertilizer treatments (Table 7, Table 8). Deficit N led to reductions of 20% and 10%, respectively, in IWUEb and IWUEg values in corn, 22% and 14% in grain sorghum, and 23% and 17% in forage sorghum (Table 7, Table 8).

Under the N supply treatment, corn recorded significantly ($p \leq 0.01$) higher values of IWUEb and IWUEg than the values measured in grain genotypes as well as those in forage genotypes (Table 5, Table 6). Under the no-fertilizer treatment, the values for these traits were significantly higher in corn than the values measured in grain genotypes, as well as in forage genotypes (Table 7, Table 8). Significant differences were also observed between the two sorghum genotypes with respect to their IWUEb and IWUEg records under both N treatments (Table 7, Table 8).

3.6. Biomass Nitrogen Fertilizer and Grain Yield Nitrogen Fertilizer Use Efficiency

Corn exhibited significant ($p \leq 0.01$) differences in grain and forage sorghum genotypes with respect to the values they recorded for NUEb and NUEg under normal irrigation treatment. Under the deficit irrigation regime, the NUEb and NUEg in corn were significantly different at the 1% level from the values obtained for these traits in grain sorghum genotypes (Table 5, Table 6).

Under the normal irrigation regime, corn recorded significantly ($p \leq 0.01$) higher values of NUEb and NUEg than those recorded for grain genotypes as well as those recorded for forage genotypes (Table 5, Table 6). Under the deficit irrigation regime, however, only corn recorded significantly ($p \leq 0.01$) higher values of NUEg than those measured in grain and forage sorghum genotypes (Table 5, Table 6).

The two sorghum genotypes exhibited significant differences in their values of NUEb and NUEg under both irrigation treatments (Table 5, Table 6). The NUEb and NUEg values recorded for corn were significantly different at the 1% level compared to those recorded for grain and forage sorghum genotypes under both N fertilizer treatments (Table 5, Table 6). Deficit N increased the NUEb and NUEg by approximately 92% and 118%, respectively, in corn, by 90% and 107% in grain sorghum, and by 86% and 101% in forage sorghum (Table 5, Table 6).

Under N supply, corn recorded significantly ($p \leq 0.01$) higher NUEb and NUEg values than those recorded by grain genotypes and then those recorded for forage genotypes (Table 7, Table 8). Significant differences ($p \leq 0.01$) were established between the two sorghum genotypes in terms of their NUEg values under both N treatments (Table 7, Table 8).

3.7. Interaction Effects of the Irrigation Regimes and Nitrogen Application Levels

The interaction effects of the two irrigation regimes and the two N levels applied were significant ($p < 0.01$) for the studied traits, except for the Chl a/Chl b ratio (Table 9). Application of N under the normal and deficit irrigation regimes was observed to increase the biological yields by 38% and 17%, grain yields by 22% and 12%, LAI_{max} levels by 34% and 17%, Fv/Fm ratios by 15% and 8%, Chl a content by 30% and 17%, Chl b content by 38% and 19%, Car content by 18% and 8%, IWUEb values by 38% and 17%, and IWUEg values by 27% and 12%, respectively. However, it decreased the NUEb values by 44% and 52% and NUEg values by 50% and 54%, respectively, under the same conditions (Table 9). Nitrogen applied only under the deficit irrigation regime led to increased CAT, POX, and APX activities by 10%, 10%, and 13%, respectively (Table 9).

4. Discussion

Increasing productivity in cropping systems by selecting the right crop in terms of water use is a major challenge, mainly in water-scarce areas. Under water-limited conditions, there is always hesitation among forage producers regarding the selection of corn, grain, or forage sorghum in order to produce the maximum quality forage for livestock units. Therefore, in the present study, corn, grain

Table 9 Interaction effects of two irrigation regimes and two nitrogen levels on some of the measured traits.

| Treatments		Dry shoot biomass	Grain yield	LAI	Fv/Fm	Chl a	Chl b	Total Chl	Car	CAT	POX	APX	IWUEb	IWUEg	NUEb	NUEg
Irrigation[1]	Nitrogen[2]	kg m^{-2}				mg g^{-1} FW				μmol H$_2$O$_2$ min^{-1} mg protein						
55% MDA	N$_0$	1.94b*	0.74b	4.18b	0.66b	0.59b	0.24b	0.84b	5.53c	0.55c	1.03c	0.32c	3.56b	1.36b	246.38a	94.18a
	N$_1$	2.67a	0.90a	5.59a	0.76a	0.77a	0.34a	1.11a	6.53ab	0.62c	1.11c	0.37c	4.90a	1.66a	138.57c	46.78c
85% MDA	N$_0$	1.25d	0.56d	3.00d	0.59d	0.43d	0.17d	0.59d	6.25b	2.43b	3.08b	0.72b	2.81d	1.25c	160.09b	70.72b
	N$_1$	1.47c	0.62c	3.53c	0.63c	0.50c	0.20c	0.70c	6.75a	2.67a	3.39a	0.81a	3.29c	1.40b	76.42d	32.38d
LSD 5%		0.08	0.02	0.17	0.01	0.04	0.02	0.06	0.37	0.16	0.09	0.05	0.16	0.04	8.99	1.62

* Mean separation by LSD test. Means within each column followed by the same letter are not significantly different at $p = 0.05$. [1] Irrigation regimes: normal irrigation (55% of the maximum allowable depletion − MAD); and deficit irrigation (85% MAD). [2] Nitrogen levels: N$_0$ – 0 N ha^{-1}; N$_1$ – 112.5 kg N ha^{-1}. LAI – leaf area index; Fv/Fm – maximal fluorescence value/variable fluorescence; Chl a – chlorophyll a content; Chl b – chlorophyll b content; Car – carotenoids content; CAT – catalase specific activity; POX – peroxidase specific activity; APX – ascorbate peroxidase specific activity; IWUEb – irrigation water use efficiency of biomass; IWUEg – irrigation water use efficiency of grain yields; NUEb – nitrogen fertilizer use efficiency of biomass; NUEg – nitrogen fertilizer use efficiency of grain yields.

sorghum, and forage sorghum cultivation systems were compared under two different irrigation regimes and N supply conditions. Considerable variation was observed in forage yield among the sorghum genotypes (Table 3). Other studies have also observed considerable genetic variation among sorghum genotypes under different stress conditions (Kapanigowda et al., 2013; Mutava et al., 2011). Pegah and GS24 from the forage and grain sorghum genotypes exhibited higher potential for dry matter production (Table 3, Table 4). Due to the negative consequences of water-limited stress (Cakir, 2004; Farré & Faci, 2006; Liu et al., 2013), the grain and biomass yields of the corn hybrids were lower than those of the sorghum genotypes (Table 3). These results have been confirmed by other researchers (Farré & Faci, 2006; Muchow, 1989). Moreover, SG28 exhibited the highest reductions in shoot biomass and grain yield; therefore, it was identified as the genotype that was the most sensitive to water scarcity (Table 3). Among forage sorghum genotypes, Pegah recorded the highest values for shoot biomass under both irrigation regimes, while it was identified as the one most sensitive to water shortage. In addition, the early June planting dates of these crops were superior to those of late July (Table 3, Table 4). However, the higher potential sorghum genotypes recorded total dry biomass (shoot biomass and grain yield) values that were similar to those of corn under both normal and deficit irrigation regimes (Table 3 and Figure 1). While the grain share of the total biomass in the corn hybrid, GS24 and Pegah were 35%, 26%, and 16%, respectively, under the normal irrigation regime (Figure 1A), this was 41%, 30%, and 18%, respectively, under the deficit irrigation regime (Figure 1B). Therefore, it may be claimed that, despite identical production rates, the corn forage due to the higher grain percentage will be of higher quality than that of sorghum, even under deficit irrigation regimes (Figure 1B). Due to the high digestibility of grains, a high grain yield is important because of the superior nutritive value of the forage produced (Millner et al., 2005). This is the reason why grain hybrids with the highest grain yields are selected in North America for corn silage production (Vattikonda & Hunter, 1983).

Water use efficiency for grain production is an important physiological trait that indicates the ability of plants to resist and survive water shortage conditions. This trait is affected by factors such as climate, soil conditions, and plant-related parameters (Asseng et al., 2001). In the current study, the drip irrigation system was used to apply 5,500 and 4,400 m^3 ha^{-1} of water under two normal and deficit irrigation treatments, respectively. Some researchers have reported that water use efficiency increases due to water scarcity stress (Pandey et al., 2000; Seghatoleslami et al., 2008), while others have shown that water stress could decrease it because of the decline in the net photosynthetic rate, Fv/Fm ratio, stomatal conductance, leaf area, and dry biomass yield (Cechin, 1998; Munamava & Riddoch, 2001; Rahman et al., 2004). Regarding the fixed values of irrigation and N fertilizer applied in this study, the genotypes with higher biomass and grain yields showed higher values of IWUE and NUE for both grain and biomass segments (Table 5, Table 6).

Despite the fact that WUE in corn was higher than the values recorded for grain and forage sorghum genotypes (Table 5, Table 6), Pegah, characterized by a high yield potential, recorded higher values for IWUEb and NUEb in comparison to those of corn under the normal irrigation regime. In contrast, these traits in the GS24 of high yield potential did not record values significantly different from those of corn (Table 5). Under the deficit irrigation regime, the IWUEb and NUEb values in Pegah and GS24 were higher than those in the corn hybrid (Table 6). However, IWUEg and NUEg in corn were significantly higher under both irrigation regimes, in comparison to those recorded for even the high-yield potential genotypes of grain and forage sorghum (Table 5, Table 6). Similarly, a lower WUE in maize, as compared to sorghum, has been reported by Amaducci et al. (2016), although the values of this attribute could also be affected by some irrigation treatments due to water-limited stress at the critical growth stages (Tolk & Howell, 2003).

Under water scarcity, the amount of N fertilizer used is another concern for crop production systems, with both economic and environmental consequences. In the present study, the shoot biomass and grain yields of different crops were observed to increase because of N application; however, the effect of this increase was
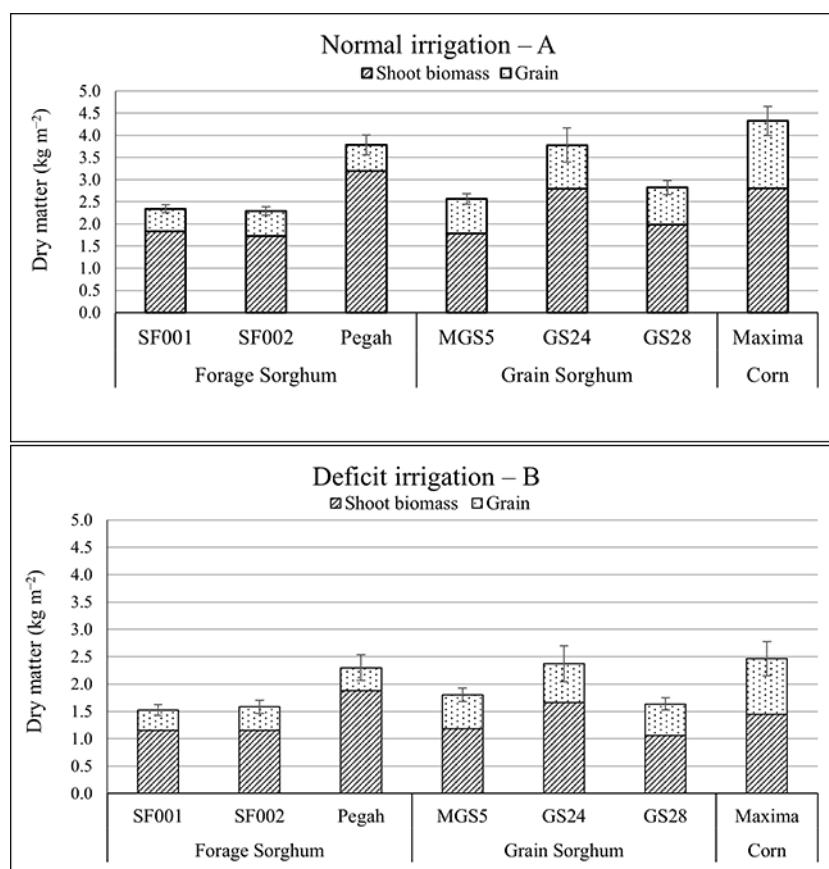
Figure 1 Effects of normal (**A**) and deficit irrigation (**B**) regimes on shoot biomass and grain yields in corn as well as grain and forage sorghum genotypes. Error bars are related to the amount of total dry matter yield (grain + shoot biomass).

more obvious in the forage sorghum genotypes (Table 4). This increase could be logically acceptable because of the main macronutrient effects of N on the structural and functional mechanisms of plants (Di Paolo & Rinaldi, 2008; Sawargaonkar et al., 2013; Zhao et al., 2005). Compared to the corn hybrid, Pegah and GS24 recorded higher shoot biomass yields in both the absence and presence of N fertilizer (Table 4). However, corn exhibited absolute superiority in terms of grain yield. Under both N fertilizer treatments, the corn grain yields were 2.5 and 1.5 times more than those of Pegah and GS24, respectively (Table 4). The total biomass of the corn hybrid was greater than that recorded for Pegah and GS24 under the two N treatments (Figure 2). However, the grain to total biomass ratios of 39%, 28%, and 17% were measured for the corn hybrid, GS24, and Pegah, respectively, under no N treatment (Figure 2A). These ratios were changed to 36%, 27%, and 16% when N was applied at 112.5 kg ha^{-1} (Figure 2B). Therefore, regardless of the amount of yield, due to the share of grain, the quality of the corn forage was higher in both N treatments.

The identification of effective physiological characteristics in different cropping systems of field crops could has a significant impact on improving production. Among the studied physiological traits, LAI$_{max}$ played a major role in increasing the dry matter produced under the normal irrigation regime (Table 5). Leaf area development is a critical index of photosynthetic activity as it plays a pivotal role in producing biomass and increasing grain yield (Rajcan & Tollenaar, 1999). In addition, the ability of a plant to maintain a larger leaf area and to grow under prolonged stress during their vegetative stage, defined as stress tolerance, in comparison to those with greater leaf areas, would obviously produce greater yields (Farooq et al., 2009; Farré & Faci, 2006). However, it was observed that LAI$_{max}$ values in corn, as well as grain and forage sorghum genotypes, decreased due to deficit irrigation. Overall, no significant differences in photosynthetic pigments
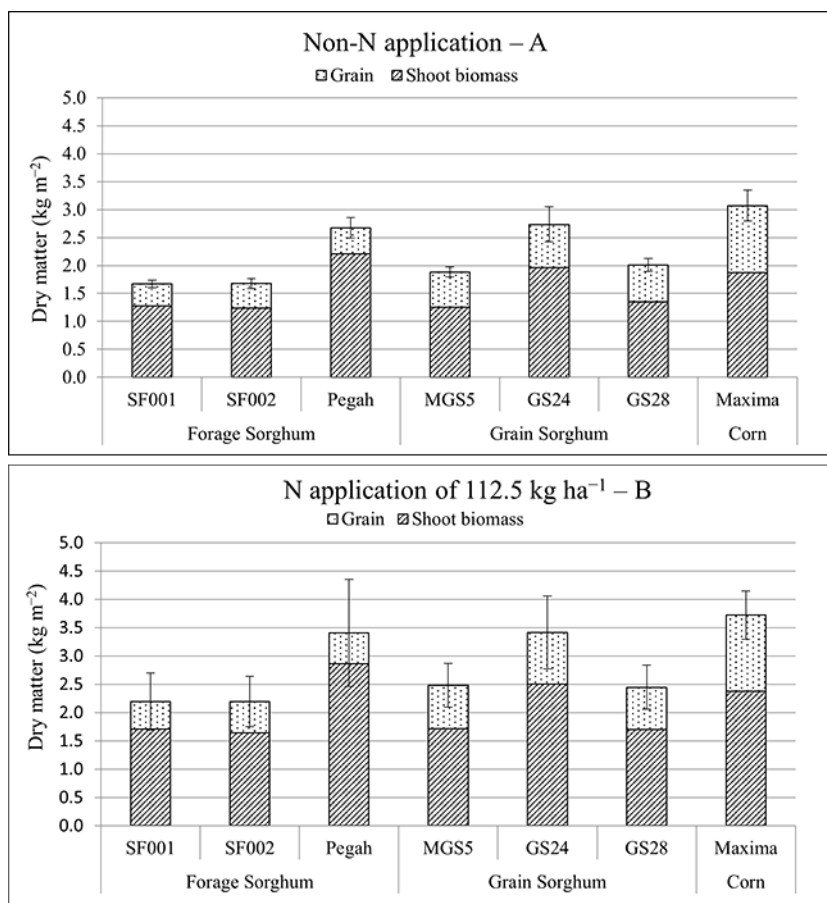
Figure 2 Effects of no-nitrogen treatment (**A**) and nitrogen application (**B**) on shoot biomass and grain yields in corn as well as grain and forage sorghum genotypes. Error bars are related to the amount of total dry matter yield (grain + shoot biomass).

and antioxidant defense systems were observed in the present study among maize, grain sorghum, and forage sorghum genotypes under the normal irrigation regime (Table 5).

Under the deficit irrigation regime, however, the higher Chl a/Chl b ratios and the lower antioxidant enzyme activities in corn hybrid, GS24, and Pegah were possibly due to their high yields (Table 6). Reportedly, the Chl a/Chl b ratio is positively correlated with the ratio of the photosystem II centers to the light-harvesting Chl a protein complex (Terashima & Hikosaka, 1995). In this regard, Devnarain et al. (2016) stated that the ability of a plant to maintain both Chl and Car levels during water-limited stress and moderate re-watering may indicate that the photosynthetic apparatus of the sorghum landraces is not functionally damaged as a result of the imposed water deficits. In their experiment, Devnarain et al. (2016) recorded significantly higher Chl and Car contents in two sorghum landraces subjected to severe stress.

Except for the Chl a/Chl b ratio, all other physiological traits studied were observed to improve as a result of applying N fertilizer. Nitrogen application (112.5 kg vs. 0 kg ha^{-1}) led to the enhancement of the LAI$_{max}$, Fv/Fm ratio, Chl a, Chl b, and Car concentrations, and the activities of CAT, POX, and APX. However, it decreased the Chl a/Chl b ratios in the above genotypes (Table 7). Zhao et al. (2005) found significantly reduced LA and leaf chlorophyll content in sorghum as a result of N deficiency. Huang et al. (2004) also reported that the activities of the three key antioxidant enzymes (i.e., CAT, POD, and SOD) exhibited a decreasing trend as N deficiency progressed. The corn hybrid, Pegah, and GS24 in the present study

showed higher values of LAI_{max} and Chl a/Chl b ratio under the no N treatment, but only higher values of LAI_{max} under the N application treatment were found (Table 7, Table 8).

The positive effects of N fertilizer on plants assumed a declining trend due to water deprivation stress (Table 9). This observation is in line with the report of Di Paolo and Rinaldi (2008), who claimed that the effect of N availability was amplified in a maximum irrigation regime. In the present study, the declining trend in the effects was associated with lower increases in the shoot biomass yield, grain yield, LAI_{max}, Fv/Fm ratio, Chl a, Chl b, Car content, IWUEb, and IWUEg under the deficit irrigation regime relative to those achieved under the normal irrigation regime (Table 9).

However, the negative effects of the N supply were larger on NUEb and NUEg under the deficit irrigation treatment, so the reductions in these two traits were greater than those under the normal irrigation treatment. These findings were in line with those reported by Muchow (1998), who observed that NUE declined in corn and sorghum when N was supplied at high levels or when the plant growth was limited by the moisture supply.

Under well-irrigated conditions, in the present study, N application did not affect the CAT, POX, or APX activities, while it did increase these activities under the deficit irrigation treatment (Table 9). Finally, the N supply was observed to reduce the negative effects of water-limited stress in the deficit irrigation treatment at 85% MAD by increasing the plant shoot biomass and grain yields as a consequence of the increases achieved not only in the LAI_{max}, Chl a, Chl b, and Car content, but also those related to the activities of the antioxidant enzymes tested (Table 9). Nitrogen nutrition in general could moderate the negative effects of water deficit stress by stimulating antioxidant activities and osmoregulation, mitigating lipid peroxidation, and ameliorating plant physiological traits (Nematpour et al., 2019).

5. Conclusions

This study revealed significant differences between grain and forage sorghum genotypes in terms of dry matter production. Although the effect of water shortage stress on corn crop was greater than that of the studied sorghum genotypes, the biomass yield produced in the corn hybrid was superior under both irrigation conditions. The grain share of the total biomass in corn was found to be higher than that of the grain and forage sorghum genotypes. The IWUEb and NUEb in Pegah and GS24 were higher than those in the corn hybrid. However, the IWUEg and NUEg in corn were higher under both irrigation regimes. In addition, the early June planting dates of these crops were superior to those of late July. Nitrogen supply was observed to reduce the negative effects of water-limited stress not only by increasing plant LAI_{max}, Chl a, Chl b, and Car contents, but also by enhancing the antioxidant enzyme activities of CAT, APX, and POX. In future studies, the qualitative parameters of the silage types produced in different treatments, as explained above, may be suggested for further investigation and evaluation.

References

Addai, I. K., & Alimiyawo, M. (2015). Graphical determination of leaf area index and its relationship with growth and yield parameters of *Sorghum* (*Sorghum bicolor* L. Moench) as affected by fertilizer application. *Journal of Agronomy*, *14*(4), 272–278. https://doi.org/10.3923/ja.2015.272.278

Aebi, H. I. (1983). Catalase. In H. U. Bergmeyer (Ed.), *Methods of enzymatic analysis* (pp. 273–286). Verlag Chemie.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration – Guidelines for computing crop water requirements*. Food and Agriculture Organization of the United Nations.

Amaducci, S., Colauzzi, M., Battini, F., Fracasso, A., & Perego, A. (2016). Effect of irrigation and nitrogen fertilization on the production of biogas from maize and sorghum in a water limited environment. *European Journal of Agronomy*, *76*, 54–65. https://doi.org/10.1016/j.eja.2016.01.019

Araya, A., Kisekka, I., & Holman, J. (2016). Evaluating deficit irrigation management strategies for grain sorghum using AquaCrop. *Irrigation Science*, *34*(6), 465–481. https://doi.org/10.1007/s00271-016-0515-7

Arnon, A. N. (1967). Method of extraction of chlorophyll in the plants. *Agronomy Journal*, *23*(1), 112–121. https://doi.org/10.1139/b79-163

Asseng, S., Turner, N. C., & Keating, B. A. (2001). Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. *Plant and Soil*, *233*(1), 127–143. https://doi.org/10.1023/A:1010381602223

Belesky, D. P., & Malinowski, D. P. (2016). Grassland communities in the USA and expected trends associated with climate change. *Acta Agrobotanica*, *69*(2), Article 1673. https://doi.org/10.5586/aa.1673

Bradford, N. A. (1976). A rapid and sensitive method for the quantitation microgram quantities of a protein isolated from red cell membranes. *Analytical Biochemistry*, *72*, 248–254. https://doi.org/10.1016/0003-2697(76)90527-3

Cakir, R. (2004). Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research*, *89*(1), 1–16. https://doi.org/10.1016/j.fcr.2004.01.005

Cechin, I. (1998). Photosynthesis and chlorophyll fluorescence in two hybrids of sorghum under different nitrogen and water regimes. *Photosynthetica*, *35*(2), 233–240. https://doi.org/10.1023/A:1006910823378

Devnarain, N., Crampton, B. G., Chikwamba, R., Becker, J. V., & O'Kennedy, M. M. (2016). Physiological responses of selected African sorghum landraces to progressive water stress and re-watering. *South African Journal of Botany*, *103*, 61–69. https://doi.org/10.1016/j.sajb.2015.09.008

Di Paolo, E., & Rinaldi, M. (2008). Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. *Field Crops Research*, *105*(3), 202–210. https://doi.org/10.1016/j.fcr.2007.10.004

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant drought stress: Effects, mechanisms and management. In E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, & C. Alberola (Eds.), *Sustainable agriculture* (pp. 153–188). Springer. https://doi.org/10.1007/978-90-481-2666-8_12

Farré, I., & Faci, J. M. (2006). Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. *Agricultural Water Management*, *83*(1–2), 135–143. https://doi.org/10.1016/j.agwat.2005.11.001

Food and Agriculture Organization of the United Nations. (2011). *The state of the world's land and water resources for food and agriculture: Managing systems at risk*. Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations. (2017a). *The future of food and agriculture – Trends and challenges*. Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations. (2017b). *Water for sustainable food and agriculture – A report produced for the G20 presidency of Germany*. Food and Agriculture Organization of the United Nations.

Frasier, I., Noellemeyer, E., Amiotti, N., & Quiroga, A. (2017). Vetch-rye biculture is a sustainable alternative for enhanced nitrogen availability and low leaching losses in a no-till cover crop system. *Field Crops Research*, *214*, 104–112. https://doi.org/10.1016/j.fcr.2017.08.016

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agricultural Water Management*, *96*(9), 1275–1284. https://doi.org/10.1016/j.agwat.2009.04.009

Herzog, V., & Fahimi, H. D. (1973). A new sensitive colorimetric assay for peroxidase using 3,3′-diaminobenzidine as hydrogen donor. *Analytical Biochemistry*, *55*(2), 554–562. https://doi.org/10.1016/0003-2697(73)90144-9

Huang, Z. A., Jiang, D. A., Yang, Y., Sun, J. W., & Jin, S. H. (2004). Effects of nitrogen deficiency on gas exchange, chlorophyll fluorescence, and antioxidant enzymes in leaves of rice plants. *Photosynthetica*, *42*(3), 357–364. https://doi.org/10.1023/B:PHOT.0000046153.08935.4c

Kapanigowda, M. H., Perumal, R., Djanaguiraman, M., Aiken, R. M., Tesso, T., Prasad, P. V., & Little, C. R. (2013). Genotypic variation in sorghum [*Sorghum bicolor* (L.) Moench] exotic germplasm collections for drought and disease tolerance. *SpringerPlus*, *2*(1), Article 650. https://doi.org/10.1186/2193-1801-2-650

Kiani, M., Gheysari, M., Mostafazadeh-Fard, B., Majidi, M. M., Karchani, K., & Hoogenboom, G. (2016). Effect of the interaction of water and nitrogen on sunflower under drip irrigation in an arid region. *Agricultural Water Management*, *171*, 162–172. https://doi.org/10.1016/j.agwat.2016.04.008

Kisekka, I., Lamm, F., & Schlegel, A. (2016). Sorghum yield response to water supply and irrigation management. *Kansas Agricultural Experiment Station Research Reports*, *2*(7), 1–7. https://doi.org/10.4148/2378-5977.1252

Liu, L., Maier, A., Klocke, N. L., Yan, S., Rogers, D. H., Tesso, T., & Wang, D. (2013). Impact of deficit irrigation on sorghum physical and chemical properties and ethanol yield. *Transactions of the ASABE*, *56*(4), 1541–1549. https://doi.org/10.13031/trans.56.10153

Maharjan, B., Rosen, C. J., Lamb, J. A., & Venterea, R. T. (2016). Corn response to nitrogen management under fully-irrigated vs. water-stressed conditions. *Agronomy Journal*, *108*(5), 2089–2098. https://doi.org/10.2134/agronj2016.01.0006

Mancosu, N., Snyder, R. L., Kyriakakis, G., & Spano, D. (2015). Water scarcity and future challenges for food production. *Water*, *7*(3), 975–992. https://doi.org/10.3390/w7030975

Millner, J. P., Aver, R. V., & Hardacre, A. K. (2005). The yield and nutritive value of maize hybrids grown for silage. *New Zealand Journal of Agricultural Research*, *48*(1), 101–108. https://doi.org/10.1080/00288233.2005.9513637

Muchow, R. C. (1989). Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment II. Effect of water deficits. *Field Crops Research*, *20*(3), 207–219. https://doi.org/10.1016/0378-4290

Muchow, R. C. (1998). Nitrogen utilization efficiency in maize and grain sorghum. *Field crops research*, *56*(1–2), 209–216. https://doi.org/10.1016/S0378-4290(97)00132-9

Muchow, R. C., & Sinclair, T. R. (1994). Nitrogen response of leaf photosynthesis and canopy radiation use efficiency in field-grown maize and sorghum. *Crop Science*, *34*(3), 721–727. https://doi.org/10.2135/cropsci1994.0011183X003400030022x

Munamava, M., & Riddoch, I. (2001). Response of three sorghum (*Sorghum bicolor* L. Moench) varieties to soil moisture stress at different developmental stages. *South African Journal of Plant and Soil*, *18*(2), 75–79. https://doi.org/10.1080/02571862.2001.10634407

Mutava, R. N., Prasad, P. V. V., Tuinstra, M. R., Kofoid, K. D., & Yu, J. (2011). Characterization of sorghum genotypes for traits related to drought tolerance. *Field Crops Research*, *123*(1), 10–18. https://doi.org/10.1016/j.fcr.2011.04.006

Nakano, Y., & Asada, K. (1981). Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. *Plant and Cell Physiology*, *22*(5), 867–880.

Nematpour, A., Eshghizadeh, H. R., & Zahedi, M. (2019). Drought-tolerance mechanisms in foxtail millet (*Setaria italica*) and proso millet (*Panicum miliaceum*) under different nitrogen supply and sowing dates. *Crop and Pasture Science*, *70*(5), 442–452. https://doi.org/10.1071/CP18501

Pandey, R. K., Maranville, J. W., & Chetima, M. M. (2000). Deficit irrigation and nitrogen effects on maize in a Sahelian environment: II. Shoot growth, nitrogen uptake and water extraction. *Agricultural Water Management*, *46*(1), 15–27. https://doi.org/10.1016/S0378-3774(00)00073-1

Pang, B., Zhang, K., Kisekka, I., Bean, S., Zhang, M., & Wang, D. (2018). Evaluating effects of deficit irrigation strategies on grain sorghum attributes and biofuel production. *Journal of Cereal Science*, *79*, 13–20. https://doi.org/10.1016/j.jcs.2017.09.002

Prażak, R. (2016). Prospects for sorghum cultivation in Poland. *Acta Agrobotanica*, *69*(2), Article 1661. https://doi.org/10.5586/aa.1661

Rahman, M. U., Gul, S., & Ahmad, I. (2004). Effects of water stress on growth and photosynthetic pigments of corn (*Zea mays* L.) cultivars. *International Journal of Agriculture and Biology*, *4*, 652–655.

Rajcan, I., & Tollenaar, M. (1999). Source:sink ratio and leaf senescence in maize: I. Dry matter accumulation and partitioning during grain filling. *Field Crops Research*, *60*(3), 245–253. https://doi.org/10.1016/S0378-4290(98)00142-7

Rimski-Korsakov, H., Rubio, G., & Lavado, R. S. (2009). Effect of water stress in maize crop production and nitrogen fertilizer fate. *Journal of Plant Nutrition*, *32*(4), 565–578. https://doi.org/10.1080/01904160802714961

Saravia, D., Farfán-Vignolo, E. R., Gutiérrez, R., De Mendiburu, F., Schafleitner, R., Bonierbale, M., & Awais Khan M. (2016). Yield and physiological response of potatoes indicate different strategies to cope with drought stress and nitrogen fertilization. *American Journal of Potato Research*, *93*(3), 288–295. https://doi.org/10.1007/s12230-016-9505-9

Sawargaonkar, G. L., Patil, M. D., Wani, S. P., Pavani, E., Reddy, B. V. S. R., & Marimuthu, S. (2013). Nitrogen response and water use efficiency of sweet sorghum cultivars. *Field Crops Research*, *149*, 245–251. https://doi.org/10.1016/j.fcr.2013.05.009

Sayed, O. H. (2003). Chlorophyll fluorescence as a tool in cereal crop research. *Photosynthetica*, *41*(3), 321–330. https://doi.org/10.1023/B:PHOT.0000015454.36367.e2

Seghatoleslami, M. J., Kafi, M., & Majidi, E. (2008). Effect of deficit irrigation on yield, WUE and some morphological and phenological traits of three millet species. *Pakistan Journal of Botany*, *40*(4), 1555–1560.

Shah, S. H., Houborg, R., & McCabe, M. F. (2017). Response of chlorophyll, carotenoid and SPAD-502 measurement to salinity and nutrient stress in wheat (*Triticum aestivum* L.). *Agronomy*, *7*(3), Article 61. https://doi.org/10.3390/agronomy7030061

Tabib Loghmani, S. M. T., Bazrafshan, F., Alizadeh, O., Amiri, B., & Bahrani, A. (2019). Influence of cut-off irrigation on seed quality and physiological indices of various safflower (*Carthamus tinctorius* L.) genotypes. *Acta Agrobotanica*, *72*(4), Article 1791. https://doi.org/10.5586/aa.1791

Terashima, I., & Hikosaka, K. (1995). Comparative ecophysiology of leaf and canopy photosynthesis. *Plant, Cell and Environment*, *18*(10), 1111–1128. https://doi.org/10.1111/j.1365-3040.1995.tb00623.x

Tolk, J. A., & Howell, T. A. (2003). Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils. *Agricultural Water Management*, *59*(2), 97–111. https://doi.org/10.1016/S0378-3774(02)00157-9

Vattikonda, M. R., & Hunter, R. B. (1983). Comparison of grain yield and whole-plant silage production of recommended corn hybrids. *Canadian Journal of Plant Science*, *63*(3), 601–609. https://doi.org/10.4141/cjps83-076

Yosefi, M., Sharafzadeh, S., Bazrafshan, F., Zare, M., & Amiri, A. (2018). Application of jasmonic acid can mitigate water deficit stress in cotton through yield-related physiological properties. *Acta Agrobotanica*, *71*(2), Article 1741. https://doi.org/10.5586/aa.1741

Yousefi, V., Ahmadi, J., Sadeghzadeh-Ahari, D., & Esfandiari, E. (2018). Influence of long-term cold stress on enzymatic antioxidative defense system in chickpea (*Cicer arietinum* L.). *Acta Agrobotanica*, *71*(3), Article 1745. https://doi.org/10.5586/aa.1745

Zhao, D., Reddy, K. R., Kakani, V. G., & Reddy, V. R. (2005). Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy*, *22*(4), 391–403. https://doi.org/10.1016/j.eja.2004.06.005