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Effects of Irrigation Level, Plant Density and Nitrogen Doses on Grain Yield and Yield Parameters of Sweet Sorghum (*Sorghum bicolor* L. Moench var. *saccharatum*)

Güngör KÖSTERELİ [1*], İlhan TURGUT [2]

[1] Product Owner, Bayer Crop Science, 16280, Bursa, Turkey
[2] Department of Field Crops, Faculty of Agriculture, Bursa Uludağ University, 16110, Bursa, Turkey

✉ Corresponding author: gkostereli@gmail.com

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ABSTRACT

Experiments were carried out at Bursa Uludağ University Faculty of Agriculture Application and Research Centre in 2022 and 2023 summer seasons to evaluate the effects of irrigation level, plant density and nitrogen dose on grain yield and yield parameters of sweet sorghum [*Sorghum bicolor* (L.) Moench var. *saccharatum*]. Each field trail included thirty-two treatments represent the combinations among four irrigation levels, two planting densities and four nitrogen fertilization doses. A split-split plot design with three replications was used in both seasons, where the four deficit irrigation levels (0%, 33%, 66% and 100% of crop evapotranspiration (ETc)) were arranged in the main plots, while two planting densities (142857 and 285714 plants ha^{-1}) were randomly allocated in the sub plots and the four nitrogen doses (0, 70, 140 and 210 kg ha^{-1}) were randomly distributed in the sub-sub plots. The results showed that the three factors and their interactions on grain yield and yield components were significant. Grain yield increased with increasing irrigation level, plant density, nitrogen doses and their interactions in both years. In the study, maximum grain yield was obtained with all N doses at I_3 in 2022, while it was obtained with N_3 in I_1, I_2 and I_3 in 2023. Grain yield increased with increasing plant density in 2022, it did not interact with nitrogen doses, but they interacted in 2023 and the highest grain yield was determined at N_3 interacting with P_2. In the plant density and irrigation level interactions, the maximum grain yield was obtained from the interaction of D_2 and I_3 in the rainy year 2022, while it was obtained from the interaction of D_2 and I_2 in the dry year 2023.

1. INTRODUCTION

Today, it is known that global climate change has a profound effect on plant production. In addition to climate change, factors such as decreased soil fertility, temperature fluctuations, unseasonal rainfall, and increased CO_2 concentration are the most critical threats to open-air factory agriculture (Cai at al. 2011). Sweet Sorghum, one of the C4 crops, has adapted to a wide range of climate and soil conditions. It is a short-term crop that matures earlier at higher temperatures. It is known not only as a "high-energy crop" due to its high photosynthesis rate but also as the "camel among crops" due to its drought resistance. It can be grown in soils ranging from heavy clay to light sand. It responds effectively to available growth factors such as water stress, planting density and nitrogen fertilization. (Taha et al. 1999).

Sorghum is an important source of food and fodder, especially in rainfed regions, and its resilience to harsh environmental conditions makes it the fifth most widely grown cereal worldwide after wheat, rice, maize and barley (FAOSTAT, 2023; Aydinsakir et al. 2021). Grain sorghum, which is grown as a main or second crop in the Mediterranean region of Turkey, stands out for its resistance to stress conditions such as high temperature, drought, salinity and waterlogging, while studies in Adana show that it requires less fertilizer and is more tolerant to environmental stresses compared to maize (İnal et al. 2020). Thanks to its strong root system, sorghum can yield even under arid and saline conditions (Tari et al. 2013) and offers higher yield and quality with appropriate fertilization and irrigation practices (Islam et al. 2012; Khelil et al. 2013). Furthermore, agronomic factors such as plant density and irrigation management play a decisive role in yield, and it has been reported that grain yield can be significantly increased by increasing plant density (Selim, 1995; Wang et al. 2024; Schatz et al. 1990).

Yield and quality of plants are affected by environmental factors as well as genetic traits. In order to reduce the effect of environmental factors, it is necessary to determine the appropriate plant density, irrigation level and nitrogen dose of sorghum varieties as genetic material suitable for different soil structures and ecological conditions. Many studies have been carried out to investigate the responses of sorghum to different irrigation and nitrogen doses and plant density on yield and yield components. On the other hand, the number of studies on the effects of these three factors on sorghum yield and yield components is limited.

This study investigated the effects of plant densities, irrigation levels and nitrogen doses on grain yield and yield parameters of sweet sorghum.

2. MATERIALS AND METHODS

Experiment design and location

Experiments were conducted at Bursa Uludağ University Faculty of Agriculture Application and Research Centre with the geographical location of 40° 13′ 47.22″ N, 28° 51′ 25.22″ W and elevation of 100 m above mean sea level during summer seasons in both 2022 and 2023 to study the effect of deficit irrigation, planting density and nitrogen fertilization on yield and some yield parameters of sweet sorghum (*Sorghum bicolor* (L.) Moench var. *saccharatum*). Each field trail included thirty-two treatments represent the combinations among four irrigation levels, two planting densities and four nitrogen fertilization doses. Field experiments were conducted in a randomized split-split block design with three replications in both seasons, where the four irrigation levels were arranged in the main plots, while plant populations were randomly allocated in the sub plots and the four nitrogen doses were randomly distributed in the sub-sub plots. Main plots were set as 11.20 m x 11.00 m, sub plots as 11.20 m x 5.00 m rows and sub-sub plots as 2.80 m x 5.00 m rows. Gulseker, a sweet sorghum variety developed at Bursa Uludağ University Faculty of Agriculture, Department of Field Crops, was used as a genetic material, four irrigation levels (% Etc) (I): 0% (I_0), 33% (I_1), 66% (I_2) and 100% (I_3) of crop evapotranspiration (ETc), four nitrogen doses (kg ha^{-1}) (N): 0 (N_0), 70 (N_1), 140 (N_2) and 210 (N_3) and two plant populations (plants ha^{-1}) (D): 142857 (D_1) and 285714 (D_2) plants ha^{-1} (sowing spacing; 0.10 x 0.70 m and 0.05 x 0.70 m, respectively). In previous studies, plant densities were obtained with row spacings of 0.10 x 0.70 m and 0.05 x 0.70 m (Turgut et al. 2005). In this context, it was decided to investigate the above two plant densities.

Soil and climate characteristics of the trial sites

Soil physical and chemical characteristics are shown in Table 1.

Table 1. Soil properties of experimental area

2022		2023	
Properties (mg kg $^{-1}$)	**Quantities**	**Properties (mg kg $^{-1}$)**	**Quantities**
Texture	Clay	Texture	Clay
pH	7.61	pH	6.63
EC (mS cm^{-1})	0.041	EC (mS cm $^{-1}$)	0.035
Lime (% $CaCO_3$)	4.79	Lime (% CaCO3)	1.58
Organic matter (%)	2.66	Organic matter (%)	1.66
Total nitrogen (N) (%)	0.13	Total nitrogen (N) (%)	0.083
Available phosphorus (P) (mg kg $^{-1}$)	6.7	Available phosphorus (P) (mg kg $^{-1}$)	3.31
Potassium (K)	178.09	Potassium (K)	64.82

Soil samples were collected before sowing through the experimental site to determine in both years. As seen in Table 1, the soil structure of Bursa Uludağ University Agricultural Research and Application Center, where the experiment was established, is rich in lime and clay values, and has a heavy texture (Katkat et al. 1985). There is no salinity problem. Na^+ 0.26 me $100g^{-1}$, K^+ 0.92 me $100g^{-1}$, Mg^{++} 10.20 me $100g^{-1}$, Ca^{++} 30.42 me $100g^{-1}$ (Aksoy et al. 2001). It is rich in potassium and phosphorus, and poor in organic matter content.

Table 2. Climatic data in the growing season

	Average Temperature (^{o}C)			**Average Humidity (%)**			**Monthly Precipitation (mm)**		
Months	2022	2023	Long Term Average (1995-2023)	2022	2023	Long Term Average (1995-2023)	2022	2023	Long Term Average
June	22.3	24.3	22.2	71.3	63.0	70.1	129.2	0.0	56.7
July	24.0	26.1	24.7	61.5	5.8	63.5	2.1	0.0	12.6
August	25.3	27.1	25.2	69.6	60.4	64.5	40.3	0.0	15.4
September	20.7	22.6	21.5	65.2	62.9	66.5	39.2	0.0	36.7
October	15.8	18.2	16.1	71.3	70.5	74.4	11.7	7.3	52.2
Total	**-**	**-**	**-**	**-**	**-**	**-**	**222.5**	**7.3**	**173.6**
Average	**21.6**	**23.7**	**21.9**	**67.8**	**52.5**	**67.8**	**-**	**-**	**-**

In the first year (2022), a total precipitation of 222.5 mm was determined during the sweet sorghum vegetation period (June-October). In 2023, a total of 7.3 mm precipitation occurred. More precipitation occurred in the first year of the experiment compared to the second year. Among the trial years, it was observed that the temperature value was warmer in 2023 than in 2022. When the rainfall amounts of the trial years are compared, it is seen that a significant amount of rainfall was received in 2022, while 2023 was a drier year.

Cultural practices

Sowing was done by pneumatic planter as 0.05 x 0.70 m in the third week of June in both years. P_2O_5 of 150 kg ha^{-1} was applied on 5cm rows side by pneumatic planter with planting in the all-experimental area. The trial area was hoed by hand twice to remove weeds and aerate the soil. Planting densities were achieved as follows; 285714 (D_2) plants ha^{-1}, resulting from 0.05 x 0.70 m planting type and 142857 (D_1) plants ha^{-1}, were thinned to be 0.10 x 0.70 m planting type. Nitrogen doses were applied by hand as urea (46% N) and ammonium sulfate (21% N) in two equal doses on 10 cm the rows side and covered; after thinning (20 days after planting) and 35 days later. Four different irrigation levels were applied by drip irrigation according to experiments were carried out in dry conditions. Irrigation treatments investigated are provided in Table 3.

Crop evapotranspiration (ETc, mm) was calculated according to:

ETc = E_0 x Kc (1)

where E_0 is the evaporation of standard Class-A pan and Kc is the crop coefficient as suggested by Doorenbos and Pruitt (1977). The Kc values used during the growing season were those proposed in FAO-56 (Allen et al. 1998) for sweet sorghum (0.30 for the initial stage, 0.30–1.20 for the crop development stage, 1.20 for the mid-season stage, and 1.05 for the late-season stage of crop development). According to the results of the water analysis, the quality of the irrigation water used in the research was determined as C_2S_1. At the beginning of field trial, sprinkler irrigation method was used for germinating and emerging seeds. Afterward, the calculated amount of irrigation water was applied at weekly intervals, and the water was used to the plots via a drip irrigation system. The laterals were placed 0.1 m next to the plant rows. The dripper lines had inline compensating emitter pressure, and the discharge rate of the emitters was 1.6 L ha^{-1} at an operating pressure of 1 bar. The emitter spacing was chosen as 0.30 m based on the soil characteristics.

Table 3. Irrigation treatments

Treatments	Description
I_3	100% ETc restoration during the whole growing season
I_2	66% ETc restoration during the whole growing season
I_1	33% ETc restoration during the whole growing season
I_0	0% ETc restoration during the whole growing season

Harvest was done by hand in first week on November in both years.

Data collection

Each plot contained four rows; each row 5.00 m long. Data were collected from the two center rows in four rows for every parcels.

During the physiological ripening period (136 days after sowing) in harvest, the following traits were determined:

Grain weight per bunch (g $bunch^{-1}$); the bunches obtained from each plant were weighed, the grain weight in the collected bunch (g $bunch^{-1}$) was weighed and determined by converting it to 14% moisture.

Thousand kernel weight (g 1000 $grains^{-1}$); 4 randomly counted 100 grains of grains obtained from the clusters of each matured plant in each plot were weighed and calculated by proportion (g 1000 $grains^{-1}$) and converted to 14% moisture.

Grain yield of sweet sorghum (kg ha^{-1}); the grains obtained from the clusters of each mature plant in each plot were weighed to determine the grain weight in the plot (g $plot^{-1}$) and converted to 14% moisture. The yield per hectare (kg ha^{-1}) was calculated taking into account the plot area.

Statistical analysis

The data from the trials were statistically analyzed according to the split-plot experimental design with 3 replications in randomized blocks. The effects of irrigations, plant populations, nitrogen doses and their interactions were evaluated using F-test at 0.05 and 0.01 probability levels. F-protected least significant difference (LSD) was calculated according to Steel and Torrie (1980) at 0.05 probability level. Analyses of variance (ANOVA) for all data were analyzed with JMP 9.0.2 software to determine the significance of treatments and their interactions.

3. RESULTS AND DISCUSSION

The results of the variance analysis of the data we obtained in our study conducted in 2022 and 2023 are given in Table 4. The ANOVA results show the effects of three main factors: irrigation levels, plant densities and nitrogen doses were significantly different at 1% probability level on grain weight per panicle in both seasons. Also, the effects of three interactions which were irrigation levels × planting densities, irrigation levels × nitrogen doses, and irrigation levels × planting densities × nitrogen doses were significantly different at 1% probability level on grain weight per panicle in 2022 and 2023. The effects of plant densities × nitrogen doses interactions were not significantly different in 2022 but significantly different at 1% probability level on grain weight per panicle in 2023. The effects of three main factors which were irrigation levels, plant densities, nitrogen doses and effects of four interactions which were irrigation levels × planting densities, irrigation levels × nitrogen doses, plant densities × nitrogen doses and irrigation levels × planting densities × nitrogen doses were significantly different at 1% probability level on 1000 grain weight in both of season. According to the results, the effects of two main factors, irrigation levels and plant densities levels, were significantly different at 1% probability level on grain yield of sweet sorghum in both seasons. However, effects of nitrogen doses were significantly different at 5% probability level in 2022 and they were significantly different at 1% probability level in 2023.

Table 4. The results of the variance analysis for both years

Year	Source of Variation	df	Mean Square		
			Grain weight of bunch	Thousand kernel weight	Grain Yield
2022	Blocks	2	6.282^{ns}	0.007^{ns}	4673.660^{ns}
	I	3	1629.630**	33.795**	775879.000**
	D	1	3106.510**	6.678**	7334329.000**
	N	3	75.169**	3.772**	14784.300*
	I×D	3	166.680**	17.552**	123610.000**
	I×N	9	75.210**	4.017**	30632.380**
	D×N	3	1.498^{ns}	6.556**	6768.380^{ns}
	I×D×N	9	90.223**	2.683**	53622.500**
	Error	48	4.471	0.463	4.144.000
	CV (%)		4	2	6
2023	Blocks	2	6.455^{ns}	0.194^{ns}	1073.580^{ns}
	I	3	4447.150**	50.183**	2415015.000**
	D	1	258.070**	0.631^{ns}	8152148.000**
	N	3	381.668**	3.360**	169383.000**
	I×D	3	312.336**	4.963**	471353.000**
	I×N	9	195.067**	8.118**	103670.000**
	D×N	3	433.649**	3.025**	182469.000**
	I×D×N	9	47.192**	5.222**	61449.500**
	Error	48	7.088	0.470	2.754.000
	CV (%)		6	2	5

I, D, N: Irrigation Level; Plant Density; Nitrogen Dose respectively.
*, **: significant difference at probability level of 5% and 1% respectively.

Grain weight per panicle (g)

Graphs of average values for irrigation levels, plant densities and nitrogen doses in the 1st and 2nd years of the study are shown in Fig.1 and Fig.2. From these figures, it is seen that the grain weight per panicle increases significantly as the irrigation levels increase in 2022. In contrast, there is a significant increase in the applications irrigated according to I_0 in 2023, but there is no significant difference between the I_1, I_2 and I_3 applications. Alderfasi et al, (2016); and Salem, (2015) stated that the increase in irrigation level led to an increase in grain weight per panicle and their results were similar to our study. In both years of the study, the grain weight per panicle decreased significantly with the increase in plant density. Many studies have reported that increasing plant density decreased grain weight per panicle (Zhou et al, 2022; Sahu et al, 2018; Alderfasi et al, 2016; Salem, 2015; Zand et al, 2014; Thakur et al, 2009). In the study, the grain weight per panicle generally increased in parallel with the increase in nitrogen doses, but there was an exception in 2022 with a decrease in N_2 and in 2023 with no significant increase in N_1 dose compared to N_0 (Fig.1 and Fig.2). Salem, (2015); Amiri et al, (2014); Thakur et al, (2009) reported that increasing nitrogen dose increased grain weight per panicle.

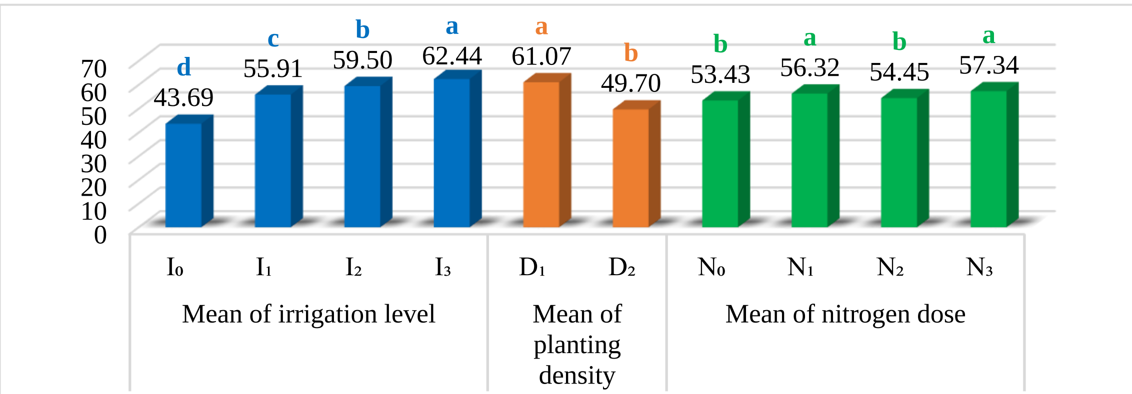

Figure 1. Effect of irrigation levels, planting densities and nitrogen doses on grain weight(g) per panicle in 2022

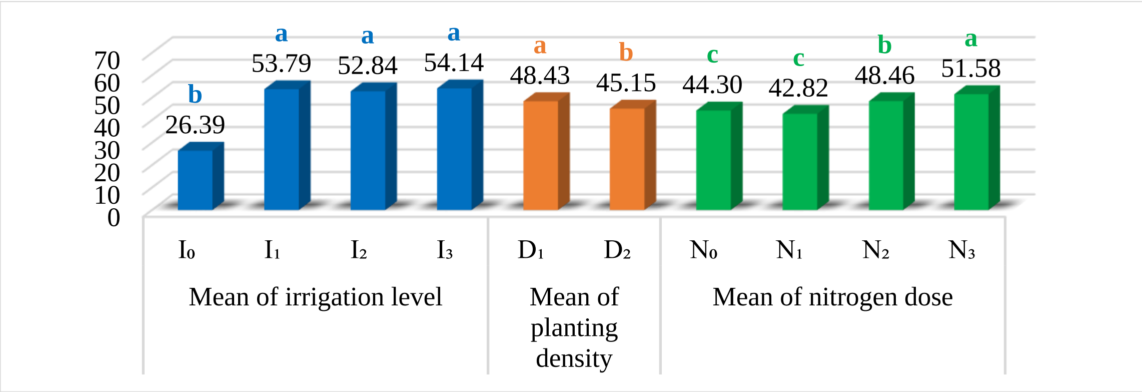

Figure 2. Effect of irrigation levels, planting densities and nitrogen doses on grain weight(g) per panicle in 2023

Table 5 shows the pairwise interactions of irrigation levels, plant densities and nitrogen doses for grain weight per panicle. The irrigation level × nitrogen dose interaction, which was significant in both years, revealed that the grain weight per panicle increased as the irrigation level increased at each nitrogen dose. However, the highest grain weight per panicle was determined in 2022 at I_2 and I_3 irrigation levels at N_1 nitrogen dose and I_3 irrigation level at N_3 nitrogen dose, while the highest values in 2023 were obtained from I_2 and I_3 irrigation levels at N_2 nitrogen dose and from I_2 irrigation level at N_3 nitrogen dose. Salem (2015) revealed in his study that increasing nitrogen dose with increasing irrigation level increased grain yield per panicle. The significance of the planting density × nitrogen dose interaction was not exhibited a stable attitude over the years. According to this interaction, which was significant in 2023, the highest grain weight per panicle was obtained from the D_1 plant density at the N_2 nitrogen dose, while there was no significant difference between the plant densities at the N_3 nitrogen dose. Salem, (2015); Turgut et al, (2005) found that increasing nitrogen dose at low plant density increased grain weight per panicle and obtained similar results with our study. The Irrigation level × planting density interaction, which was significant in 2022, revealed that the grain weight per panicle increased with increasing irrigation levels from I_0 to I_3 at the D_1 planting density, but increased up to the I_2 irrigation level at the D_2 planting density and did not change at the I_3 irrigation level. In 2023, the highest grain weight per panicle was obtained from I_3 irrigation level at D_1 planting density, while it was determined from I_1 irrigation level at D_2 planting density (Table 5). Alderfasi et al, (2016); Salem, (2015) found that increasing irrigation level at low plant density increased grain weight per panicle.

Table 5. Effects of I×N, D×N and D×I interactions on grain weight per panicle (g)

Irrigation level × Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
I_0	46.45 ^{f}	40.62 ^{h}	43.32 ^{g}	44.38 ^{fg}	I_0	25.45 ^{h}	26.50 ^{h}	21.10 ^{i}	32.50 ^{g}
I_1	51.18 ^{e}	53.83 ^{d}	58.25 ^{bc}	60.37 ^{b}	I_1	54.25 ^{c}	52.57 ^{cd}	50.40 ^{de}	57.95 ^{b}
I_2	56.70 ^{c}	65.05 ^{a}	56.23 ^{cd}	60.00 ^{b}	I_2	48.08 ^{e}	41.32 ^{f}	60.18 ^{ab}	61.78 ^{a}
I_3	59.37 ^{b}	65.78 ^{a}	60.02 ^{b}	64.60 ^{a}	I_3	49.40 ^{e}	50.90 ^{de}	62.17 ^{a}	54.08 ^{c}
Planting density × Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
D_1	59.34	61.99	59.80	63.16	D_1	46.45 ^{c}	39.78 ^{e}	55.60 ^{a}	51.89 ^{b}
D_2	47.51	50.65	49.11	51.52	D_2	42.14 ^{d}	45.87 ^{c}	41.33 ^{de}	51.27 ^{b}
Planting density × Irrigation level interaction									
2022					2023				
	I_0	I_1	I_2	I_3		I_0	I_1	I_2	I_3
D_1	47.99 ^{d}	63.27 ^{b}	62.21 ^{b}	70.83 ^{a}	D_1	28.65 ^{e}	51.07 ^{cd}	53.84 ^{bc}	60.16 ^{a}
D_2	39.39 ^{e}	48.55 ^{d}	56.78 ^{c}	54.06 ^{c}	D_2	24.13 ^{e}	56.52 ^{b}	51.84 ^{c}	48.12 ^{d}

1000 grain weight (g)

Two-year average values of 1000 grain weight are given in Fig. 3 and Fig. 4. Differences were observed between the averages obtained due to differences in the climate data of the two years. While 222.5 mm of precipitation was received in the 2022 trial season, 7.3 mm of precipitation was received in the 2023 trial season. For this reason, when the 1000 grain weight averages were compared, it was determined that 1000 grain weight increased proportionally as irrigation levels increased in 2022. While the highest 1000 grain weight was obtained from the I_3 irrigation level, a significant increase was detected between the I_0 irrigation level and other irrigation levels in 2023. Also, the highest 1000 grain weight was obtained from the I_1, I_2 and I_3 irrigation levels. The results obtained in other studies also revealed that increasing irrigation level increased 1000 grain weight (Alderfasi et al, 2016; Abadi et al, 2014). The effects of plant densities on 1000 grain weight were found to be significant in 2022 and the highest average was obtained at low plant density D_1, but the effects of plant densities on 1000 grain weight were not found to be significant in 2023. Zhou et al, (2022); Sahu et al, (2018); Alderfasi et al, (2016); Soleymani et al, (2011) found that increasing plant density decreased 1000 grain weight. In our study, it is thought that the fact that the year 2023 was both arid and hotter caused no difference between the effects of plant densities. The study showed a significant effect on nitrogen doses per 1000 grain weight in both years. However, N_0, N_1 and N_2 nitrogen doses were in the same group and gave the highest 1000 grain weight in 2022, while N_1, N_2 and N_3 nitrogen doses were in the same group and gave the highest 1000 grain weight in 2023 (Fig.3 and Fig.4). Many other studies revealed that increasing nitrogen dose increased 1000 grain weight (Zhou et al, 2022; Shahrajabian et al, (2021); Abadi et al, (2014); Amiri et al, 2014; Zand et al, (2014); Soleymani et al, 2011). In our research, it is thought that the soil characteristics of the experimental site in 2022 biased the effects of nitrogen doses on 1000 grain weight.

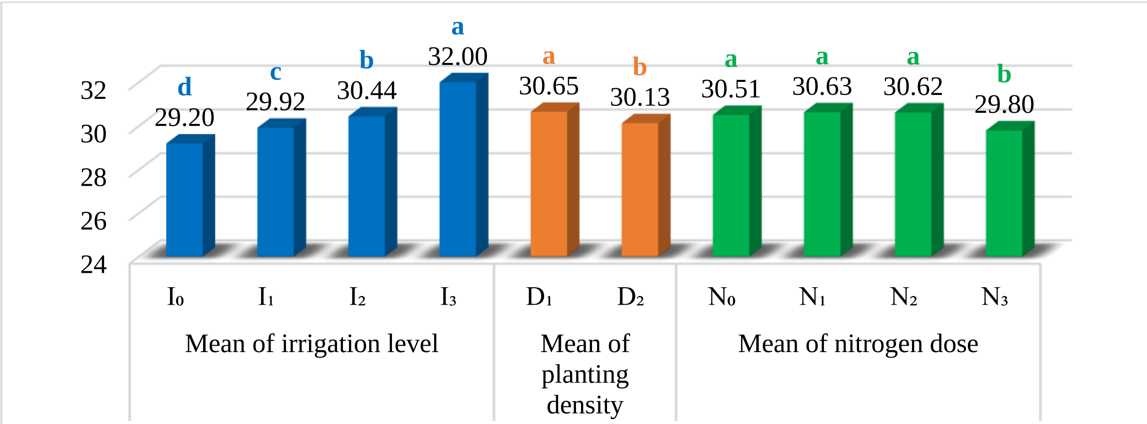

Figure 3. Effect of irrigation levels, planting densities and nitrogen doses on 1000 grain weight (g) in 2022

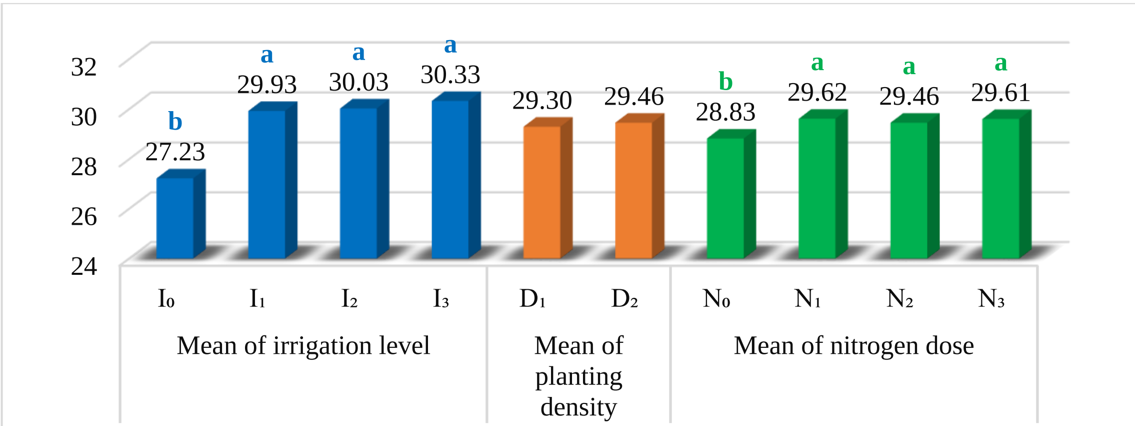

Figure 4. Effect of irrigation levels, planting densities and nitrogen doses on 1000 grain weight (g) in 2023

Binary interactions of irrigation levels, plant density and nitrogen doses on 1000 grain weight are shown in Table 6. Irrigation levels × nitrogen doses interactions were found to be significant in both years, and it was determined that as irrigation levels increased at each nitrogen dose, 1000 grain weight increased. The highest 1000 grain weight in 2022 was obtained from the interaction of I_2 irrigation level and N_0 nitrogen dose and the interaction of I_3 irrigation level and N_0, N_1, N_2, N_3 irrigation levels. In the 2023 season with a dry climate, the highest 1000 grain weight was determined by the interactions of I_1 irrigation level and N_1, N_3 nitrogen doses, the interactions of I_2 irrigation level and N_2, N_3 nitrogen dose, and the interactions of I_3 irrigation level and N_0, N_1, N_2 nitrogen doses. The effects of plant density × nitrogen dose interactions on 1000 grain weight were found to be significant in both years. According to this interaction, no significant increase in 1000 grain weight was detected despite the increasing plant density at other nitrogen doses except N_0 nitrogen dose in both years, but in 2022, N_0 nitrogen dose interacted with D_1 plant density and the highest 1000 grain weight was obtained, and in 2023, the highest 1000 grain weight was observed in D_2 plant density due to the N_0 nitrogen dose interaction and each obtained from N_1, N_2, N_3 nitrogen dose interactions at two plant densities. Zand et al, (2014); Soleymani et al, (2011) found that 1000 grain weight increased with increasing nitrogen dose at low plant density. The effects of plant density × irrigation level interactions on 1000 grain weight were found to be significant in both years. In 2022, as the irrigation level increased from I_0 to I_3 in both plant densities, 1000 grain weights increased, and the highest

1000 grain weight was determined in D_1 and D_2 plant densities at I_3 irrigation level. In the dry season of 2023, irrigation level and plant densities interacted bidirectionally. Plant densities increased 1000 grain weight from I_0 to I_1 when irrigation applications started. Still, there was no significant increase between I_1, I_2 and I_3 irrigation levels, and the interactions of increasing plant density with I_1, I_2, I_3 irrigation levels increased 1000 grain weight except I_0 irrigation level. The highest 1000 grain weight was determined in the interactions of D_2 plant density and I_1, I_2, I_3 irrigation level in 2023. In another study, it was determined that increasing the irrigation level at low plant density will increase 1000 grain weight (Alderfasi et al, 2016).

Table 6. Effects of I×N, D×N and D×I interactions on 1000 grain weight (g)

Irrigation level × Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
I_0	29.64 ^{c}	28.80 ^{de}	30.18 ^{c}	28.20 ^{e}	I_0	27.36 ^{e}	27.86 ^{cd}	27.36 ^{d}	27.86 ^{cd}
I_1	29.45 ^{cd}	30.05 ^{c}	30.06 ^{c}	30.13 ^{c}	I_1	29.39 ^{b}	30.87 ^{a}	28.60 ^{bc}	30.84 ^{a}
I_2	31.46 ^{ab}	31.45 ^{b}	30.06 ^{c}	28.78 ^{de}	I_2	29.19 ^{b}	28.89 ^{b}	31.09 ^{a}	30.97 ^{a}
I_3	31.50 ^{ab}	32.24 ^{a}	32.17 ^{ab}	32.10 ^{ab}	I_3	30.92 ^{a}	30.86 ^{a}	30.78 ^{a}	28.77 ^{b}
Planting density × Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
D_1	31.53 ^{a}	30.82 ^{b}	30.47 ^{b}	29.80 ^{c}	D_1	28.25 ^{b}	29.64 ^{a}	29.71 ^{a}	29.59 ^{a}
D_2	29.49 ^{c}	30.45 ^{b}	30.77 ^{b}	29.80 ^{c}	D_2	29.41 ^{a}	29.61 ^{a}	29.20 ^{a}	29.63 ^{a}
Planting density × Irrigation level interaction									
2022					2023				
	I_0	I_1	I_2	I_3		I_0	I_1	I_2	I_3
D_1	28.86 ^{e}	31.45 ^{b}	30.49 ^{c}	31.83 ^{ab}	D_1	27.80 ^{c}	29.64 ^{b}	29.88 ^{b}	29.87 ^{b}
D_2	29.55 ^{d}	28.40 ^{e}	30.38 ^{c}	32.17 ^{a}	D_2	26.65 ^{d}	30.21 ^{ab}	30.18 ^{ab}	30.80 ^{a}

Grain Yield of Sweet Sorghum (kg ha⁻¹)

The effects of four different nitrogen doses at four different irrigation levels with different plant densities on grain yield in sweet sorghum are shown in Figures 5 and 6. According to the figures, with the increasing irrigation level in 2022, grain yield increased significantly and the highest grain yield was obtained from I_3 irrigation level. On the other hand, there was a significant increase in applications irrigated according to I_0, and the highest grain yield was obtained from I_1 irrigation level in 2023. Many researchers have found that grain yield increases with increasing irrigation level (Wang et al, 2024; Alderfasi et al, 2016; Salem, (2015); Abadi et al, (2014). Additionally, grain yield increased significantly as the plant density increased in both years of the study. Zhou et al, (2022); Sahu et al, (2018); Alderfasi et al, (2016); Salem, (2015); Soleymani et al, (2011); Thakur et al, (2009); Turgut et al, (2005) determined that increasing plant density increases grain yield. On the other hand, Shahrajabian et al, (2021) reported that grain yield decreased as plant density increased, but the minimum plant density applied in the study was 250000 plants ha^{-1}, which is equivalent to the maximum plant density in our study. In the study, grain yield increased significantly as the applied nitrogen doses increased in both years, and the highest grain yield was obtained from N_3 nitrogen dose application (Figure 7 and Figure 8). Many studies supported our results and indicated that increasing nitrogen dose increased grain yield (Zhou et al, 2022; Salem, 2015; Abadi et al, 2014; Amiri et al, 2014; Thakur et al, 2009). In addition, Shahrajabian et al, (2021) determined that increasing nitrogen dose up to 160 kg ha^{-1} increased grain yield, while Turgut et al, (2005) determined that increasing nitrogen dose up to 150 kg ha^{-1} increased grain yield. On the other hand, Soleymani et al, (2011) concluded that grain yield decreased as nitrogen dose increased.

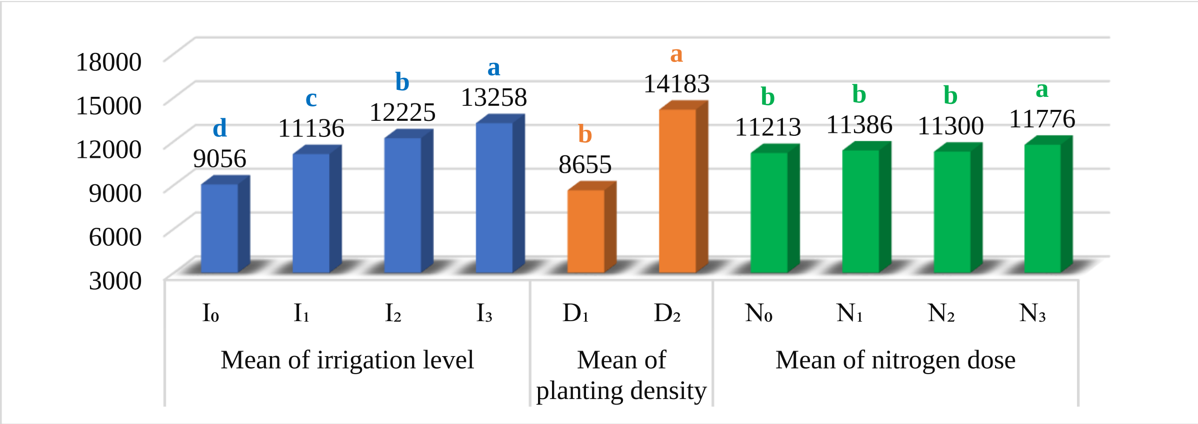

Figure 5. Effect of irrigation levels, planting densities and nitrogen doses on grain yield (kg ha $^{-1}$) in 2022

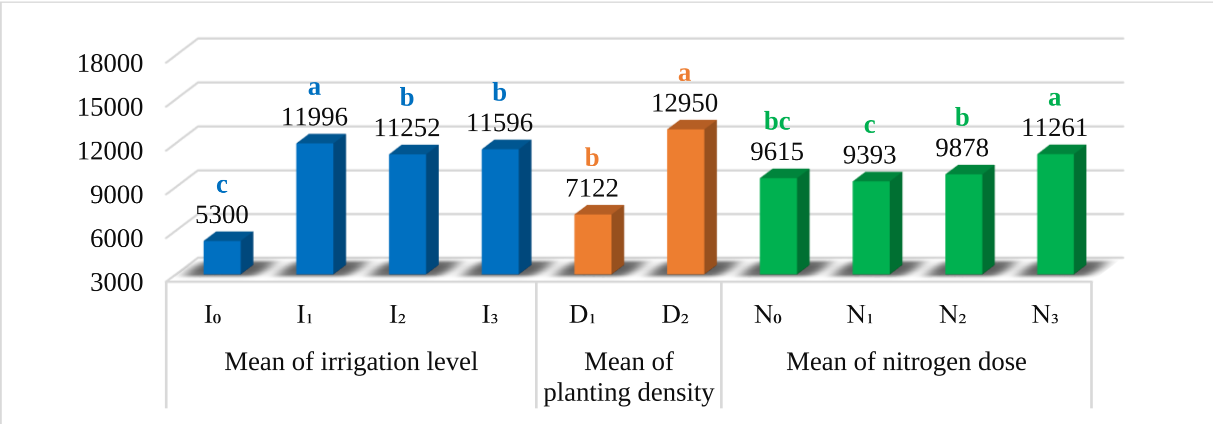

Figure 6. Effect of irrigation levels, planting densities and nitrogen doses on grain yield (kg ha $^{-1}$) in 2023

The effects of the pairwise interactions of irrigation levels, plant densities and nitrogen doses on grain yield are given in Table 7. The irrigation level × nitrogen dose interaction, which was important in both years, showed that grain yield increased as the irrigation level increased at each nitrogen dose. However, while the highest grain yield was obtained with I_3 irrigation level at all nitrogen doses in 2022, the highest grain yield in 2023 was determined at N_3 nitrogen dose at I_1, I_2 and I_3 irrigation levels. Wang et al, (2024) reported that grain yield decreased with increasing nitrogen dose at low irrigation level, but grain yield increased with increasing nitrogen dose at normal irrigation level. In another study, Salem (2015) stated that increasing the nitrogen dose with increasing irrigation level increased grain yield. When the average yields of plant density × nitrogen dose interactions were evaluated, although the increase in plant density made a significant increase on grain yield at all nitrogen doses in both years, plant density × nitrogen dose interactions did not show a significant effect on grain yield in 2022, while as the nitrogen dose increased at high plant density in 2023, grain yield also increased and the highest grain yield was detected in the interaction of D_2 plant density and N_3 nitrogen dose. In different studies, it was observed that increasing nitrogen doses at high plant density increased grain yield (Salem, 2015; Zand et al, 2014; Turgut et al, 2005). On the other hand, Shahrajabian et al, (2021) revealed that increasing nitrogen doses at low plant density increased grain yield, but the lowest plant density in their study was equivalent to the highest plant density in our study. When the grain yield averages of plant density × irrigation level interactions were compared, a two-way increase in grain yield was detected in both years of the study. While high D_2 plant density increased grain yield at every irrigation level, it was determined that grain yield increased as irrigation level increased in both plant densities. While the highest grain yield in 2022 was obtained from the interaction of D_2 plant density and I_3 irrigation level, in 2023 it was obtained from the interaction of D_2 plant density and I_1 irrigation level. Alderfasi et al, (2016); Salem, (2015) reported that increasing nitrogen doses at high plant density increased grain yield.

Table 7. Effects of I×N, D×N and D×I interactions on grain yield (kg/ha)

Irrigation level×Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
I_0	9912^{h}	8148^{j}	8815^{ij}	9348^{hi}	I_0	5864^{i}	5905^{i}	4114^{j}	5316^{i}
I_1	9967^{h}	11288^{fg}	11019^{g}	12270de	I_1	12515^{bc}	11734^{d}	10595^{ef}	13141^{a}
I_2	12001^{ef}	12770^{bcd}	11707^{efg}	12424^{cde}	I_2	9897^{g}	9113^{h}	12516^{bc}	13483^{a}
I_3	12974^{abcd}	133378^{ab}	13661^{a}	13061^{abc}	I_3	10186^{fg}	10820^{e}	12276^{cd}	13104^{ab}

Planting density×Nitrogen dose interaction									
2022					2023				
	N_0	N_1	N_2	N_3		N_0	N_1	N_2	N_3
D_1	8343	8856	8543	8876	D_1	7187^{e}	5682^{f}	7942^{d}	7678^{d}
D_2	14083	13915	14058	14675	D_2	12044^{c}	13104^{b}	11809^{c}	14845^{a}

Planting density×Irrigation level interaction									
2022					2023				
	I_0	I_1	I_2	I_3		I_0	I_1	I_2	I_3
D_1	6856^{g}	9039^{f}	8740^{f}	9984^{e}	D_1	4366^{f}	7839^{d}	7691^{d}	8593^{c}
D_2	11255^{d}	13233^{c}	15711^{b}	16532^{a}	D_2	6234^{e}	16154^{a}	14813^{b}	14600^{b}

4. CONCLUSION

The effects of irrigation levels, plant density and nitrogen doses on grain yield and yield components of sweet sorghum, a highly adaptable C_4 crop that matures early under high temperatures under changing climatic conditions were investigated. The results revealed that as the irrigation level increased from 0% to 100% of crop evapotranspiration (ETc), grain weight per panicle, 1000 grain weight and grain yield also increased. As the plant density increased from 142857 plants ha^{-1} to 285714 plants ha^{-1}, grain weight per panicle and 1000 grain weight decreased, while grain yield increased significantly. As the nitrogen dose increased from 0 kg ha^{-1} to 210 kg ha^{-1}, grain weight per panicle, 1000 grain weight and grain yield increased in both trial years. In the study, maximum grain yield was obtained with 0 kg ha^{-1}, 70 kg ha^{-1}, 140 kg ha^{-1} and 210 kg ha^{-1} nitrogen doses at 100% of crop evapotranspiration (ETc) irrigation level in 2022 with rainy climatic conditions, while it was obtained with 210 kg ha^{-1} nitrogen dose in irrigated treatments (33%, 66% and 100% of crop evapotranspiration (ETc)) in 2023 with arid climatic conditions. When the plant density and nitrogen dose interactions were compared, although grain yield increased with increasing plant density in 2022, it did not interact with nitrogen doses, but plant density and nitrogen doses interacted in 2023 and the highest grain yield was determined at 210 kg ha^{-1} nitrogen dose interacting with 285714 plants ha^{-1} plant density. In the plant density and irrigation level interactions, the maximum grain yield was obtained from the interaction of 285714 plants ha^{-1} plant density and 100% of crop evapotranspiration (ETc) irrigation level in the rainy year 2022, while it was obtained from the interaction of 285714 plants ha^{-1} plant density and 33% of crop evapotranspiration (ETc) irrigation level in the dry year 2023. According to the results obtained from our study, a plant density of 285714 plants ha^{-1}, N dose of 210 kg ha^{-1} and 100% irrigation level are recommended to obtain high grain yield in semi-humid climatic conditions for sweet sorghum production. The climatic conditions of both study years were different, with significant differences in rainfall and temperatures. In 2022, the small difference between the effects of nitrogen doses is thought to be due to the fact that the rainfall washed away the applied nitrogen and reduced the effect of nitrogen. In 2023, when there was almost no rainfall and the air temperature was about 2 ^{o}C warmer, it was observed that some plants in the experimental area did not fill the grains. Therefore, the responses of some traits to the treatments differed. The research should be carried out in different locations to further support the literature and the most appropriate treatments under different climatic conditions.

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