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Yield Quality and Water Use Efficiency of Maize as Affected by Deficit Irrigation Treatment

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Article info	Abstract
Received: 02 August, 2025 Accepted: 28 August, 2025 Published: 10 September, 2025 Available in online: 17 September 2025 *Corresponding author:  shahidul_agron@ru.ac.bd 	Maize (<i>Zea mays</i> L.) is an essential crop for food, feed, and industry, particularly in regions like Bangladesh, where water scarcity is a growing concern. This study investigates the effects of deficit irrigation (DI) on maize growth, yield, and grain quality under varying water conditions. Conducted at the Agronomy Field Laboratory, Rajshahi University using a split-plot experimental design with three replications. The experiment involved two maize varieties (V_1 and V_2) and four irrigation treatments based on pan evaporation: T_1 (125%), T_2 (100%), T_3 (75%), and T_4 (50%). Results showed significant reductions in plant height, total dry matter (TDM), and grain yield with decreasing irrigation levels. The highest grain yield of 12.07 t ha⁻¹ was recorded under T_1, while the lowest yield of 7.87 t ha⁻¹ occurred under T_4. Similarly, TDM was highest in T_1 (141.60 g plant⁻¹) and lowest in T_4 (89.60 g plant⁻¹). Carbohydrate content in grains increased under water stress, with T_4 showing the highest carbohydrate content (69.07%), whereas protein content decreased, with the lowest protein content observed in T_4 (9.52%). The results indicate that although deficit irrigation enhances water-use efficiency, it significantly reduces maize productivity and quality. The study highlights key physiological mechanisms, including reduced turgor pressure, limited photosynthesis, and resource reallocation, which contribute to these variations. Keywords: Water Use Efficiency, Deficit irrigation, Pan evaporation and Nutritional quality.

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops in the world because of its wide range of uses in food, feed, and industry. As a staple food, it supplies carbohydrates, protein, vitamins, and minerals that are vital for human health and nutrition (Palacios *et al.*, 2020). It also serves as the major grain for livestock feed, accounting for more than half of the world's maize production due to its high energy content and balanced nutrients, particularly for poultry and cattle (Tanklevska *et al.*, 2020). Beyond food and feed, maize supports numerous industries through its use in starch, sweeteners, biofuels, and biodegradable polymers, making it a truly versatile crop that contributes to both economic growth and sustainable development (Albahri *et al.*, 2023). In Bangladesh, maize has become increasingly important over the last two decades and now ranks as the third most significant cereal after rice and wheat. The cultivation area has expanded rapidly, from 487,000 hectares in 2011 to about 570,000 hectares in 2022 (BBS,

2022). This expansion has been driven by the growing demand for poultry feed, the introduction of high-yielding varieties, and supportive government policies. Farmers are also drawn to maize because of its resilience across different soils and climates, making it well-suited to Bangladesh's variable weather. Compared with traditional crops, maize provides higher profitability and helps reduce the risks of crop failure, giving farmers a more stable source of income. At the same time, its nutritional profile makes it an important tool for tackling malnutrition and improving public health in the country (Adnan *et al.*, 2021; Goredema *et al.*, 2021). However, like many other crops, maize production in Bangladesh is increasingly challenged by water scarcity. Deficit irrigation (DI) has been recognized as a promising approach to manage this problem. The idea is to apply less water than the crop's full evapotranspiration (ET) requirement while still maintaining acceptable yields (Rai *et al.*, 2022). This method improves water-use efficiency, reduces irrigation costs, and can even enhance a crop's resilience to drought (Allakonon *et al.*, 2022). Maize, as a C_4 crop, already has a more efficient photosynthetic system than C_3 cereals like rice and wheat, producing around 20 kilograms of grain per millimeter of water used (Leakey *et al.*, 2019; Liu *et al.*, 2022).

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When carefully managed, DI can encourage maize to grow deeper roots and redirect more energy into grain filling rather than vegetative growth, helping it perform better under limited water conditions (Lubajo, 2022; Zou et al., 2021). Considering Bangladesh's rising demand for food, feed, and industrial resources alongside increasing water limitations, there is a clear need to optimize irrigation strategies for maize. This study therefore investigates how different levels of deficit irrigation affect maize growth, yield components, and overall productivity, while also examining the effects on grain quality, particularly carbohydrate and protein content.

Materials and Methods

Location and Site: The experiment was carried out in the Agronomy Field Laboratory, Department of Agronomy and Agricultural Extension, Rajshahi University, from December 2022 to April 2023. The soil in our experimental field was sandy loam textured with a pH of 7.6.

Climate: The experimental field was under subtropical climate characterized by moderately high temperature and heavy rainfall during the Kharif season (April to September) and scanty rainfall with moderately low temperature during the Rabi season (October to March).

Experimental Treatments: Two maize varieties, i.e., V₁ (Bayer 8225 maize) and V₂ (Syngenta7720 maize), collected from the Local market, Nowdapara, Rajshahi, used for this experiment. Irrigation frequencies includes- T₁= irrigation based on 125% of pan evaporation, T₂= irrigation based on 100% of pan evaporation,

T₃ = irrigation based on 75% of pan evaporation and T₄= irrigation based on 50% of pan evaporation. The experiment was laid out in a split plot experimental design with three replications, keeping the four irrigation frequencies in the main plots and two maize varieties in subplots. The size of each unit plot was 20 m² (5m×4m). Total number of unit plots was 24. To maintain proper moisture level in the plot according to treatments, 1.5 m gap within the plots and 2 m gap within the blocks were maintained

Cultivation Techniques: The experimental land was opened with tractor-drawn disc plough on 25th November with a country plough followed by laddering for breaking the clods and leaving the soil to obtain desirable tilt. Weeds and stubbles were removed the corners of the land were spaded and the larger clods were hammered to break into small pieces. After land preparation basal fertilizers were applied as per the recommendation of BARI fertilizer recommendation guide. After that, the maize seeds were sown plot wise. All the intercultural operations were performed accurately. Regular observations were performed during the crop growing period. Finally, the crop was harvested at full maturity.

Collection of Experimental data: Growth parameters such as plant height, total dry matter, values were recorded from randomly selected tagged plants. At maturity, the crops from each plot were harvested, bundled separately, and properly tagged for identification. Post-harvest observations were then collected according to the respective treatments. Analysis of grain quality parameters was carried out in the laboratory following standard procedures.

Table 1. Varietal differences, Irrigation frequencies and their interaction on plant height, total dry matter production of maize at different DAS

Varieties	Plant height (cm)			Total Dry Matter (TDM) g plant ⁻¹			
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	120 DAS
V ₁	34.72±1.37	88.54±2.65a	287.41±6.99a	6.77±0.2	19.56±0.88a	115.14±3.73a	131.15±4.88a
V ₂	31.45±1.01	79.27±3.0b	260.94±7.76b	6.85±0.36	14.71±1.82b	98.91±4.46b	108.30±6.9b
LS	NS	0.05	0.05	NS	0.01	0.05	0.05
Irrigation frequencies							
T ₁	32.98±1.86	92.44±4.07a	297.11±8.89a	6.80±0.28	21.3±0.81a	120.68±4.49a	141.60±5.36a
T ₂	31.91±1.78	87.11±3.79ab	282.94±9.6ab	6.76±0.43	18.61±1.33b	111.11±5.62ab	127.13±8.21a
T ₃	32.94±1.28	80.52±3.81bc	267.33±11.03ab	7.04±.43	15.62±1.96c	101.89±7.12bc	110.76±9.00b
T ₄	34.50±2.46	75.55±3.12c	249.33±8.6b	6.64±0.63	13.01±1.16d	94.33±4.55c	100.13±6.68b
LS	NS	0.01	0.01	NS	0.05	0.05	0.05
Interaction between varieties and irrigation frequencies							
V ₁ T ₁	34.40±3.66	94.11±6.54a	303.66±14.87a	6.87±0.57	21.93±0.89a	123±7.81a	143.73±6.32a
V ₁ T ₂	32.98±1.73	92.33±5.12a	296.66±11.05ab	6.79±0.70	21.14±1.17a	120.55±6.60ab	141.86±7.18a
V ₁ T ₃	33.29±2.76	87.50±3.65ab	287.66±12.86ab	6.78±0.14	19.88±1.03a	115.68±5.86ab	129.80±2.20ab
V ₁ T ₄	38.22±3.30	80.22±2.65abc	261.66±7.87bc	6.66±0.74	15.30±0.91b	101.33±5.16bc	110.66±8.77bc
V ₂ T ₁	31.56±1.92	90.77±6.10a	290.55±11.44ab	6.73±0.23	20.67±1.43a	118.37±5.87ab	139.46±9.97a
V ₂ T ₂	30.85±3.42	81.88±3.17abc	269.22±12.28abc	6.74±0.68	16.09±1.04b	101.82±5.20bc	112.40±8.28bc
V ₂ T ₃	32.60±0.685	73.556±3.27bc	247.00±5.50c	7.30±0.92	11.36±0.23c	88.11±5.44c	91.73±6.15c
V ₂ T ₄	30.78±2.373	70.88±4.45c	237.00±12.53c	6.63±1.19	10.72±0.81c	87.33±5.31c	89.60±5.93c
LS	NS	0.01	0.01	NS	0.05	0.05	0.05
CV(%)	13.65	12.32	6.41	18.44	10.12	9.66	10.40

Mean values in a column having the same letters or without letters do not differ significantly as per Duncan's multiple range test (DMRT), NS= Non significant, CV= Co-efficient of variation, LS= Level of significant, DAS=Day's after sowing. V₁ = Variety 1 (Syngenta NH-7720), V₂ = Variety 2 (Ishpahani diamond), T₁ = 1.25 Epan, T₂ = 1.00 Epan, T₃ = 0.75 Epan, T₄ = irrigation equivalent to 0.50 Epan.

Statistical Analysis: The collected data were analyzed using the "STATVIEW" statistical package. Mean differences were assessed using Duncan's multiple-range test.

Results

Plant Height (cm): Plant heights of two maize varieties were measured 30, 60, and 90 days after sowing (DAS), as shown in **Table 1**. The plant height did not vary significantly at 30 DAS, but it did at 60 and 90 DAS. At 30 DAS, V₁ had the highest plant height (34.72cm), while V₂ had the lowest value (31.45cm). At 60 DAS, V₁ achieved the highest plant height (88.54 cm), which was 10.46 % higher than V₂. The highest plant height (287.41cm) was obtained in V₁ at 90 DAS, which was 9.31 % higher than V₂. At 30 DAS, the variation in maize plant height under different irrigation frequencies was not statistically significant, but it varied significantly at 60 and 90 DAS (**Table 1**). At all growth stages, the plant height of maize decreased gradually with decreasing irrigation amounts, with the highest value obtained with the maximum irrigation amount or T₁. Treatment T₄ had the highest plant height (34.50 cm) at 30 DAS, while T₂ had the lowest value (31.91cm). At 60 DAS, T₁ had the highest plant height (92.44cm), which decreased slightly by 5.76 % in T₂ but significantly by 12.9 % and 18.27 % in T₃ and T₄, respectively. At 90 DAS, T₁ had the highest plant height (297.11 cm), which reduced only 4.76 % in T₂ but significantly by 10.02 and 16.08 % in T₃ and T₄, respectively. At all observations (30, 60, and 90 DAS), the variation in maize plant height was statistically significant due to the interaction between varieties and irrigation frequencies (**Table 1**). At 30 DAS, the interaction of V₁ with T₁ produced the highest plant height (34.40 cm), while V₂ with T₄

produced the lowest (30.78 cm). At 60 DAS, the combination of V₁ and T₁ produced the highest plant height (94.11 cm), while V₁ and T₄ produced the lowest (70.88 cm). At 90 DAS, the tallest plant (303.66 cm) was found in V₁ with T₁ and the shortest (237 cm) in V₂ with T₄.

Total Dry Matter (TDM): During our observation, we discovered a significant difference in total dry matter (TDM) production between maize varieties (**Table 1**). At 30 DAS, total dry matter production did not differ significantly, but it did at 60, 90, and 120 DAS. V₂ had the highest TDM (6.85 g plant⁻¹) at 30 DAS, while V₁ had the lowest TDM (6.77 g plant⁻¹). The highest TDM (19.56 g plant⁻¹) was obtained in V₁ at 60 DAS, which was 24.8 % higher than V₂. The highest TDM (115.14 g plant⁻¹) was obtained in V₁ at 90 DAS, which was 14 % higher than V₂. At 120 DAS, V₁ had the highest TDM (131.15 g plant⁻¹) and was significantly 17.42 % higher than V₂. From the above result, it can be said that total dry matter production varied within the maize varieties. Maize variety Bayer 8225 be more vigorous than Syngenta 7720. In most cases, a significant variation was found in maize's total dry matter (TDM) production due to different irrigation treatments, except for 30 DAS (**Table 1**). At 30 DAS, the highest TDM (7.04 g plant⁻¹) was observed in T₃ and the lowest (6.64 g plant⁻¹) was in T₄. At 60 DAS, the highest TDM (21.3 g plant⁻¹) was observed in T₁, which was reduced by 12.62 % in T₂ but significantly by 26.66 and 38.92% for T₃ and T₄, respectively. At 90 DAS, the highest TDM (120.68 g plant⁻¹) was observed in T₁, which was reduced by 7.93% in T₂ and significantly 15.57 and 21.83% in T₃ and T₄, respectively. At 120 DAS, the

Table 2. Varietal differences, Irrigation frequencies and their interaction on Leaf area and Relative water content of maize at different DAS

Varieties	Leaf area (cm ²)			Relative Water Content (RWC)%
	30 DAS	60 DAS	90 DAS	
V ₁	106.74±3.41	1685.10±37.89a	4462.12±95.06a	89.77±0.92a
V ₂	112.02±2.94	1536.88±41.77b	4076.11±108.31b	85.54±1.27b
LS	NS	0.05	0.05	0.05
Irrigation frequencies				
T ₁	107.56±4.04	1745.65±49.17a	4589.96±113.86a	91.13±1.09a
T ₂	106.83±5.17	1650.02±52.61ab	4394.32±136.81ab	88.95±1.45ab
T ₃	113.70±3.91	1569.34±61.52bc	4151.44±167.07bc	86.53±1.82bc
T ₄	109.42±5.56	1478.95±40.74c	3940.75±116.33c	84.01±1.51c
LS	NS	0.05	0.05	0.05
Interaction between varieties and irrigation frequencies				
V ₁ T ₁	106.37±6.68	1777.27±87.66a	4655±180.50a	91.17±1.99a
V ₁ T ₂	107.57±8.84	1729.39±58.47ab	4607.85±166.30ab	91.1±1.53a
V ₁ T ₃	113.42±6.98	1689.05±45.91ab	4471.81±143.58ab	90.06±1.21a
V ₁ T ₄	99.58±6.09	1544.71±57.28bc	4113.71±167.26bc	86.2±1.58ab
V ₂ T ₁	108.76±5.96	1714.04±58.07ab	4524.82±167.31ab	90.53±1.29a
V ₂ T ₂	106.08±7.41	1570.65±64.19bc	4180.79±142.59abc	86.8±1.88ab
V ₂ T ₃	113.98±5.26	1449.63±49.91c	3831.06±127.71c	83.00±1.62b
V ₂ T ₄	119.25±4.57	1413.19±26.36c	3767.79±98.85c	81.83±2.03b
LS	NS	0.01	0.05	0.05
CV(%)	10.44	6.27	6.14	3.3

Mean values in a column having the same letters or without letters do not differ significantly as per Duncan's multiple range test (DMRT), NS= Non significant, CV= Co-efficient of variation, LS= Level of significant, DAS=Day's after sowing. V₁ = Variety 1 (Syngenta NH-7720), V₂ = Variety 2 (Ishpahani diamond), T₁ = 1.25 Epan, T₂ = 1.00 Epan, T₃ = 0.75 Epan, T₄ = irrigation equivalent to 0.50 Epan.

Table 3. Varietal differences, Irrigation frequencies and their interaction on yield contributing characters and yield of maize

Varieties	Cob length (cm)	No. of grains cob ⁻¹	1000 grain weight (g)	Grain Yield (t ha ⁻¹)	Stover Yield (t ha ⁻¹)	Biological yield (t ha ⁻¹)	Harvest Index (%)
V ₁	15.44±0.41a	433.21±7.89a	355.14±12.02a	11.53±0.30a	10.25±0.54a	21.79±0.83a	53.20±0.70
V ₂	14.04±0.39b	400.97±9.94b	319.26±9.42b	9.57±0.48b	8.06±0.53b	17.63±1.01b	54.52±0.47
LS	0.05	0.05	0.05	0.01	0.01	0.01	NS
Irrigation frequencies							
T ₁	15.97±0.57a	445.49±9.46a	372.42±16.22 a	12.07±0.25 a	11.34±0.63a	23.42±0.86a	51.70±0.87b
T ₂	15.23±0.59ab	428.20±10.51ab	349.91±18.18ab	11.10±0.47b	9.64±0.74ab	20.75±1.19b	53.75±0.88ab
T ₃	14.22±0.60bc	406.67±13.45bc	318.55±10.67bc	10.09±0.74c	8.38±0.75bc	18.47±1.49c	54.77±0.58a
T ₄	13.55±0.36c	388.00±12.62c	307.92±7.39c	8.95±0.52d	7.26±0.44c	16.21±0.96d	55.21±0.39a
LS	0.05	0.05	0.05	0.01	0.05	0.01	0.01
Interaction between varieties and irrigation frequencies							
V ₁ T ₁	16.27±1.01a	451.16±16.21a	382.62±29.08a	12.30±0.44a	11.92±1.22a	24.22±1.62a	51.00±1.71b
V ₁ T ₂	16.07±0.99a	444.31±13.38ab	378.29±28.58a	12.13±0.32a	10.95±0.98ab	23.07±1.29a	52.67±1.55ab
V ₁ T ₃	15.30±0.57a	431.77±11.39ab	338.77±10.84abc	11.71±0.31a	9.97±0.49ab	21.69±0.80a	54.05±0.58ab
V ₁ T ₄	14.12±0.24ab	405.59±13.98bc	320.88±5.61bc	10.02±0.02b	8.16±0.22bc	18.18±0.25b	55.11±0.62a
V ₂ T ₁	15.63±0.72a	439.81±12.36ab	362.20±19.13ab	11.85±0.28a	10.76±0.43a	22.61±0.68a	52.42±0.62ab
V ₂ T ₂	14.38±0.24ab	412.10±10.70abc	321.37±5.65bc	10.10±0.05b	8.32±0.24bc	18.43±0.29b	54.83±0.59a
V ₂ T ₃	13.12±0.59b	381.57±12.06c	298.34±6.62c	8.45±0.22c	6.79±0.27c	15.25±0.42c	55.50±0.90a
V ₂ T ₄	13.00±0.53b	370.40±17.07c	294.95±8.57c	7.87±0.49c	6.39±0.35c	14.25±0.82c	55.32±0.63a
LS	0.05	0.01	0.05	0.05	0.01	0.05	0.05
CV(%)	7.82	5.63	8.76	5.10	11.94	7.89	3.22

Mean values in a column having the same letters or without letters do not differ significantly as per Duncan's multiple range test (DMRT), NS= Non significant, CV= Co-efficient of variation, LS= Level of significant, DAS=Day's after sowing. V₁ = Variety 1 (Syngenta NH-7720), V₂ = Variety 2 (Ishpahani diamond), T₁ = 1.25 Epan, T₂ = 1.00 Epan, T₃ = 0.75 Epan, T₄ = irrigation equivalent to 0.50 Epan.

highest TDM (141.60 g plant⁻¹) was observed in T₁, which reduced only 10.21% in T₂ but significantly 21.77 and 29.29% in T₃ and T₄, respectively. No significant effects in TDM were observed in the interaction between variety and irrigation frequency of maize (Table 1). At 30 DAS, the highest TDM (7.30 g plant⁻¹) was observed in V₂T₃ and the lowest value (g plant⁻¹) was observed in V₁T₄. At 60 DAS, the highest TDM (21.93 g plant⁻¹) was observed in V₁T₁ and the lowest value (10.72g plant⁻¹) was observed in V₂T₄. At 90 DAS, the highest TDM (123 g plant⁻¹) was observed in V₁T₁ and the lowest value (87.33 g plant⁻¹) was observed in V₂T₄. At 120 DAS, the highest TDM (143.73 g plant⁻¹) was observed in V₁T₁ and the lowest value (89.60 g plant⁻¹) was observed in V₂T₄.

Leaf Area (LA): The total leaf area (cm²) of maize varieties did not differ significantly at 30 DAS, but it did at 60 and 90 DAS (Table 2). At 30 DAS, V₁ had the highest leaf area (106.74 cm²) and V₂ had the lowest (112.02 cm²). At 60 DAS, the highest leaf area (1685.10 cm²) was obtained in V₁, which was 8.8 % greater than V₂. At 90 DAS, V₁ had the highest leaf area (4462.12 cm²), which was significantly higher (8.65%) than V₂. At 30 DAS, the effect of irrigation frequency on maize leaf area was not statistically significant, but it varied significantly at 60 and 90 DAS (Table 2). At 30 DAS, T₁ had the highest leaf area (107.56 cm²) and T₂ had the lowest (106.83 cm²). At 60 DAS, T₁ had the most leaf area (1745.65 cm²), which decreased slightly (5.47 %) in T₂, but significantly (10.09 and 15.27 %) in T₃ and T₄, respectively. At 90 DAS, T₁ had the most leaf area (4589.96 cm²), which decreased slightly (4.26 %) in T₂, but significantly (9.54 and 14.15 %) in T₃ and T₄, respectively. The interaction between varieties and irrigation frequencies significantly influenced the total leaf area (cm²) (Table 2). At 30 DAS, the highest leaf area (119.25 cm²) was produced by

the interaction of V₂ with T₄ and the lowest leaf area (99.58 cm²) was produced by the interaction of V₁ with T₄. At 60 DAS, the highest leaf area (1777.27 cm²) was produced by the interaction of V₁ with T₁ and the lowest leaf area (1413.19 cm²) was produced by the interaction of V₂ with T₄. At 90 DAS, the highest leaf area (4655 cm²) was produced by the interaction of V₁ with T₁ and the lowest leaf area (3767 cm²) was produced by the interaction of V₂ with T₄. **Relative Water Content (RWC %):** Significant differences in the Relative Water Content (RWC) of maize leaves were observed between the two varieties. Considering the variety, V₁ exhibited the highest RWC of 89.77%, which was significantly 5% higher than that of V₂ (Table 2). Considering the treatments, the highest RWC of 91.13% was recorded in T₁, with a slight reduction of 2.4% in T₂. A more significant decline of 5.08% was observed in T₃, and the lowest RWC of 84.01% was noted in T₄, representing a 7.81% decrease (Table 2). In case of interactions, the highest RWC of 91.17% was recorded in the combination of V₁T₁, while the lowest RWC of 81.83% was observed in V₂T₄ (Table 2).

Cob Length (cm): In terms of cob length, both maize varieties differed significantly. V₁ had the longest cob length (15.44 cm), which was 9.7 % longer than V₂ (Table 3). A significant difference in the cob length of maize was observed for different irrigation frequencies (Table 3). The highest cob length (15.97 cm) was recorded in T₁, which reduced slightly (4.63%) in T₂, but significantly by 10.95 and 15.15% in T₃ and T₄, respectively. Significant interaction in the cob length of maize was observed between varieties and irrigation frequencies (Table 3). Maximum cob length (16.27 cm) was recorded in the combination of V₁ with T₁ and the minimum (13 cm) was found in V₂T₄.

Number of grains cob⁻¹: A significant difference was found in the number of grains cob⁻¹ between the two maize varieties. The highest number of grains cob⁻¹ (433.21) was observed in V₁, which was significantly (7.44%) higher than V₂ (Table 3). Significant differences in the number of grains cob⁻¹ were observed for different irrigation frequencies (Table 3). The maximum number of grains cob⁻¹ (445.49) was recorded in T₁ which reduced slightly (3.84%) in T₂, but significantly by 8.65 and 12.90% in T₃ and T₄, respectively. Significant interaction in the number of grains cob⁻¹ was observed between maize varieties and irrigation frequencies (Table 3). The maximum number of grains cob⁻¹ (451.16) was found in the combination of V₁ with T₁ and the minimum (370.40) was found in V₂ with T₄.

Thousand (1000) Grains Weight (g): Varieties differ significantly in 1000 grains weight of maize. The highest 1000 grains weight (355.14 g) was observed from V₁, which was significantly 10.10% higher than V₂ (Table 3). Significant differences in 1000 grains weight were observed for different irrigation frequencies (Table 3). The maximum 1000 grains weight (372.42 g) was recorded in T₁ which reduced slightly (6.04%) in T₂ but significantly by 14.46 and 17.32% in T₃ and T₄, respectively. A significant interaction between varieties and irrigation frequencies in 1000 grains weight of maize was observed (Table 3). A maximum of 1000 grains' weight (382.62 g) was found in the combination of V₁ with T₁, and the minimum (294.95 g) was observed in V₂ with T₄.

Table 4. Varietal differences, Irrigation frequencies and their interaction on grain quality of maize

Varieties	Carbohydrate content (%)	Protein content (%)
V ₁	66.67±0.69a	10.90±0.20a
V ₂	68.45±0.49b	10.17±0.22b
LS	0.05	0.05
Irrigation frequencies		
T ₁	65.87±1.08b	11.19±0.27a
T ₂	67.08±0.92ab	10.75±0.28ab
T ₃	68.24±0.69ab	10.33±0.31bc
T ₄	69.07±0.44a	9.88±0.23c
LS	0.05	0.05
Interaction between varieties and irrigation frequencies		
V ₁ T ₁	65.24±1.98b	11.32±0.42a
V ₁ T ₂	65.87±1.61ab	11.14±0.45
V ₁ T ₃	67.07±0.88ab	10.93±0.36a
V ₁ T ₄	68.52±0.55ab	10.25±0.19ab
V ₂ T ₁	66.50±1.22ab	11.06±0.40a
V ₂ T ₂	68.30±0.45ab	10.35±0.23ab
V ₂ T ₃	69.42±0.51a	9.75±0.17b
V ₂ T ₄	69.62±0.62a	9.52±0.32b
LS	0.05	0.05
CV(%)	2.86	5.62

Mean values in a column having the same letters or without letters do not differ significantly as per Duncan's multiple range test (DMRT). NS= Non significant, CV= Co-efficient of variation, LS= Level of significant, DAS=Day's after sowing. V₁ = Variety 1 (Syngenta NH-7720), V₂ = Variety 2 (Ishpahani diamond), T₁ = 1.25 Epan, T₂ = 1.00 Epan, T₃ = 0.75 Epan, T₄ = irrigation equivalent to 0.50 Epan.

Grain Yield (t ha⁻¹): Both maize varieties differed significantly in grain yield. The highest grain yield (11.53 t ha⁻¹) was observed in V₁ (Bayer 8225) which was significantly 16.94% higher than V₂

(Syngenta 7720) (Table 3). Grain yield showed significant differences due to different irrigation frequencies (Table 3). The maximum grain yield (12.07 t ha⁻¹) was recorded in T₁ which reduced slightly (8.03%) in T₂ but significantly by 9.7 and 25.84% in T₃ and T₄, respectively. A significant interaction between varieties and irrigation frequencies in grain yield of maize was observed (Table 3). Maximum grain yield (12.30 t ha⁻¹) was found in the combination of V₁ with T₁ and the minimum (7.87 t ha⁻¹) was observed in V₂ with T₄.

Stover Yield (t ha⁻¹): There were significant differences found between the two varieties in stover yield. The maximum stover yield (10.25 t ha⁻¹) was observed in V₁, which was significantly higher (26.92%) than in V₂ (Table 3). Stover yield showed significant differences due to different irrigation frequencies (Table 3). The maximum stover yield (11.34 t ha⁻¹) was recorded in T₁, which reduced (15%) in T₂ but significantly 23.45 and 36% in T₃ and T₄, respectively. A significant interaction was found between varieties and irrigation frequencies on the stover yield of maize (Table 3). The highest stover yield (11.92 t ha⁻¹) was observed in the combination of V₁ with T₁ and the lowest (6.39 t ha⁻¹) was in V₂ with T₄.

4.10 Biological Yield (t ha⁻¹): Significant differences in biological yield were found between the two maize varieties. Maximum biological yield (21.79 t ha⁻¹) was observed in V₁, which was significantly higher (19.09%) than V₂ (Table 3). Significant differences were observed in biological yield for different irrigation frequencies (Table 3). The highest biological yield (23.42 t ha⁻¹) was recorded in T₁, which reduced slightly (11.40%) in T₂ but significantly 21.13 and 30.78% in T₃ and T₄, respectively. A significant interaction between varieties and irrigation frequencies was observed in the biological yield of maize (Table 3). The highest biological yield (24.24 t ha⁻¹) was observed in the combination of V₁ with T₁ and the lowest (14.25 t ha⁻¹) in V₂ with T₄.

Harvest Index (%): Between two varieties harvest index didn't differ significantly. The maximum HI (53.20%) was observed in V₁, and the minimum (54.52%) was found in V₂, (Table 3). The harvest index was not statistically significant at different irrigation frequencies. The maximum HI (55.21%) was recorded in T₄ and the minimum (51.70%) was found in T₁ (Table 3). A significant interaction was observed between varieties and irrigation frequencies in the harvest index (HI), (Table 3). The maximum HI (55.32%) was observed in the combination of V₂ with T₄ and the minimum (51 %) in V₁ with T₁.

Grain carbohydrate content (%): Significant differences in carbohydrate contents (%) in maize grain were found between the two maize varieties. The highest carbohydrate (68.45%) was observed in V₂, which was significantly 2.6% higher than that in V₁ (Table 4). The highest carbohydrate (69.07%) was observed in T₄ which reduced slightly by 1.2% in T₃ but significantly by 2.8 and 4.63% in T₃ and T₄ respectively. (Table 4). The highest carbohydrate (69.62%) was observed in the combination of V₂T₄, and the lowest value (65.24%) was obtained from V₁T₁ (Table 4).

Grain protein content (%): Significant differences in protein contents (%) in maize grain were found between the two maize varieties. The highest protein (10.9%) was observed in V₁, which was significantly (6.7%) higher than that in V₂. (Table 4). The highest protein (11.19%) was observed in T₁ which reduced slightly by 3.93% in T₂ but significantly by 7.68 and 11.7% in T₃ and T₄ respectively. (Table 4). The highest protein content (11.32%) was observed in the combination of V₁T₁, and the lowest value (9.52%) was obtained from V₂T₄ (Table 4).

Discussions

This study aimed to examine the effects of deficit irrigation (DI) on maize growth, yield, and grain quality under water-limited

conditions. The findings revealed significant variations in growth and yield parameters, which can be attributed to the physiological and biochemical mechanisms plants employ to cope with water stress. As irrigation frequency decreased, maize plants exhibited a reduction in growth, total dry matter (TDM), and yield. The primary physiological mechanism behind these reductions is the loss of turgor pressure in plant cells due to insufficient water availability. Water is essential for maintaining cell rigidity and promoting cell expansion. When water is limited, the plant cells undergo plasmolysis, resulting in reduced cell growth and, ultimately, stunted overall growth (Leakey et al., 2019, Al Baarri et al., 2022). This is consistent with the observed decline in plant height and dry matter production as irrigation frequency decreased. Additionally, the reduction in growth was more pronounced under severe water stress, highlighting the plant's inability to sustain cell expansion when water supply is severely restricted (Lubajo, 2022, Huang et al., 2022). Another critical mechanism affecting growth under water-limited conditions is the plant's regulation of stomatal conductance. To conserve water, plants close their stomata during periods of water deficit, which reduces transpiration. While this minimizes water loss, it also limits CO₂ intake, thereby reducing photosynthetic activity. In maize, this reduction in photosynthesis decreases the overall biomass production, as less carbon is fixed into plant tissues (Liu et al., 2022). The observed decrease in leaf area and relative water content (RWC) in the maize plants under lower irrigation treatments supports this mechanism, where decreased photosynthesis leads to reduced growth and water retention capacity (Rai et al., 2022, Ali et al., 2020). These responses were more severe in plants subjected to extreme water deficits, as the reduction in leaf area and RWC was most significant in the lowest irrigation treatments (Hassan et al., 2022). In terms of grain yield, water stress affects yield components such as grain number and size. Grain filling, which is a critical phase for determining yield, is highly sensitive to water availability. During water stress, maize reallocates resources from reproductive organs, such as the developing grains, to vegetative growth to maintain survival (Hassan et al., 2022). This often results in smaller grains and fewer grains per cob, contributing to the reduced yield observed under low irrigation treatments. Moreover, water stress-induced hormonal imbalances, particularly the disruption of auxin and gibberellin levels, can negatively impact grain development, leading to a reduction in both grain number and size (Rasool et al., 2020). The biochemical response to water stress also explains some of the variations in grain quality, particularly carbohydrate and protein content. Under water deficit conditions, maize plants tend to accumulate more carbohydrates, as they prioritize storage over growth. This mechanism helps the plant conserve energy and prepare for continued survival in a water-limited environment. Carbohydrates, being energy reserves, are stored in the form of starch in the grains, which is why we observed increased carbohydrate content in maize under water-limited conditions (Goredema-Matongera et al., 2021). Conversely, protein synthesis is energy-intensive, and during water stress, plants allocate fewer resources toward protein production. This results in lower protein content in grains under reduced irrigation, as observed in the study, and is consistent with findings from other research on drought-stressed maize (Chen et al., 2023). Furthermore, the interaction between water availability and maize growth can be explained by the plant's ability to adapt through root system expansion. In conditions of water stress, maize roots grow deeper in search of water, a process known as hydraulic redistribution. While this may help the plant access deeper soil moisture, it is not always sufficient to meet the water demands of the crop, especially when water stress is prolonged or severe. This physiological mechanism was likely more pronounced in the higher irrigation treatments, where

plants had better access to water and could sustain more vigorous root growth, supporting higher grain yields and better growth (Liu et al., 2022; Allakonon et al., 2022). In summary, the variations observed in this study can be primarily attributed to the plant's adaptive mechanisms to water stress, including reduced cell expansion, limited photosynthesis, resource reallocation, and altered biochemical processes. These mechanisms explain the decline in growth, yield, and quality under reduced irrigation frequencies (Rai et al., 2022; Lubajo, 2022).

Conclusion

The findings of this study indicate that deficit irrigation negatively impacts maize growth, yield, and grain quality, with significant reductions in plant height, total dry matter, and grain yield under lower irrigation frequencies. While carbohydrate content increased under water stress, protein content decreased, highlighting the trade-off between water conservation and nutritional quality.

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