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MODULATION OF FIBER AND NUTRIENT COMPOSITION IN MAIZE GRAINS UNDER DIFFERENTIAL DEFICIT IRRIGATION REGIMES

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ABSTRACT

Efficient water management is critical in modern agriculture, particularly in the face of increasing water scarcity and climate variability. Maize, a major cereal crop worldwide, is highly sensitive to water availability, making irrigation management a key factor in sustaining both yield and grain quality. This study was conducted to investigate the impact of deficit irrigation, including partial root-zone drying (PRD) techniques, on the grain quality parameters of maize. The experiment evaluated the effects of different irrigation levels 100% (full irrigation), 75%, 50% (with and without PRD), and 25% on key biochemical attributes of maize grain. Results revealed a significant influence of irrigation level on most grain quality parameters. ADF content increased progressively with reduced water application, peaking at 3.90% under 25% irrigation, while the lowest value (3.43%) was recorded under full irrigation. Conversely, NDF and hemicellulose contents were highest under full irrigation (19.13% and 15.70%, respectively) and decreased under severe water stress. Starch content also declined with increasing water deficit, with the maximum value under full irrigation and the lowest (63.33%) under 25% irrigation. Protein content was highest in the fully irrigated treatment, though differences among treatments were not statistically significant. Oil content showed a similar trend, with maximum values (2.80%) under full irrigation and a marked reduction under 25% irrigation. Ash content was unaffected by irrigation treatments. In conclusion, deficit irrigation, particularly severe water stress adversely affects several nutritional components of maize grain, especially fiber, starch, and oil content. However, moderate water-saving strategies like 50% irrigation with PRD may help maintain quality with reduced water input. These findings suggest that precision irrigation strategies can be optimized to conserve water without substantially compromising grain quality.

***Keywords**: Maize, fiber composition, deficit irrigation, fodder quality*

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INTRODUCTION

Maize (*Zea mays* L.) is one of the most vital cereal crops globally, playing a central role in food security, livestock feed, and industrial applications (Ananthi and Vennila, 2022). As global water scarcity intensifies due to climate change and increasing agricultural demand, optimizing water use without compromising crop productivity and quality has become a major focus of agronomic research (Schauberger et al., 2017; Nawaz et al., 2024). Deficit irrigation, a strategy that involves applying water below full crop evapotranspiration requirements, has emerged as a promising approach for improving water-use efficiency (Fereres & Soriano, 2007). While this technique can enhance drought resilience, it also has the potential to alter the biochemical composition of crops, which may affect their nutritional and industrial value.

Previous studies have shown that deficit irrigation can significantly influence the physiological and metabolic processes in maize, leading to changes in nutrient accumulation and biomass partitioning (Farooq et al., 2009; Zea et al., 2014; Nawaz et al., 2024). Specifically, water stress conditions often result in alterations in fiber fractions such as acid detergent fiber (ADF) and neutral detergent fiber (NDF), which are critical indicators of forage digestibility and feed value (Van Soest et al., 1991). Hemicellulose, a major component of plant cell walls derived from the difference between NDF and ADF, may also be affected under varying irrigation regimes due to changes in cell wall composition and structure.

In addition to fiber components, other biochemical parameters such as ash content, crude oil, starch, and protein are highly sensitive to water availability. Ash content, representing the total mineral content of biomass, may increase under drought conditions due to concentration effects and altered nutrient uptake (Hassanein et al., 2015). Crude oil content and starch reserves are known to decline under water-deficit stress, reflecting a shift in carbon allocation and reduced photosynthetic capacity (Cakir, 2004). Conversely, protein concentration in maize kernels can exhibit variable responses, sometimes increasing due to reduced kernel size and concentration effects, or decreasing due to limited nitrogen assimilation under drought (Barnabás et al., 2008).

Deficit irrigation has been shown to affect various biochemical components in maize. For instance, (Al-Naggar et al. 2016) observed that water stress led to a significant decrease in protein yield per hectare, oil yield per hectare, and starch yield per hectare, while slightly increasing grain protein content under water stress conditions. Similarly, a study by (Ghassemi-Golezani et al. 2015) found that water deficit and nitrogen levels influenced grain yield and oil and protein contents of maize. These findings suggest that water stress can alter the biochemical composition of maize, potentially affecting its nutritional value.

Despite a growing body of research, there remains a gap in understanding how specific levels of deficit irrigation (25%, 50%, 75%, and 100% of crop water requirement) impact the integrated biochemical profile of maize, especially under field conditions. This study aims to evaluate the influence of varying deficit irrigation levels on key biochemical constituents such as ADF, NDF, hemicellulose, ash content, crude oil, starch, and protein in maize grain. The findings are expected to inform sustainable water management strategies that optimize quality in maize production under water-limited environments.

MATERIALS AND METHODS

The experiment was conducted at the experimental site of Isparta University of Applied Sciences in the summer of 2024. Isparta Türkiye (37°45′ N and 30°33′ E). The area has hot, dry summers and mild winters. From May to October 2024, temperature ranged from 20°C in May to 30°C in August, with cooler weather in September and October. Rain was heaviest in May and October, with about 85.67 mm in May, while July and August were dry. Humidity was higher in spring and fall, and wind speeds were moderate throughout the year. The long term climatic data of the experimental site is given in table 1.

Table 1. Long-term climate data for the planting period of the experimental data (1929-2023) taken from Directorate General of Meteorology, Isparta Türkiye

Climatic Parameters	**Months**						**Average / Total**
	May	**June**	**July**	**August**	**September**	**October**	
Average temperature (ºC)	15.6	20.2	23.7	23.2	18.6	13.0	19.05
Humidity (%)	57.4	51.2	45.3	46.4	52.0	62.0	52.38
Sun Rad. (cal/cm²)	453.8	507.5	518.0	466.9	393.5	284.4	437.35
Evaporation (mm)	152.7	200.0	242.9	226.2	165.3	92.9	1080.0
Wind speed (m/sn)	2.0	1.9	1.9	1.8	1.7	1.7	1.83
Percipitation (mm)	52.3	30.6	14.6	11.7	17.0	37.1	163.3

The treatments were established using the RCBD (Randomized Complete Block Design) method with three replications. The plots of the treatments were allocated with 100%, 75%, 50%, and 25% deficit irrigation in combination with alternative technique PRD (Partial Root Drying) with one right and one left side irrigation (50% deficit) of the cultivated maize crop. Maize seeds were sown with 70 cm row spacing and 20 cm plant spacing. Each plot of the treatments was arranged to have 4 rows of 5 m row length (14 m^2 plot area). Sowing was done in May before proper cultivation of the field with a cultivator and rotavator. In this experiment, a variety of KWS Kerubino hybrids (*Zea mays* L., indentata) were used. The recommended dose of nitrogen (200 kg ha^{-1}) and phosphorus (80 kg ha^{-1}) was applied as MAP (Mono ammonium phosphate) source for phosphorus and urea for nitrogen. All phosphorus was applied at planting, while the nitrogen dose was divided into two doses, 50% at planting and 50% at the 40 cm crop growth stage. Appropriate weeding and hoeing were done when necessary. The crop was irrigated with drip irrigation with a drip discharge capacity of 2 L h^{-1}. Before each irrigation, the soil's moisture was measured using the gravimetric moisture determination method. Amount of soil moisture was monitored during crop vegetation period and was maintained the amount of required water to replenish the available soil water to the field capacity.

The soil characteristics related to irrigation was determined from soil samples of experimental area classified as clay (CL) with a bulk density of

1.46 g cm^{-3} at 0-30 cm and 1.41 g cm^{-3} at 30-60 cm. The field capacity was 29.7% (130.1 mm) for 0-30 cm and 31.8% (134.6 mm) for 30-60 cm. The wilting point was 13.6% (59.4 mm) for 0-30 cm and 15.5% (65.5 mm) for 30-60 cm. The total usable water holding capacity for the 0-60 cm depth was 138.8 mm.

At the beginning of the experiment, the same amount of water (calculated amount) was applied to all plots of the treatments for proper germination and emergence of maize seedlings. Subsequently, deficit irrigation was applied throughout the crop growth cycle.

The amount of the applied irrigation water to the treatments was calculated using Equation 1. The amount of irrigation water determined as depth terms, was calculated in volume terms by multiplying with the parcel unit area and the percentage of the wetted area during the applications (Equation 2).

$$I = (FC - AW)xSd \quad 1$$

$$V = \ I\ x\ A\ x\ WA \quad 2$$

Where; I, irrigation water amount (mm); FC, Field capacity (mm); AW, available water in the soil within 60 cm depth before irrigation applications (mm); Sd, irrigation water level; V, irrigation water amount as volume (L); A, plot area (m^2); WA, percentage of the wetted area (47%).

Data was collected on parameters such as: acid detergent fiber (%), neutral detergent fiber (%), hemicellulose (%), ash content (%), starch content (%), protein content (%) and crude oil content (%) using Agr-NIR.

Maize fodder biomass (without cobs) was oven-dried at 65 °C to constant weight and ground to pass a 1 mm sieve. Nutritional traits were analyzed with 3 replicates using Near Infrared Spectroscopy (NIRS) with a FOSS Forage Analyzer 5000 and Win ISI II software, calibrated against standard wet lab methods. Outliers were re-scanned for accuracy. A basic NIRS calibration for maize fodder was developed and validated (Global H = 1) and later updated by analyzing 10% of new samples using conventional methods (Hansey et al. 2010; Reddy et al. 2013).

The analysis of variance of the data obtained was performed in statistix 8.1 package program in accordance with the randomized complete blocks experimental design and the differences between the treatments were determined using least significant difference (LSD $P<0.05$) test.

RESULTS AND DISCUSSION

Irrigation amount (mm)

The applied amount of water to respective experimental units was 90 mm-25%, 180 mm-50%, 180 mm-50%PRD, 270 mm-75% and 360 mm to control-100% irrigation (Fig. 1).

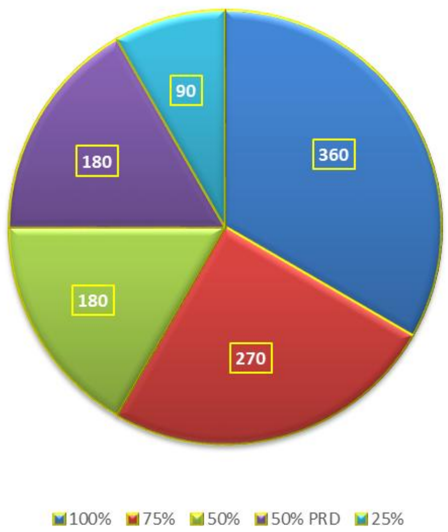

Figure 1. Amount of water (mm) applied to the crop during crop growing season

Acid detergent fiber (%)

Analysis of the data revealed significant effect of deficit irrigation on ADF content of maize grain (Table 2). Decreasing the water amount from maximum to minimum resulted in increase of ADF content (3.90 in case of 25% irrigation). However, the value of 25% was statistically at par with 50% irrigation of partial root drying approach. Lowest value of ADF (3.43) was recorded with application of 100% water (Field capacity condition). The increase in ADF could be possibly due to reduced starch deposition and relatively higher proportions of structural fibers like cellulose and lignin under drought stress. Several studies have indicated that water deficit conditions can lead to an increase in Acid Detergent Fiber (ADF) content in maize grain and forage. For example, (Tariq et al. 2022) observed a significant increase in ADF content across different developmental stages of maize under drought stress, and (Ali et al. 2021) similarly reported elevated ADF levels in forage maize subjected to water stress.

Neutral Detergent Fiber (%)

The effect of deficit irrigation was found significant on NDF content of maize (Table 2). Neutral Detergent Fiber content was increase with increase in irrigation. Maximum value of NDF (19.13) was recorded under full irrigation condition followed by 75% water application which was statistically under the same group of 50% irrigation with PRD approach. Lowest value of NDF (17.13) was observed under severe stress conditions (25% irrigation). The increase in NDF with irrigation like more in well watered and less under deficits conditions could be possibly due to less structural biomass formation, carbon reallocation, and altered grain development under water stress resulted in decreased NDF content in maize grain during deficit irrigation. Niño-Medina et al. (2018) examined the effects of drought stress on the nutraceutical properties of *Zea mays* bran and found that drought stress led to a decrease in NDF content in maize bran. Zhang et al. (2022) studied the effect of prolonged drought on the silage quality of maize and observed that drought stress at various stages significantly decreased NDF content in maize silage.

Hemicellulose (%)

Analysis of the data revealed significant effects of deficit irrigation on hemicellulose content of maize grains (Table 2). Maximum hemicellulose content (15.70) was detected under control conditions (full irrigation) followed by 75% irrigation treatment which was statistically at par with 50% irrigation and 25% irrigation. Minimum hemicellulose content was observed under 50% irrigation with PRD approach. Increased irrigation in maize cultivation leads to a rise in hemicellulose content in maize grains due to enhanced water availability, which supports better nutrient uptake and biomass accumulation. Irrigation significantly increases the dry matter accumulation in maize, particularly in the grains, as water availability supports optimal growth conditions (Shi et al. 2023). Recently, (Islam et al. 2012) observed a linear decrease in CP and in water-soluble carbohydrate contents and a linear increase in DM and NDF when increasing the supply of irrigation water.

Ash content (%)

Based on analysis of the data, there was no significant effect of irrigation on ash content of maize grains. Although. There was no effect of irrigation on ash content. However, maximum value of ash (1.40) was recorded under 25% deficit irrigation followed by rest of irrigation levels. These results are in line with those of (Kale et al. 2018) who observed lowest value of ash content under 50% irrigations (Table 2).

Starch content (%)

Analysis of data revealed significant effect of deficit irrigation on starch content of maize grains. Maximum starch content was recorded under full irrigation (control). Application of 50% water with PRD approach resulted in 66.66% starch content and the value was statistically at par with starch content of 75% water application (Table 2). Lowest starch (63.33%) content was recorded under 25% irrigation conditions. Drought-stressed cereals showed a reduced starch accumulation by up to 40%, due to alteration in starch biosynthetic enzyme activity (Beckles and Thitisaksakul 2013). Data from (Ge et al. 2010) indicated crops grown under moderate (soil relative water content of 60%) or severe (soil relative water content of 40%) stress conditions reduced grain yield from 60 to 80% and starch content from 8 to 33% with respect to the full water supply regime (soil relative water content of 80%).

Protein content (%)

Analysis of data revealed significant effect of deficit irrigation on grains protein content of maize. Highest protein content was recorded under full irrigation conditions (Table 2). However, the value of protein under full irrigation was statistically at par with the rest of irrigation treatments (25%, 50% and 75% irrigation level). Under well-watered conditions, the plant's ability to absorb and assimilate nitrogen is enhanced, leading to greater protein content in the grains. Increased irrigation enhances nitrogen uptake, promoting protein synthesis in maize grains. Optimal water levels facilitate chlorophyll production, boosting photosynthesis and carbohydrate transfer to grains, ultimately leading to higher protein accumulation (Kale et al. 2018). Irrigation enhances soil moisture, reducing drought stress, which can lead to higher protein synthesis in maize grains (Josipović et al. 2014).

Oil content (%)

A significant effect of deficit irrigation was observed on oil content of maize grains. Maximum oil content (2.80%) was recorded under full irrigation. Oil content under full irrigation was statistically at par with 75% and 50% irrigation with PRD approach (Table 2). Lowest oil content (2.20%) was observed under severe stress conditions (25% irrigation). The extent of oil content reduction under deficit irrigation can vary depending on the severity of the water deficit. The reduction in oil content under deficit irrigation can be attributed to several factors. Water stress during critical growth stages, such as grain filling, can disrupt the synthesis of lipids in the grain, leading to lower oil content (Kresović et al. 2018). Additionally, deficit irrigation may reduce the overall biomass production, which can further limit the allocation of resources to grain development, including oil accumulation (Wani and Karuku 2022). Our results are in line with those of (Kale et al. 2018) who stated that oil content of maize grains are positively correlated with increased irrigation.

Table 2. Effect of deficit irrigation on nutritional parameters of maize grains

Treatments	Examined traits						
Irrigation Levels (IL)	**ADF**	**NDF**	**HC**	**Ash**	**Starch**	**Protein**	**Oil**
25%	3.90 a	17.13 b	13.23 c	1.40	63.33 c	6.66 a	2.20 b
50%	3.80 b	17.50 b	13.70 bc	1.36	63.33 c	6.50 ab	2.30 b
50% (PRD)	3.50 a	15.46 c	11.93 d	1.36	66.66 b	6.10 b	2.80 a
75%	3.60 b	18.00 b	14.40 b	1.36	66.33 b	6.36 ab	2.63 a
100%	3.43 b	19.13 a	15.70 a	1.36	69.53 a	6.76 a	2.80 a
LSD	0.17	0.96	1.01	0.10	1.42	0.41	0.18
F-Value	12.33	20.31	20.03	0.21	35.66	4.29	24.59

ADF = Acid detergent fiber, NDF = Neutral detergent fiber, HC = Hemicellulose, LSD = Least significant difference

Heatmap analysis

Heat map results, full irrigation (100% FI) achieved the highest values in terms of starch content (SC), oil content (OC), protein content (PC), NDF, and hemicellulose content (HC), demonstrating that adequate water supply supports carbohydrate accumulation (Fig. 2). This finding is consistent with studies showing that under full irrigation conditions, photosynthetic products are transported more efficiently and accumulate in storage organs (Çakir, 2004; Farooq et al., 2009). In contrast, the 50% PRD application achieved high values for oil content (OC) but exhibited low levels of protein content (PC), NDF, and hemicellulose content (HC). This suggests that PRD may redirect metabolic responses through water stress and promote secondary metabolite synthesis (Davies et al., 2002; Kirda et al., 2005). 25% irrigation (DI 25%) resulted in high values for ADF and ash content (AC), but low levels of starch content (SC), oil content (OC), NDF, and hemicellulose content (HC). This finding is consistent with studies reporting that excessive water stress suppresses nutrient accumulation (NeSmith & Ritchie, 1992; Payero et al., 2006). In general, full irrigation increases carbohydrate accumulation, while PRD may promote oil content; however, excessive water restriction negatively affects quality components, reducing nutritional value.

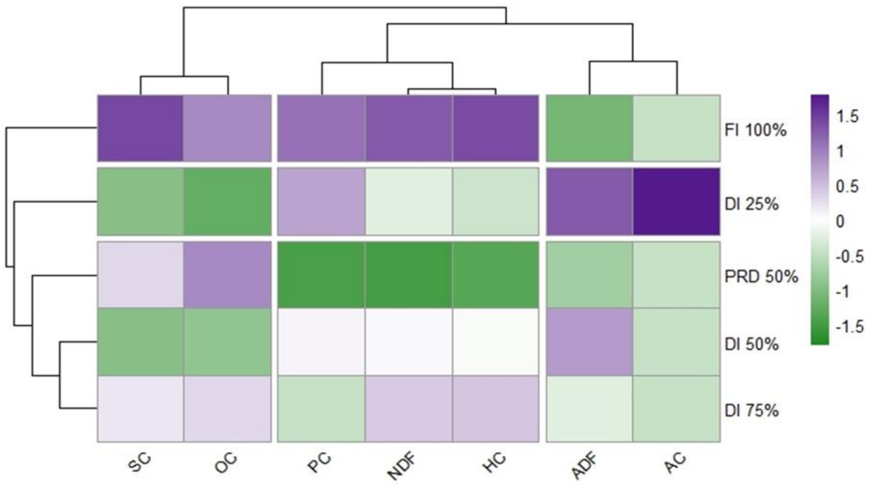

Figure 2. Heatmap representation of deficit irrigation and examined traits of maize grains

FI= Full irrigation DI= Deficit irrigation, PRD = Partial root drying

SC = Starch content, OC = Oil content, PC = Protien content, NDF = Neutral detergent fiber, HC = Hemicellulose, ADF = Acid detergent fiber, AC = Ash content

CONCLUSION

This study demonstrates that irrigation levels have a significant effect on the grain quality parameters of maize. Full irrigation consistently produced the highest values for key nutritional components, including starch, oil, and fiber fractions such as NDF and hemicellulose. In contrast, severe water stress (25% irrigation) led to a notable decline in these quality attributes, indicating that excessive water limitation can compromise grain nutritional value. While protein content remained statistically unaffected across treatments, other parameters such as starch and oil were more sensitive to water availability. Among the deficit irrigation strategies, the 50% irrigation level, particularly when applied through partial root-zone drying (PRD), emerged as a potential compromise, allowing for significant water savings while maintaining acceptable grain quality. These findings underscore the importance of optimizing irrigation practices to balance water conservation with crop quality in maize production.

RECOMMENDATIONS

Under water limited condition, use moderate deficit irrigation (50-75%) to conserve water with minimal quality loss. PRD approach can be suggested to improve grain quality of maize under the insufficient water source condition. Combine deficit irrigation with other water-saving practices (PRD) for better outcomes.

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