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Research Article

Effects of Water-Nitrogen Interactions on Cotton (*Gossypium hirsutum* L.): Growth, Yield and Water-Nitrogen Use Efficiency

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Abstract

Background and Objective: Cotton production in water-limited environments is constrained by the availability of irrigation and the efficiency of nitrogen fertilization. Optimizing the interaction between water and nitrogen inputs is essential to sustain yield while improving resource use efficiency. This study aimed to evaluate the combined effects of irrigation regimes and nitrogen application rates on the growth, yield, water use efficiency, and nitrogen use efficiency of cotton (*Gossypium hirsutum* L.). **Materials and Methods:** A field trial was conducted using a split-plot randomized complete block design, with two irrigation levels-well-watered (100% of crop ETc) and limited irrigation (75% of crop ETc)-and two nitrogen rates (100 and 200 kg N/ha). Agronomic and physiological traits, including plant height, root depth, total biomass, yield components, water use efficiency (WUE), and nitrogen use efficiency (NUE), were measured. A 10% significance level was used due to low replication (n = 3) to detect treatment differences, with significant ANOVA traits compared via mean separation accounting for replication variability. **Results:** Well-watered conditions significantly enhanced vegetative growth. The combination of limited irrigation with higher nitrogen (200 kg/ha) produced the highest seed cotton and lint yields, while also achieving maximum WUE (1.46 g/kg). In contrast, the highest NUE (59.2 g/g) occurred under full irrigation with the lower nitrogen rate (100 kg/ha). Increasing nitrogen consistently decreased NUE across both irrigation levels, highlighting the trade-off between yield and nitrogen efficiency. **Conclusion:** Optimizing water-nitrogen interactions is crucial for sustainable cotton production. Limited irrigation combined with higher nitrogen application can maintain yield performance and enhance WUE in water-scarce regions, while lower nitrogen rates favor nitrogen use efficiency. These findings provide practical guidance for resource-efficient cotton management and support strategies for sustainable agricultural production under water-limited conditions.

Key words: Cotton, limited-irrigation, nitrogen use efficiency, water use efficiency

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Understanding crop growth and developmental responses to projected climate changes, particularly to water deficits, is crucial, as water stress is one of the most significant abiotic factors that alters both the quantity and quality of crop products[1]. A lack of irrigation water influences the morphological and physiological processes, leading to limited plant development and reduced output[2,3].

As a primary source of natural fiber globally, cotton (*Gossypium hirsutum* L.) plays a crucial role in the agricultural economy of warm climate zones[4]. However, the escalating severity and occurrence of drought conditions pose a significant threat to productivity, creating economic risks for both growers and the textile sector[4,5]. The indeterminate variety of cotton (*Gossypium hirsutum* L.) is particularly vulnerable to drought stress, especially during blooming and boll formation[6,7]. Additionally, cotton's drought resilience is significantly influenced by nutrient availability, particularly nitrogen (N), which regulates key physiological processes during water stress[8].

Water scarcity driven by climate variability and shifting precipitation patterns is increasingly limiting global and regional agricultural productivity, with one-third of the world's cultivated land already affected[9]. Cotton, a water-demanding crop, is particularly vulnerable to these conditions, making efficient irrigation management essential. Recent studies emphasize that the expansion of drought-affected areas necessitates the adoption of water-saving strategies such as deficit irrigation[10].

Extensive research across Mediterranean and Middle Eastern regions has highlighted the benefits of reducing irrigation levels in sustaining cotton yield while improving Water-Use Efficiency (WUE). Drip irrigation generally produces higher yields and WUE than furrow systems[11]. For example, studies in Turkey and Syria reported seed cotton yields ranging from 2,550 to 5,850 kg/ha, with WUE values between 0.62 and 1.12 kg m^3 depending on irrigation levels[12-13]. Although reduced irrigation often lowers boll number and weight, moderate water reductions (~75% ETc) can maintain acceptable yields while significantly enhancing WUE[14]. These findings underline the urgent need for innovative irrigation approaches to conserve water resources and sustain cotton production.

Nitrogen stands out as a fundamental macronutrient governing plant productivity[15]. Adequate nitrogen supply is widely recognized for its ability to bolster drought resilience[16,17]. Contemporary research highlights the pivotal function of nitrogen in regulating physiological adaptations to water scarcity in crops[18,19]. These findings highlight a consistent trend across studies, underscoring the multifaceted role of nitrogen in drought adaptation.

Nitrogen is vital for plant growth and productivity, yet drought stress often limits its uptake and metabolism due to reduced transpiration and membrane permeability, ultimately impairing photosynthesis[20]. Recent studies have emphasized that sufficient nitrogen supply enhances growth and stress tolerance, whereas its regulatory role depends on both stress intensity and application level[21,22]. High nitrogen availability improves nitrogen metabolism, maintains photosynthetic activity, and supports osmotic adjustment through compounds such as proline, thereby mitigating drought effects[23]. These findings highlight the need to further investigate the interactive effects of nitrogen and drought on cotton physiology and productivity under changing climatic conditions.

This study aimed to evaluate the interactive effects of irrigation levels and nitrogen fertilization on cotton (*Gossypium hirsutum* L.) by assessing growth traits, yield, Water-Use Efficiency (WUE), and Nitrogen-Use Efficiency (NUE), to provide evidence for integrated water and nutrient management under water-limited conditions.

MATERIALS AND METHODS

Experimental site and design: The field experiment was conducted during the 2025 growing season at the experimental area of the Department of Field Crops, Faculty of Agriculture, Ege University (38.452383, 27.226027), İzmir, Türkiye. The soil at the experimental site was classified as clay loam with a slightly alkaline pH. During the 2024 growing season (May to November), the total recorded rainfall was only 66.4 mm. Air temperature (°C) and relative humidity (%) were continuously monitored on an hourly basis using a Tinytag Plus 2® data logger, while rainfall data were obtained from the Turkish State Meteorological Service. Long-term temperature and precipitation data (1938 to 2024) are presented in Table 1.

The experiment was established as a split-plot design in randomized complete blocks with three replications. Irrigation levels were assigned to the main plots, while nitrogen applications were assigned to the subplots. In this study, the cotton cultivar MAY 455 (*Gossypium hirsutum* L.) was used, selected for its early maturity, high germination rate, superior yield potential, and drought tolerance. Before sowing, seeds were treated with a fungicide to enhance germination and improve resistance against seed-borne pathogens.

Table 1: Rainfall, temperature, and relative humidity values during the growing season at İzmir-Bornova, and long-term rainfall means (1938-2024)

Month	Average temperature (°C)	Average humidity (%)	Total precipitation(mm)	Long-term average temperature (1938-2024)	Long-term total precipitation (1938-2024)
May	21.4	57.0	23.9	20.8	31.0
June	29.9	44.4	0.4	25.4	13.0
July	31.7	44.3	5.7	28.0	4.2
August	30.3	45.9	0.1	19.0	6.4
September	25.4	58.4	36.1	14.3	15.6
October	20.2	58.4	0.2	10.6	43.6

Field management and treatments: The cotton cultivar MAY 455 was sown on May 1, 2024. Two different irrigation treatments were applied. The control treatment (WW) received a total of 669 mm of irrigation water throughout the season, in addition to 66.4 mm of rainfall. This amount was determined based on regional irrigation recommendations for cotton production[10,24]. The limited irrigation treatment (LW) received 75% of the control amount (506 mm irrigation water+66.4 mm rainfall). Irrigation started on June 5, 2024, and a total of 7 irrigations were applied.

Nitrogen was applied in two stages to optimize nutrient uptake[25] and assess cotton response to different N levels. Total of 20:20:0 N:P:K containing fertilizer was used by sowing, while during flowering (July 12), ammonium sulfate (20.5% N) was applied as a second fertilizer application. In total, 200 kg N/ha was applied in the N200 treatment and 100 kg N/ha in the N100 treatment. To promote flowering, all treatments also received a foliar spray of potassium at 250 g pure K/ha on July. The standard recommended practices for cotton cultivation in the Aegean region were carried out, including manual weed control, thinning, pest management, and control of fungal diseases.

During the growing season, plant sampling was carried out twice: At mid-season 41 DAS (days after sowing) stage and at final physiological maturity. At harvest, a wide range of agronomic and morphological traits were recorded, including plant height, root depth, total biomass, root/shoot ratio, dry shoot, root and leaf weights, boll number, seed cotton yield, lint yield, leaf area (mid-season), Water-Use Efficiency (WUE), and Nitrogen-Use Efficiency (NUE). To minimize border effects, five plants were randomly selected from the two central rows of each plot, while border rows were excluded[26]. Plant samples were oven-dried at 105°C for 24 hrs to determine dry weights. After removing border rows, the remaining plants in each plot were hand-harvested, weighed, and yields were converted to kg/ha. Lint yield was calculated after ginning with a roller gin. WUE was determined by dividing seed cotton yield (kg/ha) by the total water input (irrigation+rainfall, mm), while NUE was calculated as yield per unit nitrogen applied[27] According to the following equations.

$$\mathrm{WUE}_{\mathrm{agronomic}} = \frac{\mathrm{Yield}_{\mathrm{IR100}} - \mathrm{Yield}_{\mathrm{IR75}}}{\mathrm{Water}_{\mathrm{IR100+Rain}} - \mathrm{Water}_{\mathrm{IR75+Rain}}}$$

$$\mathrm{NUE}_{\mathrm{agronomic}} = \frac{\mathrm{Yield}_{\mathrm{N200}} - \mathrm{Yield}_{\mathrm{N100}}}{\mathrm{Nitrogen}_{\mathrm{N200}} - \mathrm{Nitrogen}_{\mathrm{N100}}}$$

Statistical analyses: Statistical analyses were performed using R statistical software. A Two-way Analysis of Variance (ANOVA) was applied to evaluate the effects of irrigation, nitrogen levels, and their interactions. The agricolae package, as a component of R, was used for the statistical evaluations. To determine differences among treatments, the Least Significant Difference (LSD) test was applied at 0.5 significance level.

Considering the variation structure of the data and the low number of replications in the experiment (n = 3), a 10% significance level was preferred over 5% to more sensitively detect potential differences among treatments. For traits found significant in the ANOVA, treatment means were classified using mean separation (letter grouping), taking into account deviations among replications.

RESULTS AND DISCUSSION

The mean values and analysis of variance (ANOVA) results are presented for the studied agronomic traits of cotton under different irrigation and nitrogen treatments in Table 2. Irrigation regimes had significant effects on key parameters such as seed cotton yield, lint yield, boll number, and water-use efficiency (WUE). Nitrogen application also significantly influenced most yield-related and efficiency traits, while the interaction between irrigation and nitrogen was particularly significant for yield and NUE. These results indicate that both water and nitrogen management play decisive roles in determining cotton productivity and resource-use efficiency under Mediterranean conditions.

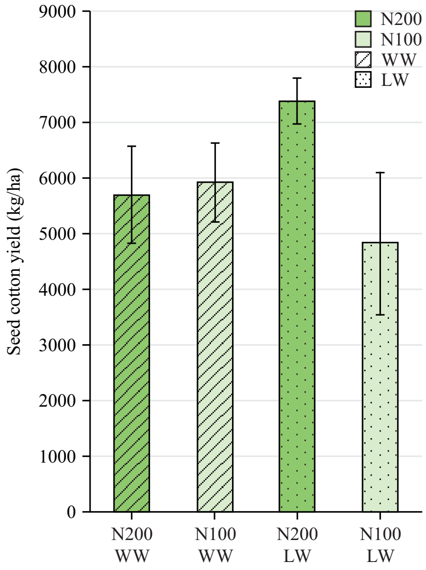

Fig. 1: Effect of different nitrogen (N100: 100 kg N/ha and N200: 200 kg N/ha) and irrigation (WW: 669 mm and LW: 506 mm) applications on seed cotton yield of cotton (*Gossypium hirsutum* L.)

Table 2: Mean values and Analysis of Variance (ANOVA) results for the effects of irrigation, nitrogen, and their interaction on some agronomic traits of cotton

Traits	WW	LW	P (Irr)	N200	N100	P (Nit)	P (Int)
PH (cm/plant)	57.2	49.0	0.005	57.2	60.8	0.257	0.738
RD (cm/plant)	28.3	22.5	0.135	28.3	29.2	0.364	0.545
R:S ratio	0.63	0.62	0.851	0.63	0.71	0.066	0.737
DRW (g/plant)	53.4	38.4	0.077	53.4	57.1	0.564	0.935
DSW (g/plant)	83.0	61.5	0.051	83.0	81.5	0.837	0.956
DLW (g/plant)	76.7	72.9	0.085	76.7	83.4	0.666	0.998
TB (g/plant)	136.4	99.9	0.058	136.4	138.6	0.895	0.997
LA_1 sample (cm^2)	1,480	708	0.007	1,480	374	0.481	0.557
LA_2 sample (cm^2)	1,545	778	0.006	1,545	1,470	0.130	0.450
SCY (kg/ha)	5,690	7,369	0.787*	5,690	5,920	0.280	0.203
LY (kg/ha)	2,479	32.3	0.885*	2,479	2,583	0.578	0.494
NB (n/plant)	30	26.7	0.717*	30	26	0.903	0.676
WUE (kg/ha)	0.85	1.46	0.003*	0.85	0.88	0.907	0.283*
NUE (g/g)	28.4	36.8	0.234	28.4	59.2	0.003	0.711*

WW: Well-watered (669 mm), LW: Limited irrigation (506 mm), N200: 200 kg kg/ha, N100: 100 kg N/ha, PH: Plant height (cm/plant), RD: Root depth (cm/plant), R:S ratio: Root/shoot ratio, DRW: Dry root weight (g/plant), DSW: Dry shoot weight (g/plant), DLW: Dry leaf weight (g /plant), TB: Total biomass (g /plant), LA_1 sample: Leaf area, first sampling (cm^2/plant), LA_2 sample: Leaf area, second sampling (cm^2/plant), SCY: Seed cotton yield (kg/ha), LY: Lint yield (kg/ha), NB: Number of bolls (boll/plant), WUE: Water-use efficiency (g/kg) and NUE: Nitrogen-use efficiency (g/g)

Yield parameters: Seed cotton yield was not statistically significant among treatments (p>0.1, Fig. 1), but clear numerical differences were evident. The highest yield was obtained under limited irrigation with high nitrogen (LW+N200, 7,369 kg/ha), while the lowest yield occurred under LW+N100 (4,806 kg/ha). Under WW, yields were intermediate and similar (5,921 and 5,691 kg/ha for N100 and N200, respectively). These findings suggest that nitrogen supply had a stronger compensatory role under water deficit, narrowing the gap between LW and WW.

Our results partly contrast with several earlier studies in the Mediterranean, which generally reported higher yields under full irrigation[10,13,24,28-30]. For instance, Dağdelen *et al.*[29] observed a 20-30% yield reduction when irrigation was reduced to 50% of ETc, and Tunalı *et al.*[10] showed that reducing irrigation to 67% of ETc lowered yield by ~32%. However, those studies did not explicitly examine the interaction between irrigation and nitrogen. In our trial, the yield advantage of LW+N200 indicates that nitrogen availability is a key factor determining whether limited irrigation leads to yield penalties or can be mitigated. This aligns with recent evidence that nitrogen enhances physiological adaptation and sustains photosynthesis under water-limited conditions, thereby supporting yield formation[31].

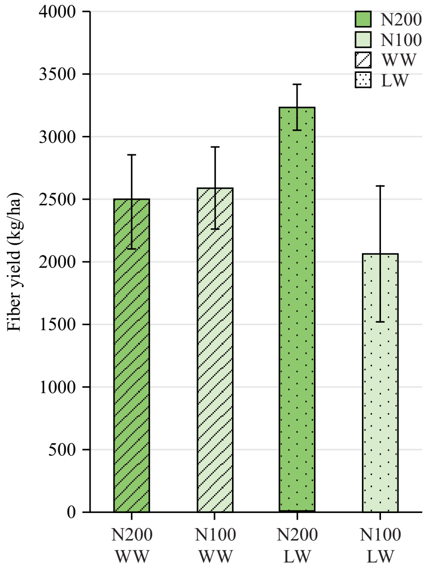

Fig. 2: Effect of different nitrogen (N100: 100 kg N/ha and N200: 200 kg N/ha) and irrigation (WW: 669 mm and LW: 506 mm) applications on fiber yield of cotton (*Gossypium hirsutum* L.)

Lint yield also showed no statistically significant differences at the 0.1 level (Fig. 2), yet clear mean contrasts were observed. The highest lint yield was obtained from LW+N200 (3,226 kg/ha), surpassing WW+N100 (2,583 kg/ha), WW+N200 (2,480 kg/ha), and LW+N100 (2,060 kg/ha). The relative benefit of nitrogen was therefore greater under limited irrigation, while under WW, lint yield remained relatively stable regardless of N input. These results indicate that nitrogen supply is particularly important for sustaining lint productivity when water is restricted.

Previous studies have reported variable responses of lint yield to irrigation and nitrogen management. Some authors found that moderate water deficits did not significantly reduce lint yield, provided sufficient nitrogen was supplied[1,14]. Basal *et al.*[14], for example, showed that drip irrigation at 75% ETc maintained lint yield and fiber quality. In contrast, Ertek and Kanber[32] and Blakcom *et al.*[33] noted that increasing irrigation sometimes reduced lint percentage, suggesting that excessive water may prolong vegetative growth and delay boll maturation. Our findings support the more recent evidence that nitrogen application can buffer lint yield against water stress, especially under moderate water limitation[31].

Boll number per plant was not statistically significant at the 0.1 level (Fig. 3), but mean values revealed some clear tendencies. The highest boll number was observed under WW+N200 (30 bolls/plant), while WW+N100 decreased boll number by 13.3% (26 bolls/plant). Both LW treatments (LW+N200 and LW+N100) produced nearly identical values (26.7 bolls/plant), representing an ~11% reduction compared with WW+N200. These results indicate that higher nitrogen enhanced boll formation only under full irrigation, whereas under limited irrigation the N response disappeared, suggesting that boll retention is primarily constrained by water availability.

Our findings align with previous[34], who demonstrated that while higher nitrogen rates increased yield components under well-watered conditions, this advantage was significantly diminished or lost under water deficit stress. In contrast, Rochester[35] indicated that nitrogen rates exceeding the crop requirement did not increase yield but rather reduced nitrogen use efficiency, leading to excessive vegetative growth. On the other hand, Iqbal *et al.*[31] reported that under water-deficit conditions, higher nitrogen supply is crucial for alleviating physiological stress by enhancing antioxidant enzymatic activities and osmotic adjustment. Such contrasting results highlight the strong dependency of cotton response to nitrogen on environmental conditions and management strategies.

Overall, yield traits (seed cotton, lint, and boll number) did not show statistically significant differences. The combination of limited irrigation with high nitrogen (LW+N200) consistently produced the highest seed and lint yields, while boll number was maximized under WW+N200. These findings indicate that nitrogen has a stronger compensatory effect under water deficit for yield, whereas boll production responds mainly under full irrigation. Taken together, the results emphasize the interactive role of water and nitrogen management in stabilizing cotton yield under Mediterranean conditions.

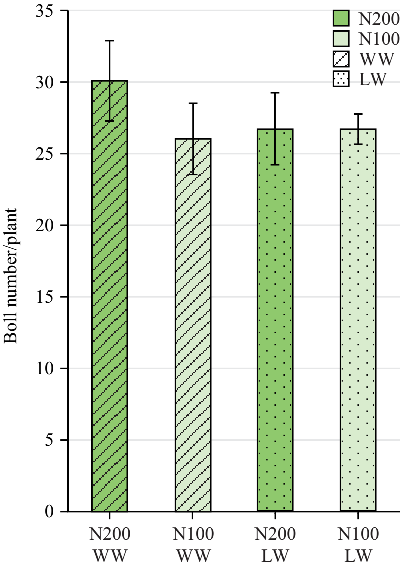

Fig. 3: Effect of different nitrogen (N100: 100 kg N/ha and N200: 200 kg N/ha) and irrigation (WW: 669 mm and LW: 506 mm) applications on number of bolls of cotton (*Gossypium hirsutum* L.)

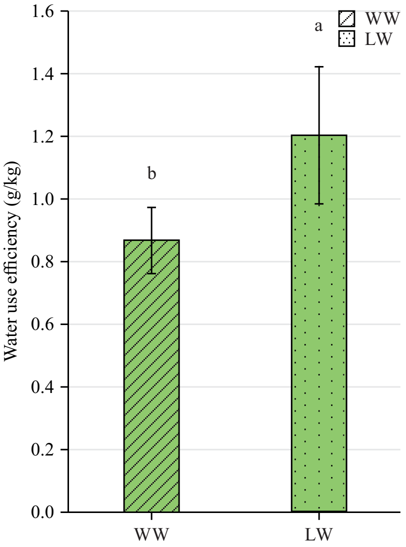

Fig. 4: Effects of full irrigation (WW) and limited irrigation (LW) on Water-Use Efficiency (WUE)
Different letters (a, b) indicate statistically significant differences

Resources use efficiency: Water-Use Efficiency differed significantly between treatments (Fig. 4). The LW treatment achieved the highest WUE (~1.20 g/kg), which was 38% greater than under WW (~0.87 g/kg). This confirms that plants used water more efficiently when the supply was limited, reflecting a physiological adjustment to drought stress. Similar results have been reported by Dağdelen *et al.*[24] and Hussein *et al.*[12], who observed that WUE was maximized at ~75-80% ETc. Xu *et al.*[36] further showed that moderate water deficits enhanced WUE by 7-25%, although yield decreased proportionally with stress intensity. Collectively, these findings indicate that controlled water limitation, especially when integrated with nutrient management, can improve WUE without severely compromising yield under Mediterranean conditions.

Nitrogen-Use Efficiency was significantly affected by N application rate (Fig. 5). The highest NUE was recorded at the lower N rate (N100: 54.7 g/g), which was 41% higher than under N200 (32.1 g/g). This decline at higher N indicates that excess fertilizer was not effectively utilized by the crop, reducing efficiency and increasing the risk of losses. Comparable outcomes have been reported in cotton and

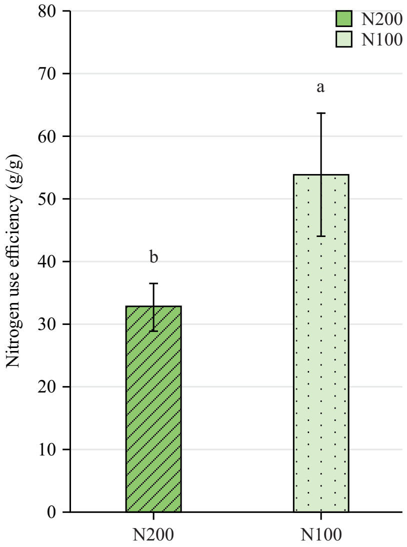

Fig. 5: Effects of different nitrogen applications (N100: 100 kg N/ha and N200: 200 kg N/ha) on Nitrogen-Use Efficiency (NUE) of cotton (*Gossypium hirsutum* L.)

Different letters (a, b) indicate statistically significant differences

other field crops, where NUE consistently decreases as N supply exceeds crop demand[37]. Our findings therefore, underline the importance of optimizing N dosage in cotton to maximize yield benefits while minimizing environmental costs.

Efficiency traits revealed clear treatment effects at the 0.1 level. Water-use efficiency (WUE) was significantly higher under limited irrigation (LW) than under full irrigation (WW), confirming that plants utilize available water more efficiently under controlled deficit conditions. Conversely, nitrogen-use efficiency (NUE) was maximized at the lower nitrogen rate (N100), while excess fertilization (N200) reduced efficiency by over 40%. Together, these findings highlight the importance of integrating moderate water limitation with optimized nitrogen supply to improve resource-use efficiency in cotton production.

Growth parameters: Plant height was significantly affected by irrigation regime, while nitrogen rate and the N× irrigation interaction were not significant. The mean plant height was 54.5 cm, with WW plants reaching 59.0 cm compared with 49.9 cm under LW, representing a 15% reduction. This result is consistent with earlier findings that water stress shortens plant height in cotton[7,31]. In contrast, nitrogen supply did not significantly affect height, indicating that even the lower rate (100 kg N/ha) was sufficient for vegetative growth under the experimental conditions.

Root depth did not differ significantly among treatments. However, mean values showed a decrease under LW (25.6 cm) compared with WW (28.8 cm). Interestingly, nitrogen tended to have the opposite effect: N100 increased root depth (27.9 cm) relative to N200 (25.4 cm), suggesting compensatory root development under lower N availability, as reported by Iqbal *et al.*[31].

Similarly, root/shoot ratio was not statistically significant (Fig. 3), with values of 0.67 under WW and 0.68 under LW. Nitrogen again showed a trend, with higher ratios under N100 (0.69) compared to N200 (0.65). This reflects the allocation of more biomass to roots under low nitrogen supply, which enhances soil exploration and nutrient uptake under stress conditions. Comparable responses were reported in other crops as well, where water or nutrient stress increased root/shoot ratios as an adaptive strategy[38].

Dry matter traits were significantly affected by irrigation regime but not by nitrogen rate or the N× irrigation interaction. Across traits, WW consistently produced higher dry weights than LW, while nitrogen effects were minor. Mean root dry weight was 55.3 g/plant under WW compared with 40.8 g/plant under LW, while N100 tended to increase root mass (50.2 g) relative to N200 (45.9 g). Shoot dry weight followed the same pattern, with WW plants averaging 82.2 g versus 60.2 g under LW, reflecting a 22% reduction. Leaf dry weight showed the largest decline under water stress, falling from 83.4 g in WW+N100 to 47.3 g in LW+N200 (-38%). Total biomass was maximized in WW+N100 (139 g/plant), slightly higher than WW+N200 (136 g), whereas LW treatments produced only ~100 g/plant.

These results confirm that water availability was the primary determinant of biomass accumulation, while excess nitrogen offered little advantage and in some cases, exacerbated drought sensitivity. Similar findings have been reported in cotton and other crops, where moderate nitrogen improved drought resilience, but higher rates reduced efficiency and increased sensitivity[39]. Comprehensive reviews also indicate that optimal biomass production occurs under full irrigation with moderate N inputs, while excessive N supply can depress stress tolerance[40]. Taken together, our findings suggest that balanced nitrogen fertilization combined with adequate irrigation supports maximum biomass production, whereas limited water availability sharply reduces root, shoot, and leaf growth regardless of N rate.

Leaf area was significantly influenced by both irrigation and nitrogen levels, with their interaction also showing a strong effect. The highest values were consistently obtained in WW+N200, confirming that sufficient water and nitrogen create the most favorable conditions for vegetative growth. In the first sampling (July 10), differences among treatments were more pronounced, with the lowest leaf area observed under LW+N100, reflecting the high sensitivity of early vegetative stages to water and nutrient stress. By the second sampling (July 25), differences narrowed, particularly between WW+N200 and WW+N100, suggesting that cotton plants partially compensated later in the season through adaptive mechanisms or reduced vegetative demand.

These results agree with previous findings that both water and nitrogen deficiencies significantly reduce leaf area and photosynthetic capacity[41]. In this context, Faver *et al.*[8] emphasized that leaf expansion is the physiological process most sensitive to resource deficits, often ceasing before photosynthesis is affected. Similar synergistic responses have been documented in other crops; for instance, Shangguan *et al.*[18] demonstrated in wheat that nitrogen deficiency exacerbates the effects of water stress, restricting leaf area development and photosynthetic efficiency. Overall, our findings highlight that canopy growth is highly dependent on the coordinated availability of both water and nitrogen.

CONCLUSION

This study demonstrated that irrigation regime and nitrogen supply exerted distinct effects on cotton (*Gossypium hirsutum* L.) performance. The highest seed cotton yield (7,369 kg/ha) and lint yield (3,226 kg/ha) were obtained under limited irrigation combined with high nitrogen (LW+N200), indicating a synergistic effect between moderate water deficit and adequate nitrogen in maximizing reproductive output. Efficiency traits also showed clear responses: Water-Use Efficiency (WUE) peaked under LW (1.20 g/kg), while Nitrogen-Use Efficiency (NUE) was highest at the lower nitrogen rate (N100), declining by over 40% when the rate was increased to N200. These results highlight that excessive nitrogen does not translate into greater efficiency and may even reduce returns under well-watered conditions.

Growth traits were more strongly promoted by full irrigation (WW), which enhanced plant height, biomass, and leaf weight relative to LW, confirming that vegetative development is primarily water-dependent. However, root allocation patterns indicated adaptive responses under reduced nitrogen, with higher root/shoot ratios supporting resource capture under stress.

Overall, the findings emphasize that integrated water and nitrogen management is essential for sustainable cotton production. While WW favors vegetative vigor, a strategy combining moderate water limitation with sufficient nitrogen (LW + N200) can maximize yield and resource-use efficiency, offering a practical approach for cotton cultivation in water-scarce Mediterranean environments.

SIGNIFICANCE STATEMENT

This study highlights the critical role of optimizing water and nitrogen management in cotton production under water-limited conditions. By demonstrating that limited irrigation paired with higher nitrogen can sustain yield and improve water use efficiency, while lower nitrogen enhances nitrogen use efficiency, the findings offer practical strategies for balancing productivity with resource conservation. This knowledge is significant for developing sustainable cotton farming practices that maximize yield and efficiency in water-scarce regions.

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