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Impact of Early-Season Supplementary Irrigation on Durum Wheat Production in a Semi-Arid Environment: A Case Study of the Upper Chélif Plain, Algeria

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Abstract

This study evaluates the impact of early-season supplementary irrigation — also referred to as establishment irrigation — on the growth, yield components and grain yield of durum wheat (Triticum turgidum L. var. durum, cv. Simeto) under semi-arid conditions. A field experiment was conducted over three growing seasons (2021–2024) in the Upper Chélif plain, Northern Algeria, at the experimental farm of the University of Djilali Bounaama, Khemis-Miliana (UDBKM), using a randomized complete block design (RCBD) with four irrigation regimes: full irrigation (PI), early-season irrigation with terminal stress (SF), late-season irrigation with early-cycle stress (SD), and a rainfed control (P). The traits assessed were plant height (PH), spike density (number of spikes m^{-2}; NSM), number of grains per spike (NGS), thousand-kernel weight (TKW) and grain yield (GY). Data were analysed by analysis of variance (ANOVA). Year, irrigation regime and their interaction had highly significant effects on all measured traits ($p < 0.0001$), with coefficients of determination (R^2) ranging from 0.93 to 0.99. The PI and SF treatments consistently produced the highest values for every trait and significantly outperformed the water-deficit treatments; notably, SF achieved this while using approximately 33% less water than PI. Despite pronounced interannual climatic variability and recurrent spring water deficits, early-season irrigation improved and stabilised durum wheat productivity. These findings demonstrate that early-season supplementary irrigation is an effective, water-efficient management strategy for enhancing grain yield and strengthening the resilience of durum wheat to water stress in semi-arid Mediterranean environments.

Keywords: Triticum turgidum var. durum; early-season irrigation; grain yield; ANOVA; water stress; semi-arid environment; Simeto.

1. Introduction

The rational use of water for cereal production in regions where water is scarce and costly requires targeted, innovative and evidence-based research, together with heightened awareness among agricultural stakeholders (Bouthiba et al., 2008).

Geographically, the Upper Chélif plain lies within the sub-humid bioclimatic stage (Kelkouli et al., 2024); however, its climatic characteristics — long, hot summers, cold winters, and markedly shortened autumns and springs — place it within a continental climatic regime. The total cereal-growing area in this region covers 58,000 hectares, of which durum wheat accounts for 45,000 hectares (77%). The average yield of this crop is 2,000 kg ha^{-1}, with peaks exceeding 6,000 kg ha^{-1} under irrigation (Grosse-Heilmann et al., 2024).

Water resources in the region originate mainly from dams, seasonal watercourses (wadis) and groundwater; however, their limited availability during periods of peak demand, particularly in drought years (Rezzouk et *al.,* 2022), constitutes a major agronomic constraint (Merouche et al., 2014). Most of Algeria's cereal-growing areas are located where rainfall is both insufficient and irregular, which severely compromises attainable yield levels (Smadhi et al., 2017). Durum wheat requires approximately 550–600 mm of water to complete its cycle,

whereas mean annual rainfall of 350 mm covers only 58% of this requirement. Winter rainfall is generally adequate, but late-winter and spring rainfall is frequently insufficient, occurring at an adequate frequency in only one year out of five (ITGC, 2021). In other words, the Upper Chélif plain faces recurrent constraints associated with drought, declining precipitation and elevated temperatures, all of which directly affect durum wheat cultivation (Claus & Legoupil, 1972).

Supplementary irrigation has helped to mitigate these water deficits and improve yields (Royo, et al., 2006). , yet overall production remains below desired levels. Field experience has shown that supplementary irrigation has shifted from an optional practice to an absolute agronomic necessity (Merabet & Boutiba, 2005).

In the semi-arid Upper Chélif zone, early-season irrigation — sometimes termed establishment irrigation — constitutes a strategic technique for improving not only plant stature and grain yield, but also the specific yield components defined by FAO (2012): spike density, spike fertility, and individual grain weight (Giunta, et al., 1993).. The frequent water constraints characteristic of this region strongly limit the expression of the genetic yield potential of durum wheat cultivars (Farooq et al., 2014), particularly during the critical tillering and grain-filling stages.

Under early-season irrigation, the resulting soil water reserve comfortably meets the plant's early water demand, and yields become more stable, with grains generally exhibiting better calibre and greater homogeneity. Previous work conducted in the Upper Chélif plain has shown that mean irrigated yields reach approximately 5,400–5,900 kg ha^{-1}, compared with only 1,500–3,000 kg ha^{-1} under rainfed management (Merabet & Boutiba, 2004).

The overall objective of this study was therefore to monitor durum wheat production under four contrasting water regimes over three consecutive growing seasons: full irrigation covering 100% of crop water requirements (PI); early-season irrigation covering 80% of requirements, with stress imposed at the end of the cycle (SF); late-season irrigation covering 80% of requirements, with stress imposed at the beginning of the cycle (SD); and a rainfed treatment without irrigation (P) (Borbón-Gracia et al., 2023). The results obtained make it possible to characterise the effect of the Upper Chélif plain's climatic variability, over three years, on durum wheat production under these different water regimes, with particular emphasis on early-season irrigation (Bellague et al., 2023). Specifically, this study aims to demonstrate that under the semi-arid conditions of the Upper Chélif plain, early-season irrigation represents a major agronomic lever for improving plant height, spike density, spike fertility, thousand-kernel weight and overall grain yield, thereby mitigating the impact of climatic hazards on durum wheat production.

2. Materials and Methods

2.1 Study site and plant material

The durum wheat cultivar used was Simeto, a semi-dwarf, semi-early cultivar derived from the cross Capeiti × Valvona. It is widely grown by cereal farmers in the semi-arid and sub-humid regions of Algeria owing to its excellent adaptability and efficient use of irrigation water. Trials were carried out at the experimental farm of the University of Djilali Bounaama, Khemis-Miliana (UDBKM; altitude 289 m; latitude 36°15′–36°35′ N; longitude 1°30′–2°40′ E), located approximately 40 km inland from the Mediterranean coast (Fig. 1).

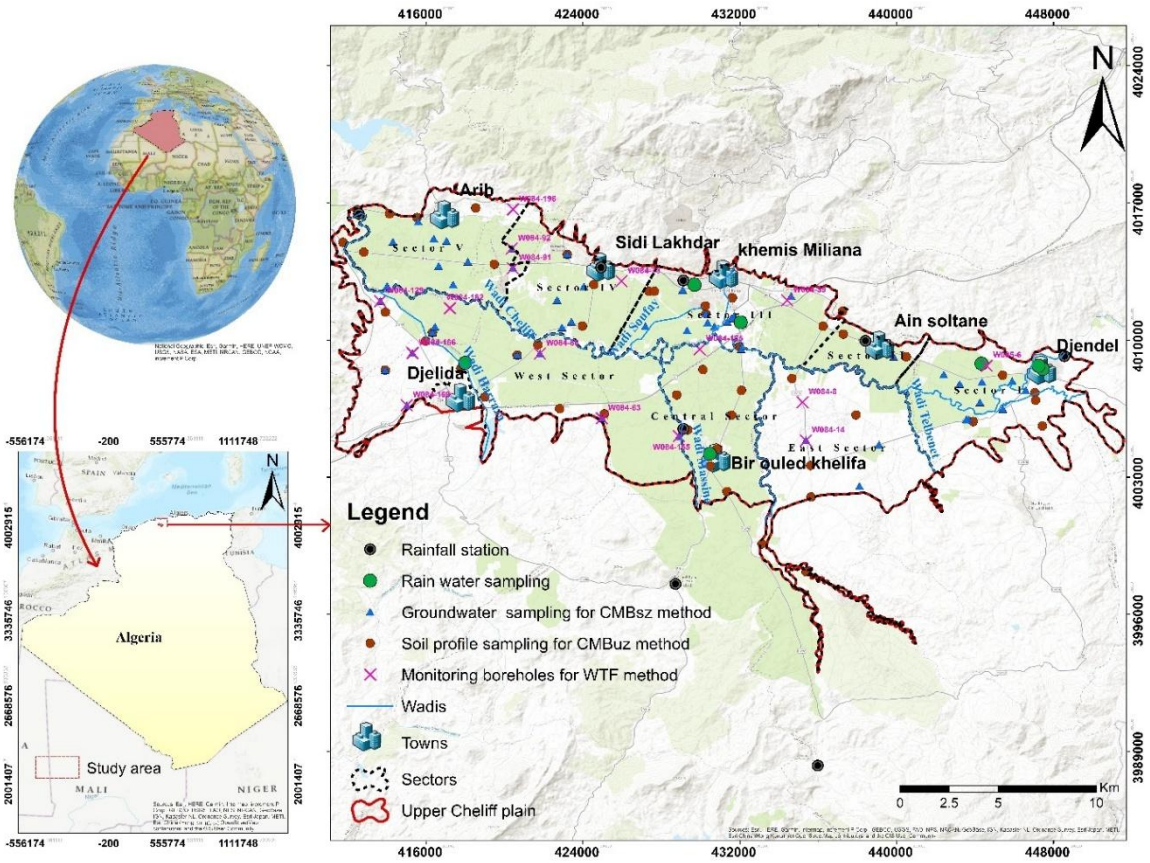


Fig. 1. Limit of study area (Upper Cheliff in plain of Khemis Miliana)

2.2 Experimental design and treatments

The choice of irrigation dose is based on the principle of the durum wheat crop's needs, which vary between 500 and 600 mm of water to complete its cycle, well distributed throughout the crop's growth stages (Karrou, et *al*., (2012).

Given the average annual rainfall of the last three decades (1990-2020), which is 380 mm according to the ITGC meteorological bulletin, the difference—which is simply the amount of supplemental irrigation needed to meet the total water requirement—will be between 120 mm, if we consider the minimum total requirement to be 500 mm, and 220 mm, if we consider the total requirement to be 600 mm. For good distribution, we used values of 210 mm for the initial irrigation (PI) and 140 mm for the final irrigation (SF) and the continuous irrigation (SD). Irrigation is only initiated when soil moisture reaches 60% of the water retention capacity or when 40% of the water retention capacity is depleted. Soil moisture is sampled and monitored at the following depths:

0 to 20 cm from sowing until stem elongation;
0 to 40 cm from stem elongation until heading;
0 to 60 cm from heading until maturity.

The trial followed a randomized complete block design (RCBD) with four replications (Fig.2). The four treatments corresponded to distinct water regimes:

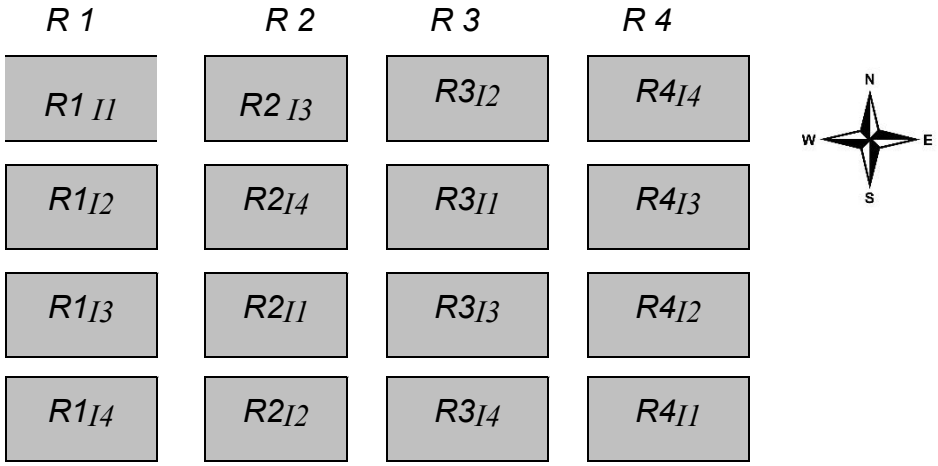
T1 (PI) — Full irrigation (210 mm): applied at three phenological stages — early tillering, stem elongation, and the milky-grain stage.

T2 (SF) — Early-season irrigation, stress at the end of the cycle (140 mm): applied at two stages — early tillering and stem elongation.

T3 (SD) — Late-season irrigation, stress at the beginning of the cycle (140 mm): applied at two stages — stem elongation and the milky-grain stage.

T4 (P) — Rainfed control: no irrigation applied throughout the cycle.

Treatments T1 (PI) and T2 (SF) both received water during the early stages of the cycle and therefore represent early-season irrigation, whereas T3 (SD) was deliberately withheld water at the start of the cycle and irrigated only later, representing late-season irrigation. These treatments were compared with one another and with the rainfed control to assess the specific efficacy of early-season irrigation under the contrasting climatic conditions encountered during the three years of experimentation.



R: Replication I: Irrigation

Fig. 2. Layout of the experimental design adopted for three years

2.3 Agronomic management

Each experimental unit consisted of six rows, 5 linear meters in length, with 0.20 m inter-row spacing (Fig.2). Sowing was carried out with an experimental HEGE 80 seed drill at a density of 350 seeds m^{-2} in all three years, on 23 December 2021 (Year 1), 21 December 2022 (Year 2) and 26 December 2023 (Year 3); in every case the preceding crop was a tilled summer fallow.

Soil tillage consisted of mouldboard ploughing with a reversible two-furrow plough at the end of summer, followed by secondary tillage with an 8/16 cover-crop cultivator in mid-November, and harrowing immediately before sowing to ensure adequate soil tilth and levelling. Following soil analysis, phosphorus (Super 46, 46% P_2O_5) was applied at 50 units ha^{-1} and potassium (K_2O) at 45 units ha^{-1}. Nitrogen, in the form of 46% urea, was applied in two fractions of 50 units ha^{-1} each: the first at the two-to-three-leaf stage and the second at active tillering, both applied manually to ensure even distribution. Weeds were controlled manually, given the high temperatures typical of late winter and spring in this region and the associated phytotoxicity risks of chemical herbicides. Harvesting was carried out in two stages: manual cutting at physiological maturity (13% grain moisture), followed by stationary threshing with a Wintersteiger sheaf thresher. Monitoring focused on plant height — a key parameter reflecting the crop's response to irrigation and climatic variability — together with grain yield and its components.

2.4 Climatic conditions (2022–2024)

The climatic conditions recorded during the three growing seasons (2021/2022 to 2023/2024) in UDBKM weather station revealed marked interannual variability in both temperature (Fig.3) and rainfall (Fig. 4), consistent with the semi-arid character of the Upper Chélif climate.

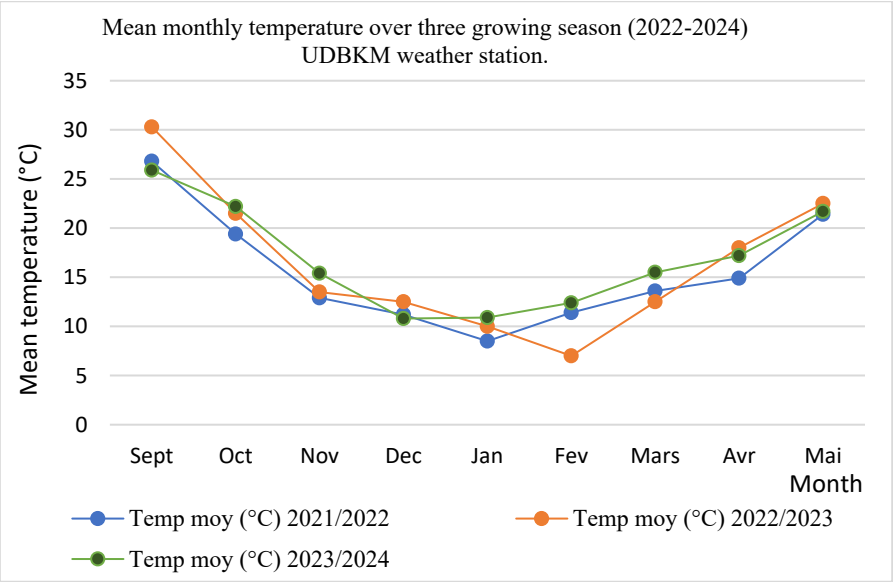


Figure 3. Mean monthly temperature over the three growing seasons (2022–2024).

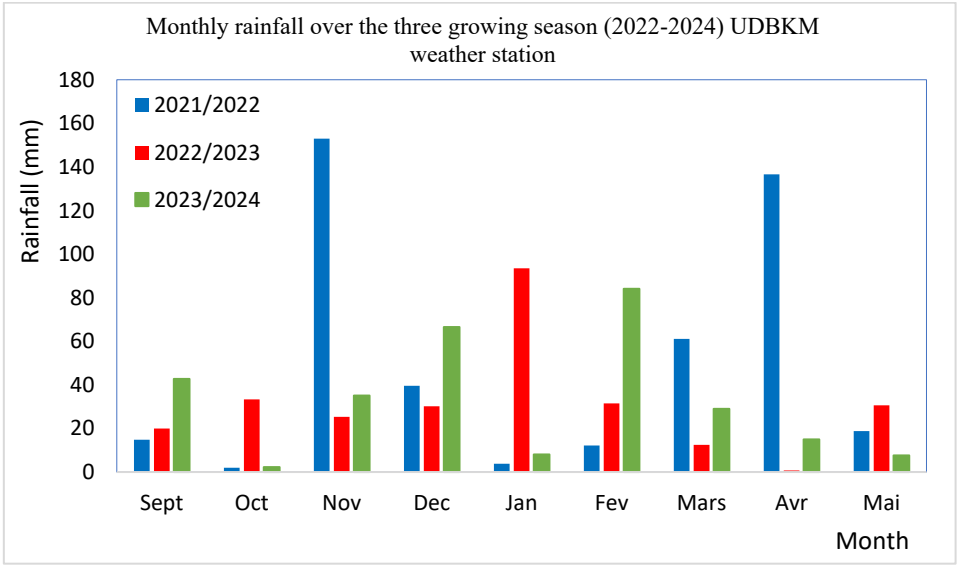


Figure 4. Monthly rainfall over the three growing seasons (2022–2024).

Year 1 (2021/2022) was the wettest season (441.9 mm), whereas Years 2 (2022/2023, 277.6 mm) and 3 (2023/2024, 290.4 mm) showed a marked rainfall deficit relative to the 30-year normal (346 mm). Temperatures followed a normal seasonal pattern, with elevated values towards the end of the crop cycle. The limited water availability in spring, combined with rising temperatures, likely intensified water stress during the critical stages of durum wheat development. These climatic conditions justify the evaluation of early-season irrigation as a strategy for improving wheat productivity in semi-arid environments.

2.5 Soil characteristics of the experimental field

a. Physical and chemical soil analyses

Regarding soil physical properties, the analyses performed at the University Laboratory presented in Table 1 revealed that the experimental soil exhibited a texture ranging from clay loam in the surface horizon (0–40 cm) to clay in the deeper layers, with clay content increasing progressively from 31% to 47% with depth, accompanied by a corresponding decline in silt content. This fining-downward textural gradient reflects a typical clay-accumulation profile and suggests a relatively high water-holding capacity in the subsurface horizons, favorable for sustaining moisture reserves under supplementary irrigation. However, this same clay enrichment may reduce soil permeability and increase the risk of compaction in deeper layers, potentially restricting root penetration and slowing water movement through the profile — factors that warrant consideration when defining irrigation timing and depth in this type of soil.

Table 1. Physical properties of the soil, and particle size distribution (%)

0–40	31.0	45.7	21.5	Clay loam
40–60	41.8	30.3	27.2	Silty clay
60–100	46.0	20.0	30.4	Clay
>100	47.0	16.9	26.5	Clay

b. Chemical soil analysis

The chemical analyses performed at the University Laboratory (Table 2) indicated that the soil was moderately calcareous (10.5–16.5% $CaCO_3$), slightly saline (electrical conductivity of 2.53–3.02 mmhos cm^{-1}), and had a neutral to slightly alkaline *p*H (6.59–7.55). Soil organic carbon and organic matter contents decreased markedly with depth, reflecting the enrichment of the surface horizon with organic residues. Potassium and sodium contents increased slightly with depth but remained within levels that are not considered restrictive for durum wheat cultivation. Overall, these results characterize a soil generally suitable for durum wheat production, where water availability is likely to be the main limiting factor, thereby supporting the assessment of the effects of starter irrigation.

Table 2. Chemical properties of the soil

0–40	10.50	2.55	6.59	0.56	0.87	0.32	1.09
40–60	11.33	2.53	6.95	0.41	0.58	0.48	1.76
>60	16.50	3.02	7.55	0.09	0.12	0.59	1.64

2.5 Statistical analysis

Data were processed using Statistica for Windows (version 8) and SAS (version 9.1), using one-way ANOVA with standard settings at a significance threshold of $\alpha = 5\%$. Mean separation was performed using Tukey's

HSD and Fisher's Least Significant Difference (LSD) tests; homogeneous groups were determined at the 5% and 1% probability thresholds.

3. Results

The results obtained are presented and interpreted with a view to evaluating the effect of early-season irrigation on the growth and yield components of durum wheat (cv. Simeto). Statistical analyses, in particular analysis of variance (ANOVA), were used to identify differences among treatments and experimental years.

3.1 Overview of mean values and analysis of variance

Table 3. Mean values of the studied traits by irrigation regime (averaged over three years)

PI	65.91	266.06	54.10	35.89	31.44
SF	63.45	238.61	50.14	32.81	26.96
SD	59.96	210.77	45.10	28.83	23.34
P	54.46	170.72	39.19	23.98	19.76

PH: plant height; NSM: number of spikes per square metre; NGS: number of grains per spike; TKW: thousand-kernel weight; GY: actual grain yield.

Table 4. Summary of the analysis of variance (irrigation regime × year)

Standard error	0.35	2.185	0.564	0.457	0.583
Standard deviation	15.34	50.99	14.38	6.164	14.65
R^2	0.994	0.978	0.981	0.932	0.981
Adjusted R^2	0.992	0.971	0.975	0.912	0.975
F-value	521.49	142.22	170.08	45.21	165.15
Pr > F	0.0001	0.0001	0.0001	0.0001	0.0001
Significance	***	***	***	***	***

*** *denotes significance at $p < 0.0001$.*

The mean values of the studied traits (Table 3) show that the PI regime recorded the highest values for plant height (65.91 cm), spike density (266.06 spikes m^{-2}), number of grains per spike (54.10), thousand-kernel weight (35.89 g) and grain yield (31.44 q ha^{-1}), with SF values only slightly lower, whereas the P treatment consistently recorded the lowest values. These results highlight the favourable effect of early-season irrigation on the growth and productivity of durum wheat. The statistical indicators derived from the analysis of variance reveal an excellent goodness of fit for all studied variables (Table 4). The very high F-values, associated with extremely low probabilities ($p < 0.0001$), show that the experimental factors exert a highly significant effect on all agronomic traits analysed. The coefficients of determination (R^2) indicate that the models explain between 93.2% and 99.4% of the total variability of the observations, and the corresponding adjusted R^2 values, very close to the R^2 values themselves, confirm the absence of overfitting and underline the robustness of the statistical models employed.

The low standard-error values observed for the different traits reflect good estimation precision and low residual-error variability. In contrast, the higher standard deviations, particularly for NSM (50.99) and grain yield (14.65 q ha^{-1}), reflect the biological variability inherent to these traits without compromising the overall quality of the models. The highly significant effect (***; $p < 0.0001$) observed for all variables confirms that the differences recorded among treatments are genuine and do not result from random fluctuation.

3.2 Plant height (PH)

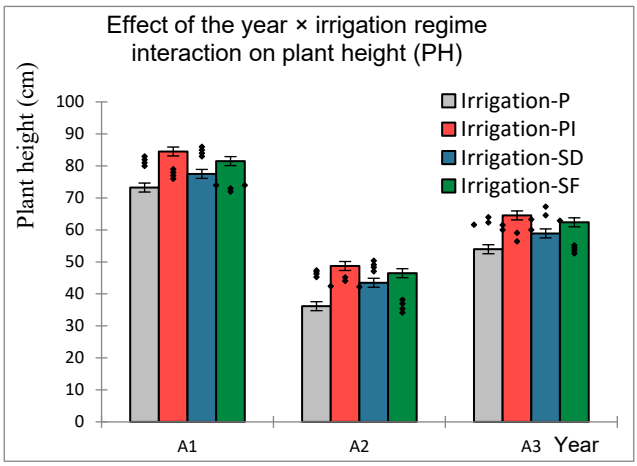


Figure 5. Effect of year × irrigation regime interaction on plant height

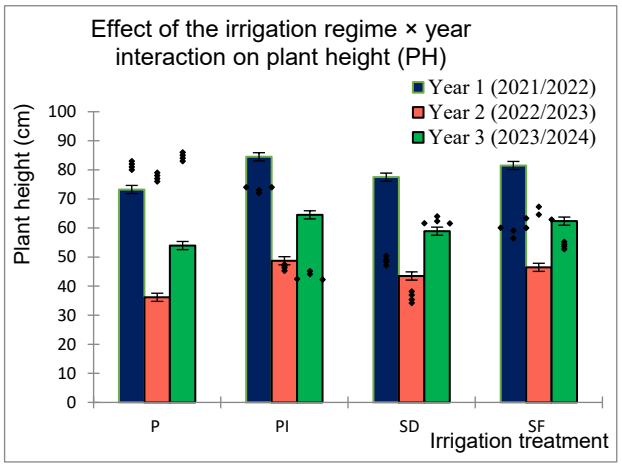


Figure 6. Effect of the irrigation regime × year interaction on plant height.

Figures 5 and 6 show that plant height was consistently influenced by the irrigation regime across the three growing seasons. Full irrigation (PI) produced the tallest plants, followed by supplemental irrigation (SF), whereas late irrigation (SD) and the rainfed control (P) resulted in significantly shorter plants, confirming the positive effect of early water supply on vegetative growth.

The ANOVA confirmed these observations (Table 2). The effects of year ($F = 2537.55$, $P < 0.0001$) and irrigation regime ($F = 148.85$, $P < 0.0001$) were highly significant, indicating that both climatic conditions and irrigation management strongly affected plant height. In contrast, the **year** × irrigation interaction was not significant ($F = 1.06$, $P = 0.4087$), demonstrating that the response of plant height to irrigation was consistent among years. The experiment also showed excellent statistical precision. The residual mean square was only 1.99, while the coefficient of variation (CV = 2.31%) indicated very low experimental variability and high measurement accuracy. The overall mean plant height was 60.95 cm, confirming the good agronomic performance of the crop under the experimental conditions. These statistical indicators demonstrate the robustness of the experimental design and the reliability of the observed treatment differences.

Overall, the results indicate that adequate water supply, particularly during the early growth stages, significantly enhances stem elongation and vegetative development in durum wheat under semi-arid conditions. The absence of a significant year × irrigation interaction further suggests that the beneficial effect of irrigation on plant height was stable across different climatic conditions, highlighting the consistency of the irrigation strategy.

3.3 Spike density (NSM)

Figure 7. Effect of year irrigation × regime interaction on the number of spikes per square meter

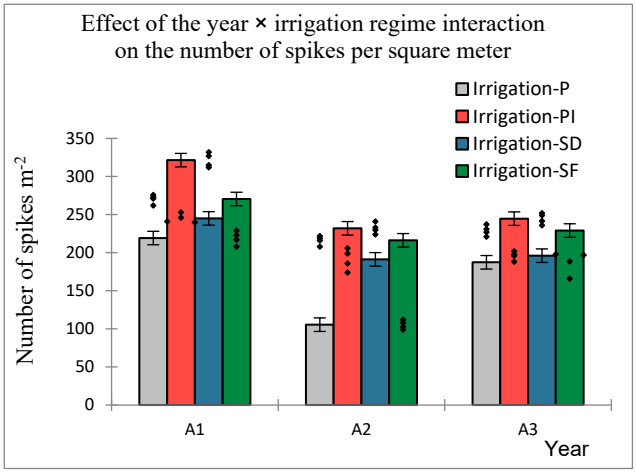
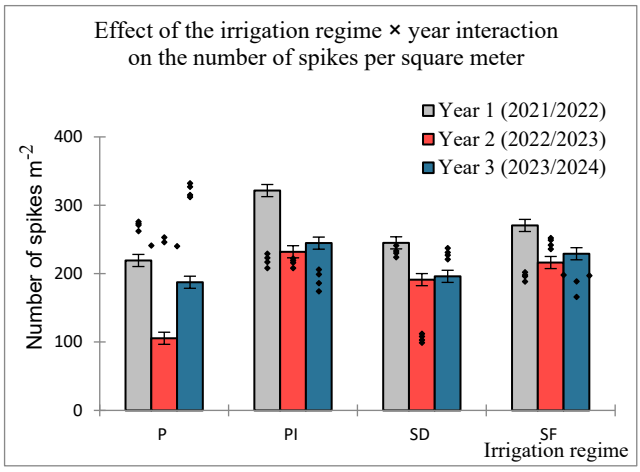


Figure 8. Effect of the irrigation regime × year interaction on the number of spikes per square meter



Figures 7 and 8 clearly demonstrate that spike density was markedly affected by both irrigation regime and growing season. Across the three experimental years, full irrigation (PI) consistently produced the highest number of spikes per square meter, followed by supplemental irrigation at sowing (SF), whereas late supplemental irrigation (SD) and the rainfed control (P) resulted in significantly lower spike densities. Although climatic conditions varied among years, the ranking of irrigation treatments remained generally stable, confirming the beneficial effect of early water supply on tiller survival and spike formation.

The ANOVA revealed a highly significant effect of the experimental factors on spike density ($F = 142.22$; $P < 0.0001$), indicating that irrigation management explained a large proportion of the observed variability. The LSD test ($P \leq 0.05$) further confirmed significant differences among irrigation treatments, with mean spike density decreasing in the order PI (266.05 spikes m^{-2}) > SF (238.61 spikes m^{-2}) > SD (210.77 spikes m^{-2}) > P (170.72 spikes m^{-2}), each treatment belonging to a distinct homogeneous group.

The year effect was also highly significant, with average spike density declining from 264.06 spikes m^{-2} in 2022 to 214.31 spikes m^{-2} in 2024 and 186.25 spikes m^{-2} in 2023, reflecting differences in seasonal climatic conditions. The combined year × irrigation comparison identified seven homogeneous groups, with the highest value recorded under PI in 2022 (321.50 spikes m^{-2}) and the lowest under the rainfed treatment in 2023 (105.50 spikes m^{-2}). These results indicate that climatic conditions influenced the magnitude of spike production, whereas irrigation consistently maintained its positive effect across years.

The higher spike density observed under PI and SF is attributed to improved water availability during tillering, which enhanced tiller emergence, survival, and the development of fertile spikes. In contrast, water deficit under rainfed conditions reduced tiller survival and spike initiation, leading to lower spike density. These findings demonstrate that early supplemental irrigation is an effective agronomic practice for increasing spike density and improving the yield potential of durum wheat under semi-arid Mediterranean environments.

3.4 Number of grains per spike (NGS)

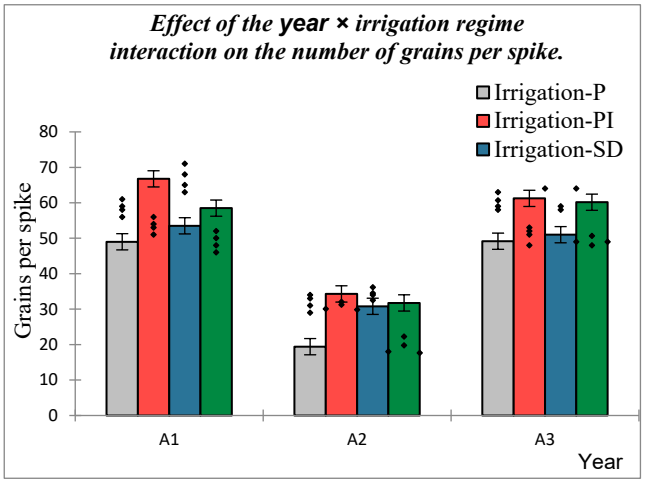


Figure 9. Effect of the year × irrigation regime interaction on the number of grains per spike.

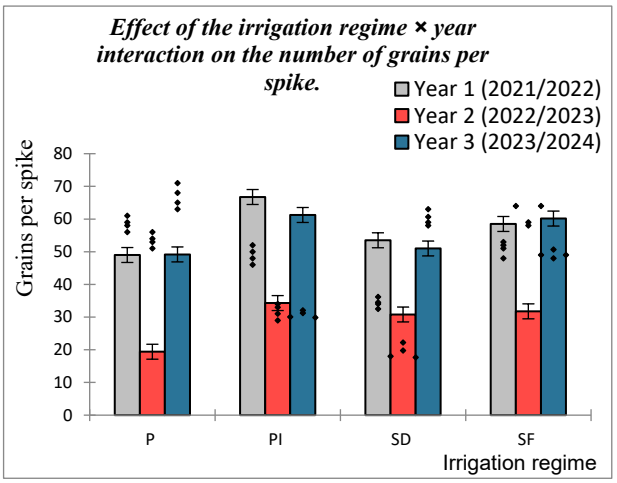


Figure 10. Effect of the irrigation regime × year interaction on the number of grains per spike.

Figures 9 and 10 show that the number of grains per spike (NGS) was strongly influenced by irrigation regime and growing season. Across all three experimental years, full irrigation (PI) consistently produced the highest NGS values, followed by supplemental irrigation at sowing (SF), whereas late supplemental irrigation (SD) and the rainfed control (P) recorded progressively lower values. Despite seasonal climatic variability, the superiority of PI and SF remained evident, confirming the beneficial effect of early water supply on spike fertility. The ANOVA revealed a highly significant treatment effect ($F = 170.08$; $P < 0.0001$), while the low residual mean square (MSE = 5.095) indicated high experimental precision. The LSD test ($P \leq 0.05$) confirmed significant differences among all irrigation regimes, with mean NGS decreasing in the order PI (54.10 grains spike^{-1}) > SF (50.14 grains spike^{-1}) > SD (45.10 grains spike^{-1}) > P (39.19 grains spike^{-1}), each treatment belonging to a distinct homogeneous group.

The year effect also revealed clear differences. Mean NGS was statistically similar in 2022 (56.94 grains spike^{-1}) and 2024 (55.40 grains spike^{-1}), whereas 2023 (29.07 grains spike^{-1}) formed a separate homogeneous group with significantly lower values, reflecting less favourable environmental conditions during that growing season. The year × irrigation comparison identified seven homogeneous groups, with the highest NGS recorded under PI in 2022 (66.75 grains spike^{-1}) and the lowest under the rainfed treatment in 2023 (19.41 grains spike^{-1}). These results indicate that climatic conditions strongly affected grain set, although supplemental irrigation substantially reduced the negative impact of seasonal water stress.

The higher number of grains per spike under PI and SF suggests that adequate water availability during stem elongation and flowering improved floret survival, pollination success and grain set. Conversely, water deficit during these critical reproductive stages reduced spike fertility, leading to fewer grains per spike. Overall, these findings demonstrate that early supplemental irrigation is an effective strategy for maintaining spike fertility and increasing the yield potential of durum wheat under semi-arid Mediterranean conditions.

3.5 Thousand-kernel weight (TKW)

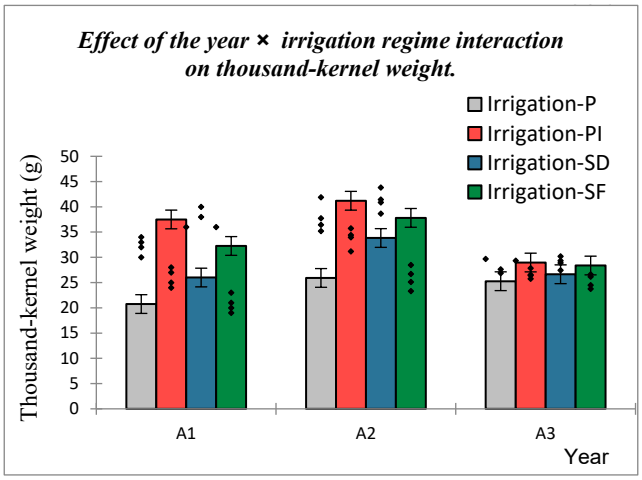


Figure 12. Effect of the irrigation regime × year interaction on thousand-kernel weight.

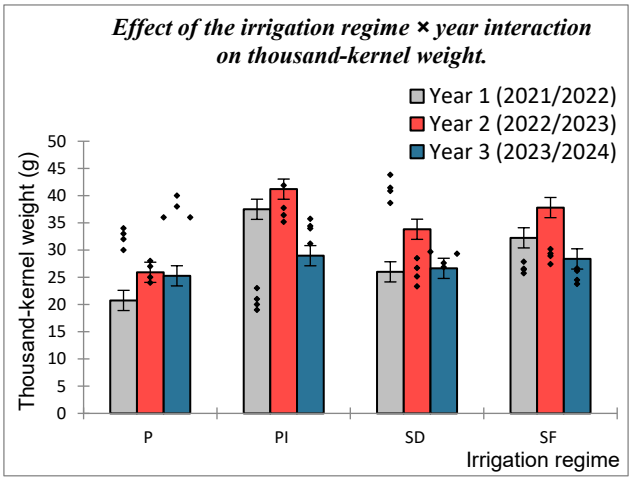


Figure 11. Effect of year × the irrigation regime interaction on thousand-kernel weight.

Figures 11 and 12 show that thousand-kernel weight (TKW) was markedly influenced by irrigation regime and growing season. Across the three experimental years, full irrigation (PI) consistently produced the highest TKW, followed by supplemental irrigation at sowing (SF), whereas late supplemental irrigation (SD) and the rainfed control (P) recorded progressively lower kernel weights. This consistent ranking demonstrates the positive effect of early water availability on grain filling.

The ANOVA confirmed these observations, revealing a highly significant treatment effect ($F = 45.21$; $P < 0.0001$). The low residual mean square (MSE = 3.349) indicates good experimental precision and supports the reliability of the observed treatment differences. The LSD test ($P \leq 0.05$) showed significant differences among all irrigation regimes, with mean TKW decreasing in the order PI (35.89 g) > SF (32.81 g) > SD (28.83 g) > P (23.98 g), each treatment belonging to a distinct homogeneous group.

The year effect was also highly significant, with 2023 (34.69 g) producing the highest mean TKW, followed by 2022 (29.13 g) and 2024 (27.32 g), all belonging to different homogeneous groups. The year × irrigation comparison identified seven homogeneous groups, with the highest TKW recorded under PI in 2023 (41.20 g) and the lowest under the rainfed treatment in 2022 (20.75 g). These results demonstrate that both seasonal climatic conditions and irrigation management strongly influenced grain filling.

The superior kernel weight observed under PI and SF indicates that adequate water availability during stem elongation and grain filling enhanced assimilate production and translocation to developing grains, resulting in heavier kernels. Conversely, water deficit under rainfed conditions limited grain filling, leading to lighter kernels. Overall, these findings confirm that supplemental irrigation, particularly full irrigation, is an effective practice for improving grain filling and maximizing kernel weight in durum wheat grown under semi-arid Mediterranean conditions.

3.6 Grain yield (GY)

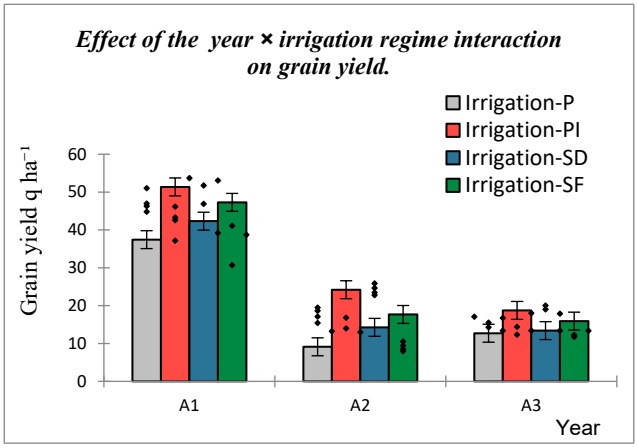


Figure 13. Effect of the year × irrigation regime interaction on grain yield.

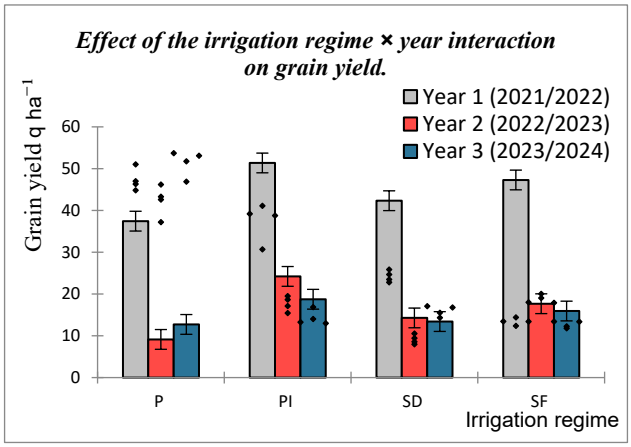


Figure 14. Effect of the irrigation regime × year interaction on grain yield.

Figures 13 and 14 clearly show that grain yield was strongly influenced by both irrigation regime and growing season. Across the three experimental years, full irrigation (PI) consistently produced the highest grain yield, followed by supplemental irrigation at sowing (SF), whereas late supplemental irrigation (SD) and the rainfed control (P) recorded progressively lower yields. Although grain yield varied considerably among years, the ranking of irrigation treatments remained unchanged, confirming the stability of the crop response to supplemental irrigation under contrasting climatic conditions.

The ANOVA confirmed these observations, revealing a highly significant treatment effect ($F = 165.15$; $P < 0.0001$), indicating that the experimental factors explained a large proportion of the observed variation in grain yield. The LSD test ($P \leq 0.05$) further demonstrated significant differences among irrigation treatments, with mean grain yield decreasing in the order PI (31.44 q ha^{-1}) > SF (26.96 q ha^{-1}) > SD (23.34 q ha^{-1}) > P (19.76 q ha^{-1}), each treatment belonging to a distinct homogeneous group. With q = quintal = 100 Kilogram.

The year effect was also highly significant. Mean grain yield reached 44.61 q ha^{-1} in 2022, whereas 2023 (16.32 q ha^{-1}) and 2024 (15.20 q ha^{-1}) formed a second homogeneous group and did not differ significantly from each other, reflecting the adverse climatic conditions that prevailed during these two growing seasons. The year × irrigation comparison identified eight homogeneous groups, with the highest grain yield recorded under PI in 2022 (51.37 q ha^{-1}) and the lowest under the rainfed treatment in 2023 (9.13 q ha^{-1}). These results demonstrate that seasonal climatic conditions strongly affected grain yield, while supplemental irrigation substantially reduced the negative effects of water deficit. The superior grain yield achieved under PI and SF can be attributed to improved soil water availability during the critical stages of tillering, stem elongation and grain filling, which enhanced spike density, grain number per spike and thousand-kernel weight. Conversely, rainfed conditions reduced the expression of these yield components, resulting in significantly lower grain production. Overall, these findings demonstrate that supplemental irrigation, particularly full irrigation, is an effective strategy for improving grain yield and enhancing yield stability of durum wheat under semi-arid Mediterranean conditions.

4. Economic analysis of supplemental irrigation water use

Table 5. Simplified economic analysis of supplemental irrigation.

P (Rainfed control)	0	0	19.764	0.000	0.0	0	0
SD	140	1,400	23.335	3.571	18.1	4,200	180.0
SF	140	1,400	26.964	7.200	36.4	4,200	155.8
PI	210	2,100	31.441	11.677	59.1	6,300	200.4

*Calculated assuming an irrigation water cost of 3 DA (Algerian Dinar) m^{-3}**.**

**1 quintal (q) = 100 kg.*

- The equation is : $IWP = (Y_i - Y_p)/I$, with : IWP = Irrigation Water Productivity (kg/m^3) Y_i = grain yield under irrigation ($kg\ ha^{-1}$), Y_p = grain yield under rainfed conditions ($kg\ ha^{-1}$) and I = irrigation water applied ($m^3\ ha^{-1}$).

Table 6. Irrigation Water Productivity (IWP).

P	0.0	0	-
SD	357.1	1400	0.26
SF	720.0	1400	0.51
PI	1167.7	2100	0.56

Supplemental irrigation improved grain yield under all irrigation treatments (Table 5). Full irrigation (PI, 210 mm) produced the highest grain yield (31.44 q ha^{-1}), corresponding to an increase of 11.68 q ha^{-1} (59.1%) compared with the rainfed control. The SF treatment, receiving only 140 mm of irrigation water, achieved a grain yield of 26.96 q ha^{-1}, representing a 36.4% increase over the control (Table 6). In contrast, the SD treatment resulted in a more moderate yield improvement (18.1%). Although PI incurred the highest irrigation water cost (6,300 DA ha^{-1}), it also exhibited the highest irrigation water productivity (0.56 kg of additional grain per m^3 of irrigation water), followed by SF (0.51 kg m^{-3}), whereas SD showed the lowest irrigation water productivity (0.26 kg m^{-3}). As expected, the rainfed control (P), which received no irrigation, recorded the lowest grain yield (19.76 q ha^{-1}).

5. Discussion

The results of this three-year study demonstrate that early-season supplementary irrigation is a critical agronomic lever for durum wheat production in the semi-arid Upper Chélif plain. The highly significant ANOVA results ($p < 0.0001$) confirm that water management strategy directly governs the expression of the Simeto cultivar's genetic potential.

Vegetative growth, as reflected by plant height and spike density, was significantly enhanced by early-season irrigation under both the PI and SF regimes. Water availability during the tillering and stem-elongation phases supports robust root system development and maximises the number of fertile tillers (Farooq et al., 2014). When early-cycle stress occurs, as in the SD and P treatments, the plant redirects limited resources toward

basic metabolic maintenance at the expense of tiller survival, resulting in a markedly reduced sink capacity — fewer spikes and fewer grains per spike.

The thousand-kernel weight data further indicate that early-season water status exerts a carry-over effect on the subsequent grain-filling period. Adequate early moisture reserves allow the plant to establish a larger photosynthetic canopy, which in turn supports better carbohydrate partitioning and grain filling during the critical spring months, even where terminal drought subsequently occurs (FAO, 2012).

The pronounced interannual climatic variability observed in this study — particularly the severe rainfall deficits recorded in Years 2 and 3 — is consistent with the increasingly erratic weather patterns projected for the wider Mediterranean basin (Kelkouli et al., 2024). Under these conditions, the SF treatment (early-season irrigation followed by terminal stress) proved to be a particularly efficient water-use strategy: it produced significantly higher yields than the late-irrigated (SD) and rainfed (P) treatments, while using approximately 33% less water than the fully irrigated (PI) treatment (140 mm versus 210 mm). This finding highlights the agronomic and hydrological viability of early-season irrigation as a water-efficient, climate-smart strategy for durum wheat production, of particular relevance in contexts of increasing water scarcity such as the Upper Chélif plain.

Taken together, these results reinforce and extend earlier observations from the same production basin (Merabet & Boutiba, 2004, 2005; Bellague et al., 2023), confirming that securing water availability during the early phenological stages is agronomically more valuable, and more water-efficient, than concentrating irrigation later in the crop cycle.

6. Conclusion

This study confirms that early-season supplementary irrigation significantly improves the vegetative growth, yield components and final grain yield of durum wheat (cv. Simeto) under semi-arid conditions. Statistical analyses (ANOVA, $p < 0.0001$) demonstrate a highly significant effect of year, irrigation regime and their interaction on all evaluated parameters. Among the treatments assessed, the full-irrigation (PI) and early-season irrigation (SF) regimes were the most productive, sustaining higher yields despite pronounced interannual climatic variability and severe spring water deficits — with SF achieving comparable performance to PI using roughly one-third less water. Securing water availability during the early cycle (tillering and stem elongation) therefore proved more beneficial than irrigating later in the season. These findings support the promotion of early-season irrigation as a primary, water-efficient strategy for enhancing and stabilising durum wheat productivity, strengthening crop resilience to climate variability, and enabling more rational management of limited water resources in semi-arid Mediterranean environments such as the Upper Chélif plain.

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