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Research Article

Enhancing barley resilience to thermo-hydric stress through conservation agriculture in semi-arid western Tunisia

Olfa Somrani[1,2], Oussama Oueslati[3*], Houcine Bchini[1], Mounir Rezgui[2], Salem Marzougui[2,4], Haithem Bahri[1], Mohamed Annabi[1], Mohsen Rezgui[1]

[1] University of Carthage, National Institute of Agricultural Research of Tunisia (INRAT), Laboratory of Agronomic Sciences and Techniques (LR16 INRAT 05), Tunisia
[2] University of Jendouba, Higher School of Agriculture of Kef, Boulifa, El Kef, Tunisia
[3] University of Jendouba, Higher School of Agriculture of Kef, Laboratory of Support for the Sustainability of Agricultural Production Systems in the Northwest Region (LR14AGR04) Boulifa, El Kef, Tunisia
[4] University of Carthage, INRAT, LR16INRAT02, Laboratory of Field Crops, Tunisia
***** Correspondence: oussamaoueslati@yahoo.fr , [*]ORCID: https://orcid.org/0000-0002-7684-4862

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ABSTRACT

This study aimed to evaluate the resilience of two barley varieties (‘Ardhaoui’ and ‘Manel’) to thermo-hydric stress under conservation agriculture (CA) compared to conventional agriculture, across different sowing dates (normal, late) and water regimes (rainfed, irrigated). Field experiments were conducted during the 2020–2021 winter growing season at a representative semi-arid site in Western Tunisia, and climatic trends over the past 24 years were analyzed to contextualize current stress conditions. A severe water deficit, coupled with a rise in temperature and increased ET0, occurred during grain filling. This tendency towards climate change is confirmed by the site's climatic characterization over 24 years, during which temperatures have risen by 0.16 °C per year ($r = 0.800$, $p = 0.01$). Results showed that CA significantly improved barley performance, increasing biological and grain yields by 26% and 29%, respectively, suggesting more efficient rainfall utilization. Supplemental irrigation further enhanced grain yield (51%) relative to biological yield (45%). The local variety ‘Ardhaoui’ demonstrated higher tolerance to drought and heat stress than the improved variety ‘Manel’. Biomass was more sensitive to heat stress than grain yield (32% vs. 24%), indicating a potential shift in harvest index under extreme conditions. Stress tolerance indices (HSTI and STI) and phenolic compound analysis confirmed that CA and supplemental irrigation mitigated the negative effects of thermo-hydric stress. The significant positive interaction ($p = 0.001$) between tillage method and sowing date confirms that tillage practices alleviate heat stress expression. These findings highlight that CA, when combined with appropriate variety selection and irrigation management, can improve barley resilience under semi-arid conditions. The study also underscores the importance of local varieties in adapting to climate variability, while cautioning that results are based on a single season and site, and multi-year evaluations are needed to confirm long-term benefits.

Keywords: Barley, Conservation Agriculture, Phenolics, Resilience, Thermo-Hydric Stress

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INTRODUCTION

With climate change, the area of arid and semi-arid land on the African continent is expected to increase by 5 to 8% by 2080 in a projection under a range of IPCC's climate scenarios that assess the potential impacts of climate change. If conventional practices continue, food security will be jeopardized, and crops will suffer increased water and heat stress (IPCC 2001, 2007). In fact, yields of major crops in these areas are expected to decline by more than 50% by 2050 and by nearly 90% by 2100 due to climate change. These projections have been made based on the correlation between the drought risk index and yield reduction rates in major crop lands between 2050 and 2100 (Li *et al*. 2009). To mitigate these effects, conservation agriculture (CA) offers a set of resilient and sustainable management practices (Bechikh *et al*. 2024). It maintains agricultural production while having a positive impact on the environment (Su *et al*. 2021). It should also be pointed out that this study was designed to fill the gap in research on CA resilience in Tunisia, particularly the lack of studies addressing resilience to heat and water stress.

According to Michler *et al*. (2019), CA limits yield losses due to rainfall variability in response to climate change. This practice mitigates the adverse effects of ploughing by improving soil water retention, reducing the effects of drought associated with rainfall fluctuations, and increasing yields (Madejón *et al*. 2023; Zhang *et al*. 2022). In addition, it minimizes the effects of heat stress and promotes cereal development during the grain filling stage (Kumar *et al*. 2023). CA improves the adaptability of summer cereal production to drought and heat stress in sub-Saharan Africa (Komarek *et al*. 2021). Furthermore, CA is a cost-effective approach to reducing irrigation water consumption for barley while decreasing greenhouse gas emissions (Fonteyne *et al*. 2021). Results obtained under natural and simulated drought conditions confirm that CA systems improve resilience to the increased stress risks associated with projected national and global climate change (Bahri *et al*. 2019; Steward *et al*. 2018).

Crops respond to various abiotic stresses by accumulating phenolic compounds, with the specificity of this accumulation depending on the type of stress and the plant species. In barley (*Hordeum vulgare* L.), phenolic compounds, particularly flavonoids, accumulate primarily during the visible flag leaf stage under water deficit conditions, coinciding with spring growth (Sassi *et al*. 2021). These flavonoids neutralize harmful reactive oxygen species (ROS), thus protecting the plant from oxidative damage (Kumar *et al*. 2020). Heat stress initially induces the biosynthesis of phenolic acids in plant cells (Chowdhary *et al*. 2022). According to Rivero *et al*. (2001), this stress also promotes phenolic accumulation in certain crops by activating biosynthesis and inhibiting oxidation, probably serving as an acclimation mechanism. Phenolic compounds are involved in plant responses to various environmental stresses (Chalker-Scott & Fuchigami 2018; Gil & Tuteja 2010), making their concentration in plant tissues a reliable indicator of stress.

The objective of this study is to develop a climate characterization to detect the occurrence of climate change and investigate the resilience of CA as a management strategy for barley (*Hordeum vulgare* L.) production in the Tunisian semi-arid environment.

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MATERIALS AND METHODS

Climatic characterization

The experimental site is located at the Experimental Station of the National Institute of Agricultural Research of Tunisia (INRAT) on the Boulifa plain of the Kef delegation, northwest Tunisia (36°07'N, 08°43'E, 518 m altitude). A medium semi-arid Mediterranean bioclimate with moderate rainfall variability characterizes the site. The soil is alkaline (pH = 8.3) with a clayey-sandy texture. Meteorological data, including mean monthly precipitation, reference evapotranspiration (ET_0) according to FAO (2016), and mean monthly temperature, were collected over 24 cropping seasons (2000/01–2023/24) from the agrometeorological station at the experimental site. In addition, climate data for the 2021/22 growing season are presented in Table 1. This meteorological data was used to characterize the site by identifying the periods of water deficit and potential active vegetation. The period of water deficit was determined graphically using the mean monthly rainfall curve and the reference evapotranspiration ET_0 curve (Gardner *et al*. 1985). The potential active vegetation period was determined using the ombrothermic diagram. According to Dupont & Compère (1997), this period corresponds to the interval on the diagram where the rainfall/2 curve exceeds the mean temperature curve.

Table 1: **Climatic data, ET_0, and Water deficit in rainfed conditions during the life cycle, 2021-2022**

	Mean temperature (°C)	Monthly rainfall (mm)	ET_0 (mm)	Water deficit (mm)
November 2021	16.3	1 0.8	65.3	-54.4
December	9.8	54.0	56.2	-2.2
January 2022	10.1	72.0	50.7	21.3
February	10.6	37.0	59.7	-22.7
March	12.4	32.0	84.7	-52.7
April	15.2	30.6	123.3	-92.7
May	22.0	8.8	151.0	-142.2
Total	96.4	245.2	590.9	-345.6
Mean/month	13.8	35.0	96.3	-49.4
CV (%)	31.9	64.3	39.9	-112.3

Source: Meteorological Station of Boulifa/Kef, adjacent to the experimental site; ET_0: reference evapotranspiration

The meteorological data were used to characterize the site by identifying the periods of water deficit and potential active vegetation.

Experimental conduct

The field trial was initiated in the 2017/18 growing season, with cultivation operations conducted according to protocols adapted for the semi-arid conditions. Two barley varieties, "Ardhaoui" and "Manel", were used. 'Ardhaoui' is derived from a local ecotype (El Faleh 1998), while 'Manel' is an improved variety registered in the official catalog in 1996 (Déghaïs *et al*. 2007). The trial was conducted under i) three crop rotation systems (barley monoculture, biennial: faba bean/barley, triennial: faba bean/durum-wheat/barley), ii) two sowing dates, iii) two water regimes (rainfed and irrigated), and iv) two tillage methods (Conservation Agriculture: CA and Conventional Agriculture: Co). Irrigation was applied when the available

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soil water reserve fell below 40% (Table 2).

Table 2: Phenological stages of barley, irrigation, and water balance (mm) under two sowing dates

Month	Sowing date 1 Phenological stage*	Irrigation	Water balance	Sowing date 2 Phenological stage*	Irrigation	Water balance
Nov.	Sowing		-54.4			-54.4
Dec.	Emergence		-2.2	Sowing	10	7.8
Jan.	Tillering	20	41.3	Emergence	20	33.3
Feb.		10	-12.7	Tillering	10	-12.7
Mar.			-52.7			-52.7
Apr.	Heading, Anthesis	120	27.3		120	27.3
May	Milky, Maturity	80	-12.7	Anthesis	80	-62.2
Jun.				Maturity		
Total		230	-66.1		240	-113.6

**Phenological stages according to Feekes scale*

Sowing was performed manually at a rate of 350 grains/m^2 in six rows, each 1.5 m long and spaced 25 cm apart. Each experimental plot covered an area of 2.25 m^2. Two sowing dates were tested: the first sowing date was the last week of November (optimum date advised by the agriculture ministry for the El Kef region), and the second was the last week of December (late: inducing heat stress). Mineral fertilization consisted of Diammonium Phosphate (DAP) applied at 100kg/ha. Nitrogen fertilizer (33.5% ammonium nitrate) was applied in two fractions of 100 kg/ha each at the tillering and bolting stages. Weeding and harvesting were performed manually, with threshing conducted using an ear thresher.

The field trial followed a split-split-split-plot design with three replications. The main factor was tillage method (CA, Co), the sub-factor was water regime, the sub-sub-factor was sowing date, and the sub-sub-sub-factor was crop rotation.
Agronomic parameters

During the 2021/22 growing season, at grain maturity, barley plants in each experimental plot were harvested manually, and samples of the above-ground biomass were collected to determine the biological yield (BY) and grain yield (GY). Both were measured at the plot level, expressed in g/m^2, and then converted to q/ha. The thousand-grain weight (TGW in g) was determined using a grain counter and a precision balance.

Heat and Drought Stress Indices

Heat Stress Indices

During the optimal sowing period (late November), barley was exposed to an average temperature of 15.2 °C at anthesis, whereas during late sowing (late December), it experienced 22.0 °C at the same stage. According to Lamba *et al*. (2023), this 6.8°C temperature difference during grain filling (Tables 1 and 2) likely accelerated ripening and reduced grain yield. Late-sown barley was subjected to heat stress during and after anthesis. The sensitivity of barley to heat stress, influenced by tillage method, water regime, and crop rotation, was evaluated by harmonic mean productivity (HMP) and stress tolerance index (HSTI). Both were calculated as follows:

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HMP = $\frac{(GYn + GYs)}{2}$ ……………. Eq. 1 (Rosielle & Hamblin 1981).

HSTI = $\frac{GYn \: X \: GYs}{MGYn^2}$ …………….. Eq. 2 (Fernandez, 1992).

With,
GYn: Average grain yield/variety under normal conditions (date 1).
GYs: Average grain yield/variety under heat stress (date 2).
MGYn: Average grain yield of both varieties under normal conditions (date 1).

Drought Stress Indices

The sensitivity of barley to drought, across two varieties, between tillage methods, sowing date, and rotation, was evaluated by calculating the sensitivity index using the method of Fischer & Maurer (1978), based on the following relationship:

MP = $\frac{(GYr + GYi)}{2}$……………. Eq. 3

STI = $\frac{GYr \: X \: GYi}{MGYi^2}$……………..Eq. 4

With,
GYr: Grain yield/variety in rainfed conditions,
GYi: Grain yield/variety in irrigated conditions,
MGYi: Average grain yield of both varieties in irrigated conditions,
MP: Mean Productivity,
STI: Stress Tolerance Index.

Phenolic analysis

At maturity, entire barley plants were harvested, separated into leaves, stems, and roots, then washed with tap water and distilled water. The plant parts were cut into 1 cm pieces and dried at 50 °C for 24 hours. Tissue extraction was performed following the procedure described by Ben-Hammouda *et al*. (1995).

The Denis-Folin method, with gallic acid as standard, was used for the analysis of total phenolics (TP). A standard gallic acid solution was prepared by dissolving 50 mg of gallic acid in 100 ml of distilled water, following Ereifej *et al*. (2016). The absorbance was measured at 750 nm (AOAC, 1990), and the TP content was estimated using the standard curve, expressed as µg of gallic acid equivalent per ml of water extract. To express the TP in µg of gallic acid equivalent per g of dry tissue, concentrations were multiplied by 20, based on a 1:20 extraction ratio (5 g of tissue per 100 ml of solvent).

Data analysis

A nested analysis was conducted to evaluate the effects of tillage methods (CA, Co), water regime, sowing date (heat stress), and crop rotation on agronomic parameters, drought sensitivity indices, heat stress tolerance indices, and TP content of barley. The data were subjected to an analysis of variance using the Statistical Analysis System (SAS Institute, 2023) software. Treatments with significant effects were separated using Fisher's protected LSD test at $p = 0.05$ (Steel & Torrie, 1980). Regression analysis of agronomic parameters on TP content was performed, with plant components as qualitative variables.

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RESULTS AND DISCUSSION

Climatic characterization

Rainfall and evapotranspiration

During the 2020-2021 barley growing season, total rainfall was 245.2 mm, below the regional average and the optimal requirement for barley crops (Mellouli *et al*., 2007). January was the wettest month, with 72,0 mm of rain, while the grain-filling period (April-May) experienced the greatest water deficit. Inter-month rainfall variability was high with a coefficient of variation (CV) of 64.3% (Table 1).
Figure 1 shows the distribution of rainfall and mean reference evapotranspiration (ET_0) over 24 growing seasons (2000/01–2023/24). Two periods of water deficit were identified: the first at the beginning of the season (September-October) and the second at the end (April-May), coinciding with ear formation and grain filling.

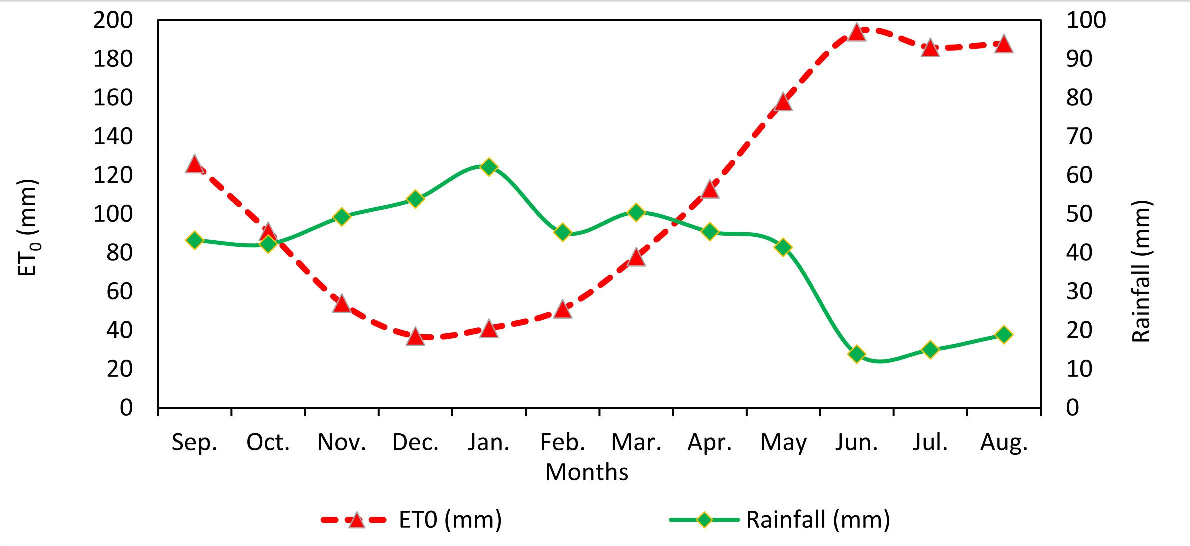

Figure 1: Rainfall deficit curve at Boulifa, means from 2000/01-2023/24

The 2020/21 agricultural year was way below average for 24 growing seasons throughout the barley growing cycle, except for January (Table 1 vs. Fig. 1). These conditions let us test how resilient the CA system is to thermo-hydric stress.

Temperature

To remedy the water deficit, supplemental irrigation is necessary in April and May (Fig. 1).

Spring 2022 (March-May) was characterized by higher temperatures and reduced precipitation. The latter was highly variable, with a coefficient of variation (CV) almost double that of temperatures, confirming the need for water supply during this period (Table 1). Figure 2 shows a rising temperature trend over the 24 growing seasons (2000/01-2023/24). The trend followed a binomial pattern, with an initial decline and a subsequent steeper increase (r^2 = 72%). The initial phase showed a slope of -8%/year, indicating a mean annual temperature decrease, while the second phase showed a slope of 16%/year, reflecting a temperature increase (r^2 = 64%). The highest temperature levels were recorded in the last four years of the study period. Since 2023, the El Niño effect, combined with climate change, has contributed to record-high

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temperatures (WMO, 2024). According to the IPCC (2021), every 0.5°C increase in mean temperature results in a noticeable increase in the intensity and frequency of heatwaves and agricultural droughts.

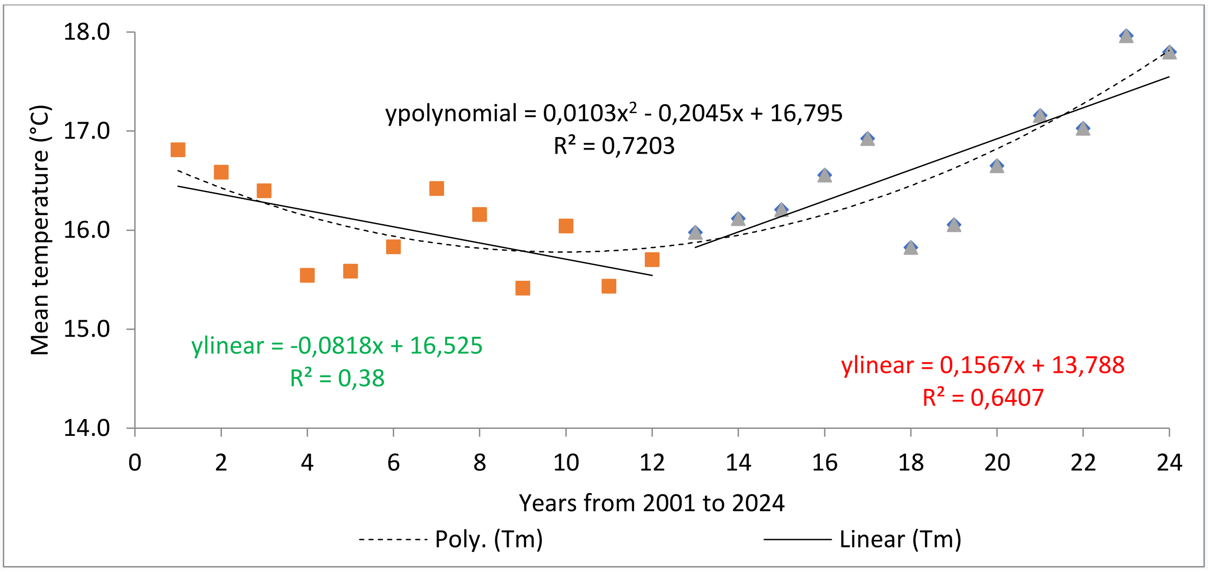

Figure 2: Variation in mean temperatures at Boulifa during the last 24 years of study

These results confirm the impact of global warming in the Boulifa-Kef region over the last 12 years. The average temperature increase (0.16°C/year) during this period exceeds that predicted by the IPCC's most pessimistic scenario (8.5), which forecasts a 4 °C rise by 2100 (IPCC, 2023).

Potentially active vegetation period

The ombrothermic diagram identified a favorable vegetation period for barley extending from sowing to heading (early April). This period is mostly pronounced from December to February (Figure 3).

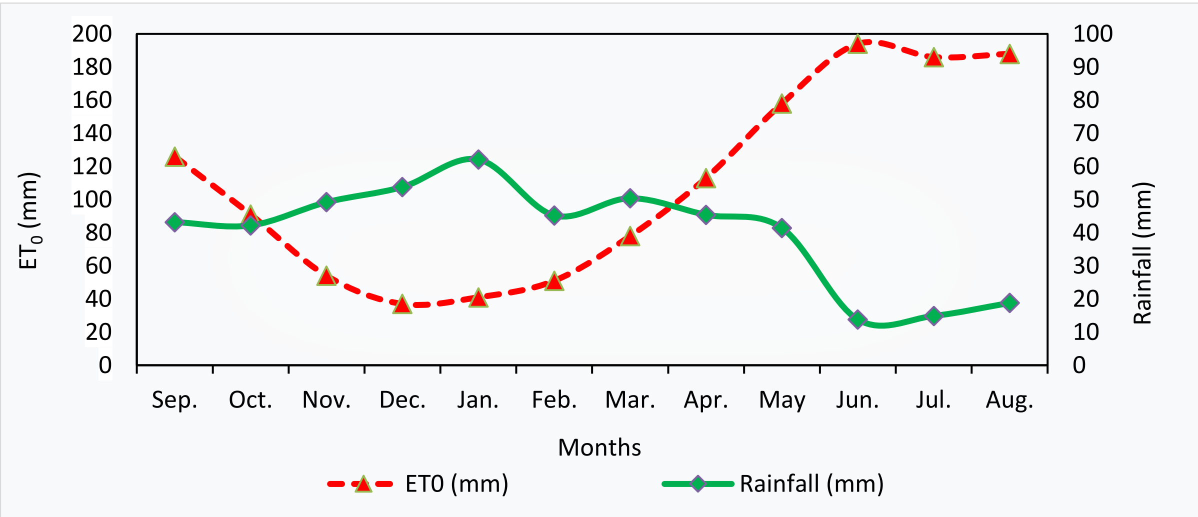

Figure 3: Ombrothermic diagram at Boulifa, means from 2000/01 to 2020/21

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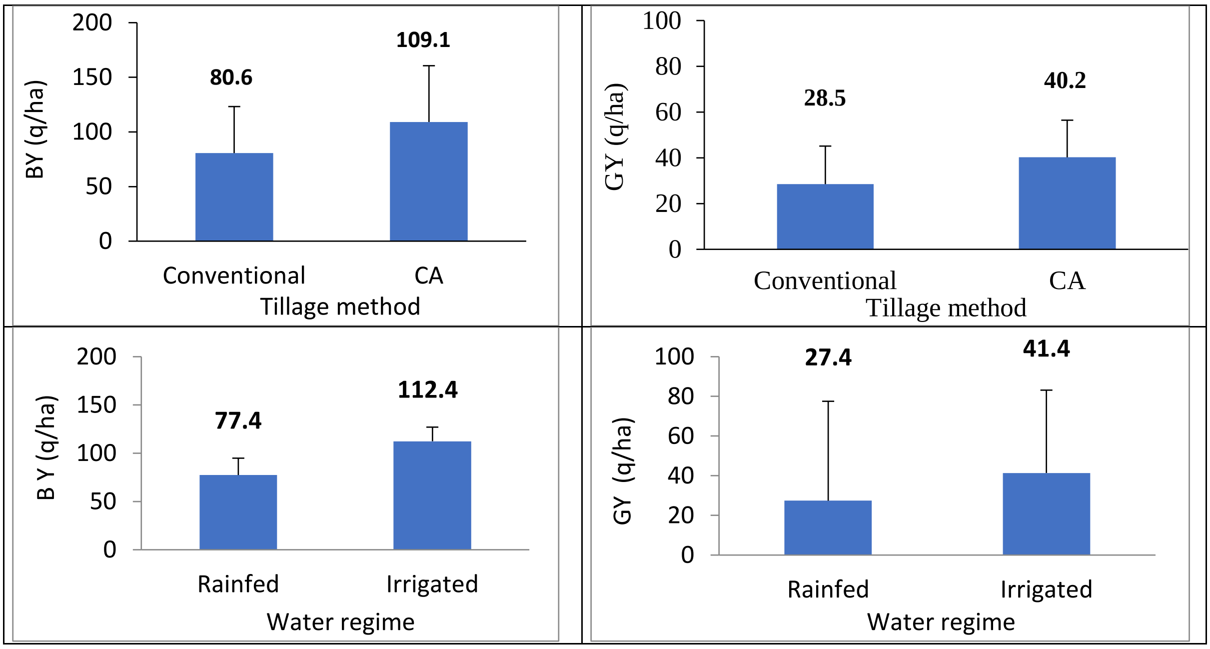
Agronomic parameters

Analysis of variance (ANOVA) showed no significant differences (p = 0.05) among tillage methods, water regimes, sowing dates, and crop rotations for biological yield (BY), grain yield (GY), and thousand-grain weight (TGW) of barley. However, mean BY and GY, averaged across all treatments, were 26% and 29% higher, respectively, under CA compared to Co.
Supplemental irrigation increased BY and GY by 45 and 51%, respectively. For the late sowing date (late December, Date 2), yields were reduced, with BY decreasing by 32% and GY by 24% compared to the optimal sowing date (late November, Date 1) (Fig. 4). Jacott & Boden (2020) report that high ambient temperatures negatively affect barley yields, with an increase of 1 °C above the optimal temperature, reducing productivity by 5-6%. Whereas TGW was 6% higher for the late sowing date, indicating larger kernels under heat stress during grain filling. These findings contrast with Abdelghany *et al*. (2024), who observe reduced grain size in 29 barley genotypes under heat stress, but align with Shirdelmoghanloo *et al*. (2022), who note that heat stress reduces grain number per unit area but increases grain size. Similar responses were observed in durum-wheat under heat stress (El Hassouni *et al*., 2019). The variability of BY and GY was greater than that of TGW (Fig. 4). The measured agronomic parameters were highest under biennial rotation (faba bean/barley), followed by monoculture (barley/barley), and lowest under triennial rotation (faba bean/durum-wheat/barley). This pattern may be explained by the legume precedent in the biennial rotation, which enhances soil fertility, whereas barley in the triennial rotation follows durum-wheat, potentially affected by heterotoxic allelopathic effects of wheat residues (Oueslati *et al*. 2017; Weiner *et al*. 2024). Additionally, combining CA practices with legume-cereal rotations increased cereal yields (Nyagumbo *et al*. 2020). The local variety ‘Ardhaoui’ showed 3% higher BY and 4% higher GY than the improved variety ‘Manel’, while TGW was 3% higher for ‘Manel’ (Fig. 4).



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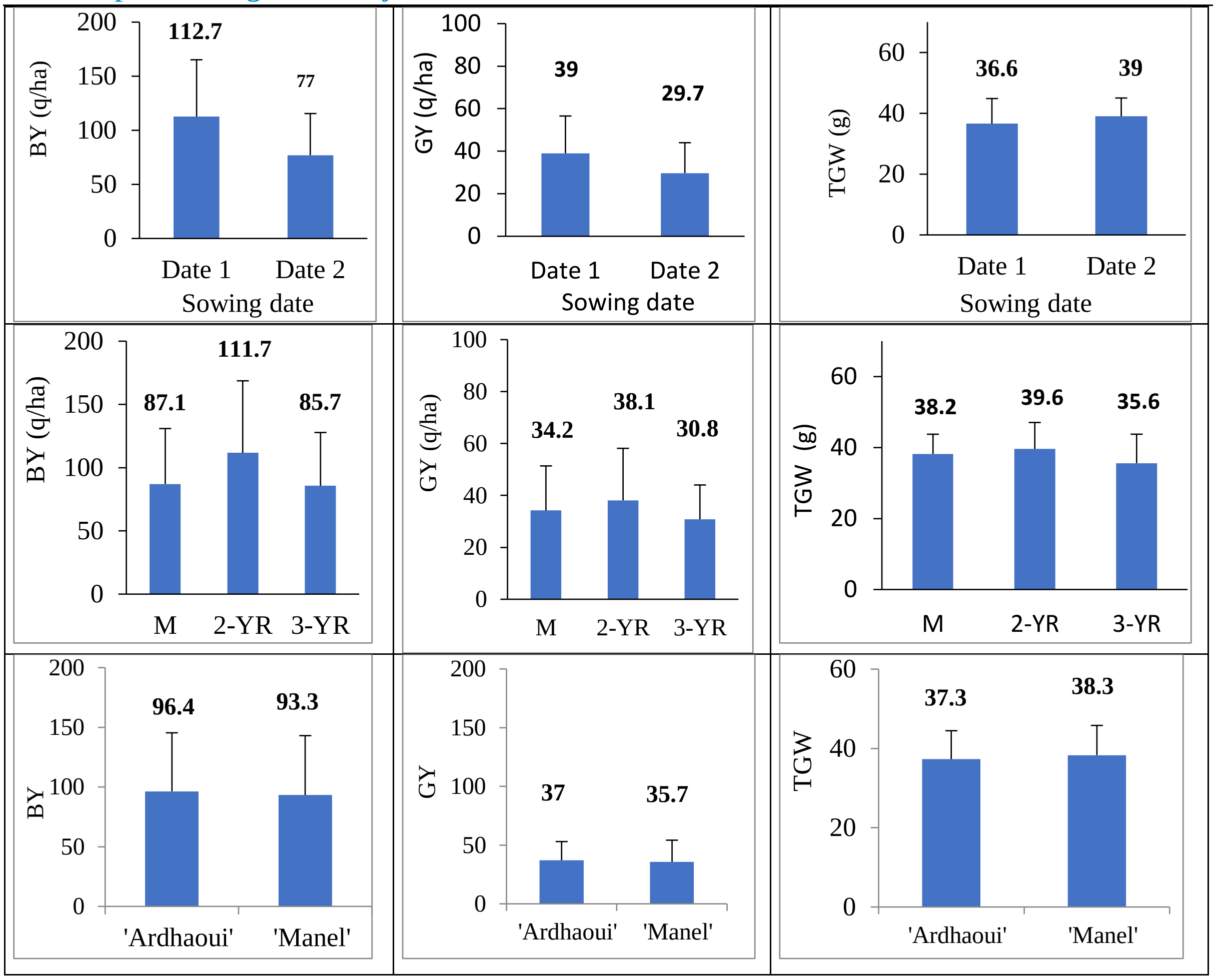

Figure 4: Effect of tillage method, water regime, sowing date, and rotation on biological yield (BY), grain yield (GY), and thousand grain weight (TGW) of two barley varieties, 'Ardhaoui' and 'Manel'. (M: monoculture,2-YR: biennial rotation,3-YR: triennial rotation). Error bars denote the standard error

Heat stress indices

ANOVA showed significant effects of tillage method, water regime, and rotation on the two heat stress indices (p = 0.05). The significance level of the first two parameters was higher than that of rotation. There were no significant differences between varieties (Table 3).

Table 3: Mean squares of heat stress indices: Heat Mean Productivity (MP), and Heat Stress Tolerance Index (STI) under tillage method (TM), water regime (WR), and rotation

Parameter	Heat stress indices	
	HMP	HSTI
TM	2492.77^{***}	4.00^{***}
WR	3529.54^{***}	7.59^{***}
Rotation	320.53^{**}	0.41^{*}
Variety	19.86^{NS}	0.002^{NS}

Significantly different at p = 0.05; * Significantly different at p = 0.001; ^{NS} Not significantly different at p = 0.05*

Figure 5 showed that barley under CA was 29% more productive (HMP) and 46% more tolerant

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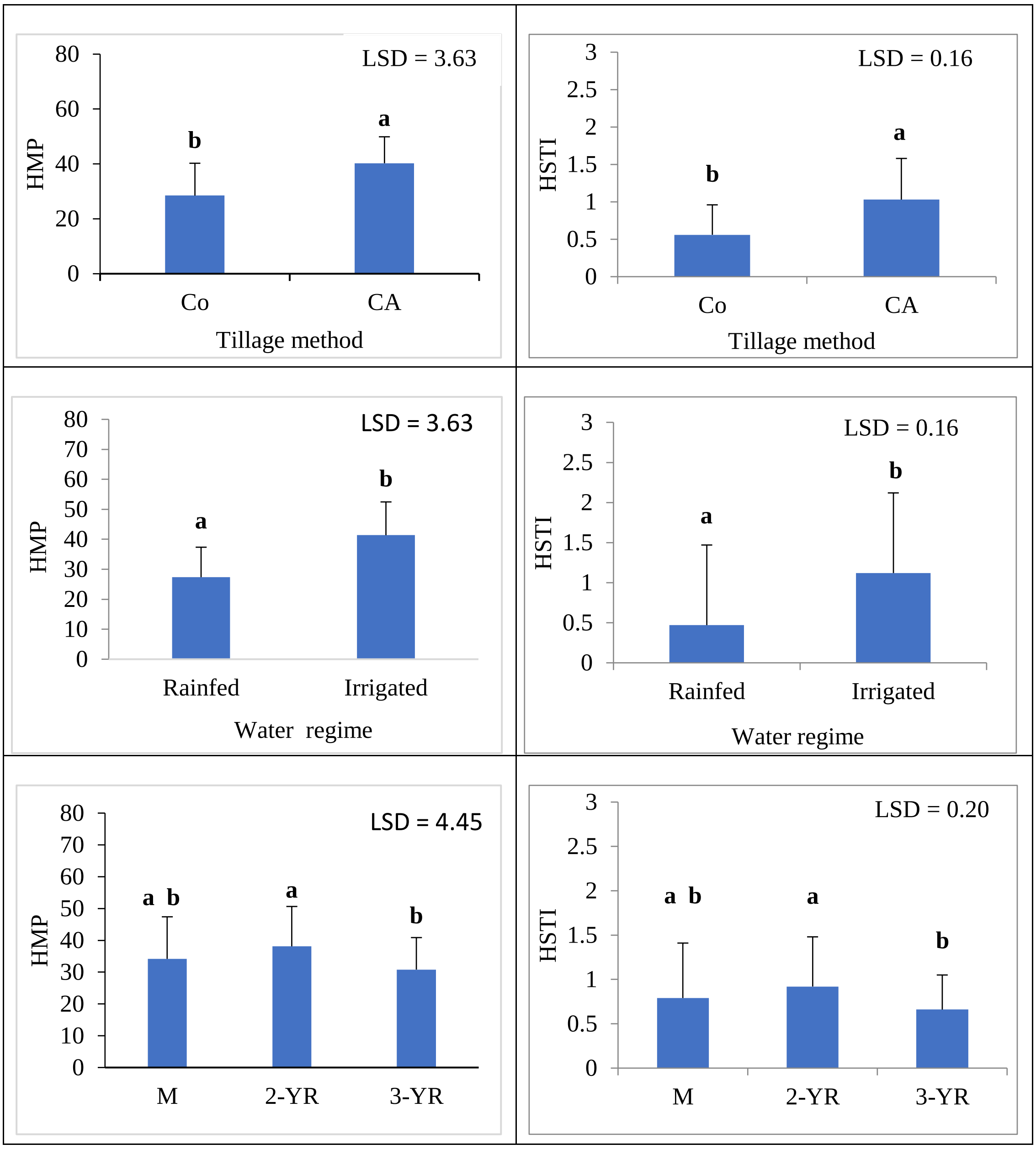
to heat stress (HSTI) than that under Co. Supplemental irrigation increased HMP by 34% and HSTI by 58% compared to rainfed conditions, indicating that irrigation enhances yield and mitigates heat stress, consistent with Birthal *et al*. (2021). Mean productivity and heat stress tolerance were higher in the biennial rotation, followed by monoculture, and lowest in the triennial rotation, confirming the results obtained with yield parameters (Figures 4 vs 5). The combination of CA and legume-based rotations enhances cropping resilience to thermal stress (Komarek *et al*. 2021). Although no significant differences were found between varieties, the local variety 'Ardhaoui' is 3% more productive and 1% more tolerant to heat stress than the improved variety 'Manel', consistent with its higher BY (3%) and GY (4%) observed in figure 4.



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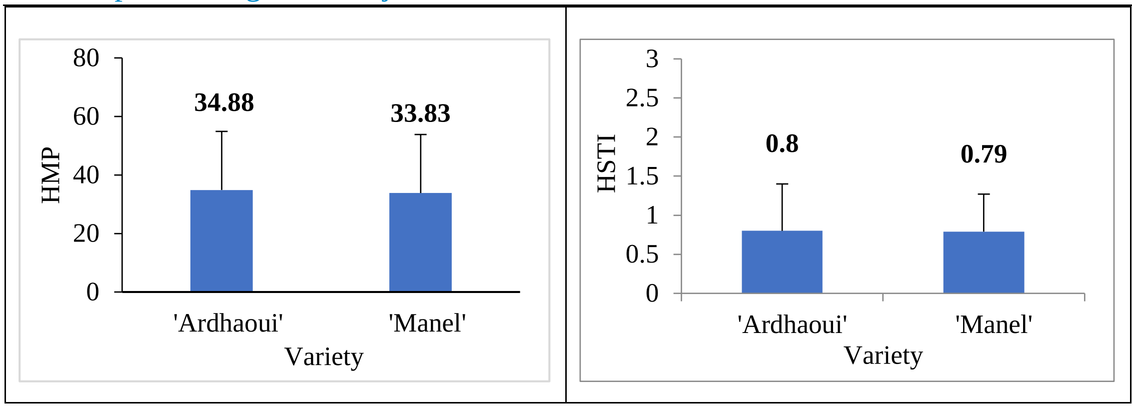

Figure 5: Effect of tillage method, water regime, rotation, and variety on Heat Mean Productivity (HMP), and Heat Stress Tolerance Index (HSTI) of two barley varieties (‘Ardhaoui’, ‘Manel’). *(M: monoculture,2-YR: biennial rotation,3-YR: triennial rotation). Error bars denote the standard error. Bars having different letters are significantly different at p = 0.05 based on Fisher's protected LSD test*

Drought stress indices

ANOVA revealed a highly significant effect of tillage method (p = 0.001). Sowing date had a highly significant effect (p = 0.001) on MP and STI, with a significant positive interaction between tillage method and sowing date, indicating that the heat stress expression is mitigated by tillage practices. Crop rotation also significantly (p = 0.05) affected both studied indices (Table 4).

Table 4: Mean squares of drought stress indices: Mean Productivity (MP), and Stress Tolerance Index (STI) under tillage method (TM), sowing date (SD), and rotation

Treatments	Drought stress indices	
	MP	**STI**
TM	2492.77***	3.65***
SD	1575.38***	0.79*
Interaction TM and SD	74.07NS	0.46*
Rotation	320.49*	0.37*

*Significantly different at p = 0.05; ***Significantly different at p = 0.001; NS Not significantly different at p = 0.05

CA increased MP index by 29% and STI by 51% compared to Co, reflecting greater drought tolerance and confirming higher yields under CA (Figs 4 and 6). These results align with those of Mhlanga & Thierfelder (2021), who attribute higher yields under CA to an increase in available water and enhanced buffering capacity against water stress, facilitated by soil cover that promotes water absorption and storage (Zhang *et al*. 2022). These findings support CA as a resilient climate change adaptation strategy in semi-arid regions, enhancing crop yields (Cheikh M’hamed *et al*., 2025; Dusingizimana *et al*., 2025).

The optimal sowing date increased MP by 24% and STI by 27% compared to the late sowing date, indicating reduced drought tolerance under heat stress (Fig. 6). This explains the higher biological yield (BY) and grain yield (GY) for the optimal sowing date, though thousand-grain weight (TGW) was higher under heat stress (Figs 4 and 6). Under a biannual rotation, barley expressed the best MP as well as better drought tolerance, as was the case for all studied yield

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parameters (Figures 6 vs 4). The local variety 'Ardhaoui' showed 3% higher MP and 18% higher STI than the improved variety 'Manel' (Figure 6), indicating its drought tolerance as noted in the southern sub-Saharan of Tunisia (Thameur *et al*., 2012).

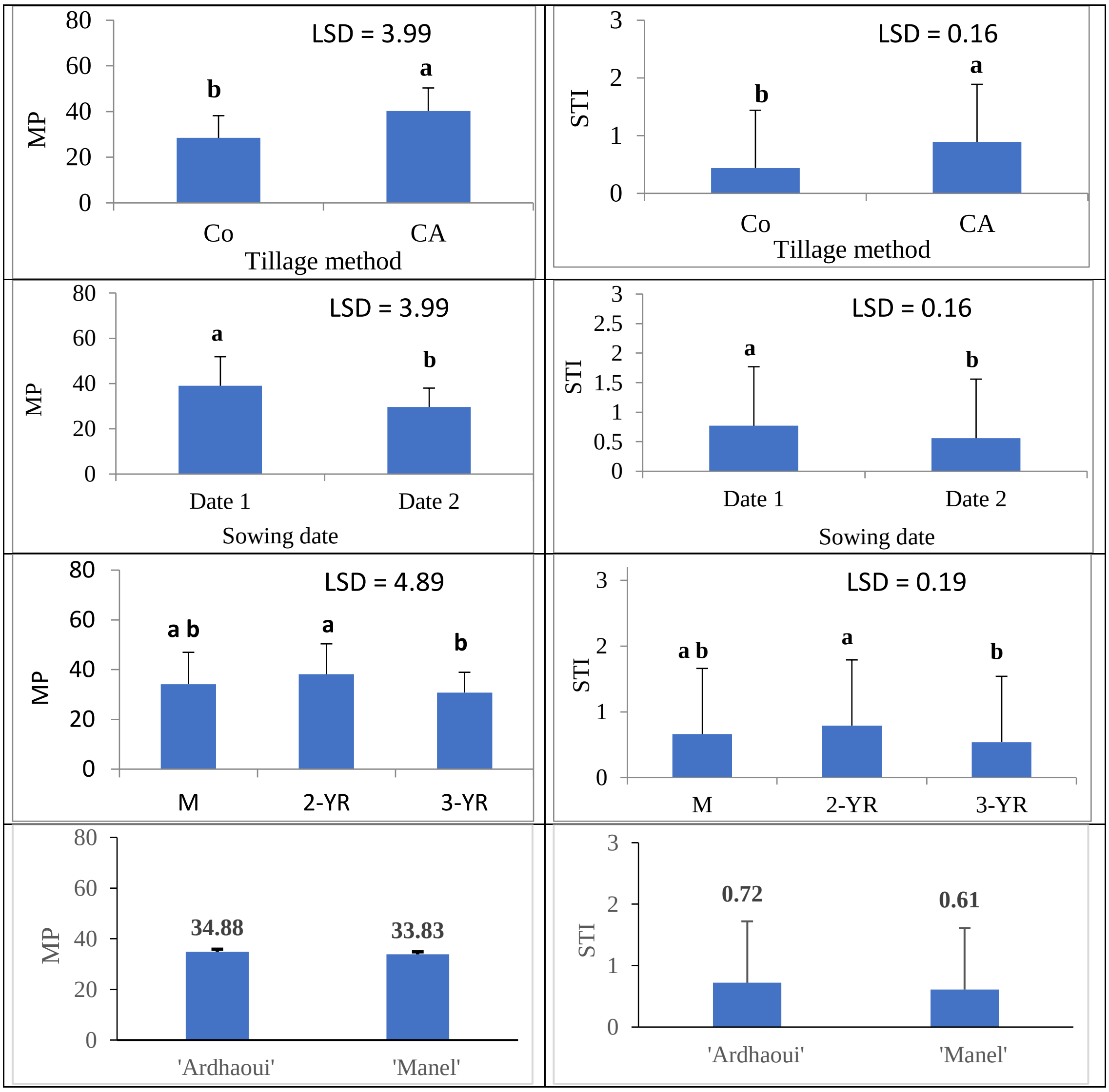

Figure 6: Effect of tillage method, sowing date, and rotation on MP (Mean Productivity), and Stress Tolerance Index (STI) of two barley varieties ('Ardhaoui', 'Manel').
(M: monoculture,2-YR: biennial rotation,3-YR: triennial rotation). Error bars denote the standard error. Bars having different letters are significantly different at p = 0.05 based on Fisher's protected LSD test

Phenolic analysis

The ANOVA showed a highly significant effect of water regime on total phenolic content (TP) in barley, but no significant differences ($p = 0.05$) among tillage methods (Table 5). However, a significant interaction ($p = 0.05$) was observed between water regime and tillage method. Additionally, TP differed significantly among plant components (roots, stems, and leaves).

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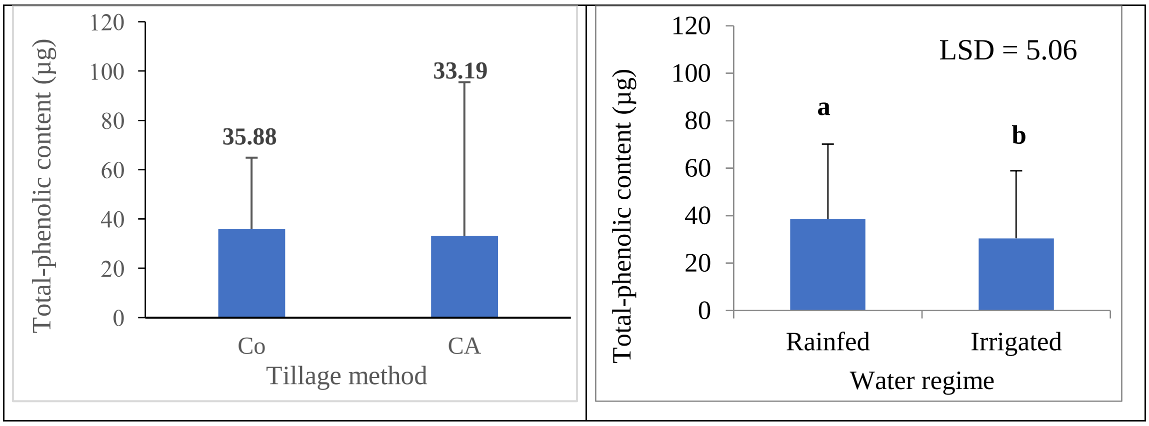
Table 5: Mean squares of total-phenolic contents of plant components (root, leaf, stem) of two varieties ('Ardhaoui', 'Manel') of barley under tillage method (TM), water regime (WR), sowing date (SD), and rotation

	Total-phenolic content[††]
TM	173.18[NS]
WR	1613.27[***]
Interaction TM and WR	917.85[*]
SD	39.14[NS]
Rotation	319.47[NS]
Plant components	68352.03[***]

*Significantly different at $p = 0.05$; ***Significantly different at $p = 0.001$; [NS] Not significantly different at p = 0.05; [††]µg of gallic acid equivalent per gram of dry tissue.

Despite lower TP at maturity, probably due to the phenolic mobilization for lignin biosynthesis (Chalker-Scott & Fuchigami, 2018), differences were observed across treatment levels. Barley under CA produced lower phenolic compounds than under Co, with no significant difference, suggesting greater stress under Co practice (Naikoo 2019; Sassi *et al*. 2021). Rainfed barley showed 21% higher TP than irrigated barley, indicating that water stress enhanced phenolic production, potentially contributing to drought tolerance (Sarker & Oba 2018; Sassi *et al*. 2021). This aligns with CA's higher yields and resilience to thermos-hydric stress (Figures 4 and 5 vs 7). Under heat stress (date 2), barley produced 4% less phenolic compounds than under optimal sowing, probably due to the involvement of other metabolites, such as proline and starch, in heat stress responses (Chowdhary *et al*. 2022; Dawood *et al*. 2020) or shorter exposure to heat stress for date 2, during key growth stages. Temperature increases from anthesis onward have been shown to shorten critical growth periods under climate change (Tan *et al*. 2021; Xiao *et al*. 2021). The triennial rotation resulted in 10% lower phenolic compounds than the biennial rotation and 17% lower TP than monoculture. Higher TP in monoculture may reflect barley autotoxicity (Oueslati *et al*. 2016, 2017) and transgenerational stress memory from thermo-hydric stress during the inter-season, between July and November (Lamelas *et al*. 2024). Conversely, barley under triennial rotations appeared less stressed (Figure 6). The local variety 'Ardhaoui' produced 3% less phenolics than 'Manel' but was more tolerant to water stress and more productive. The 3% reduction in TP for 'Ardhaoui' coincided with a 3% reduction in TGW, both indicating drought tolerance. According to figure 6, leaves showed significantly higher TP than stems, while no phenolic compounds were detected in roots, consistent with Sassi et al. (2021).



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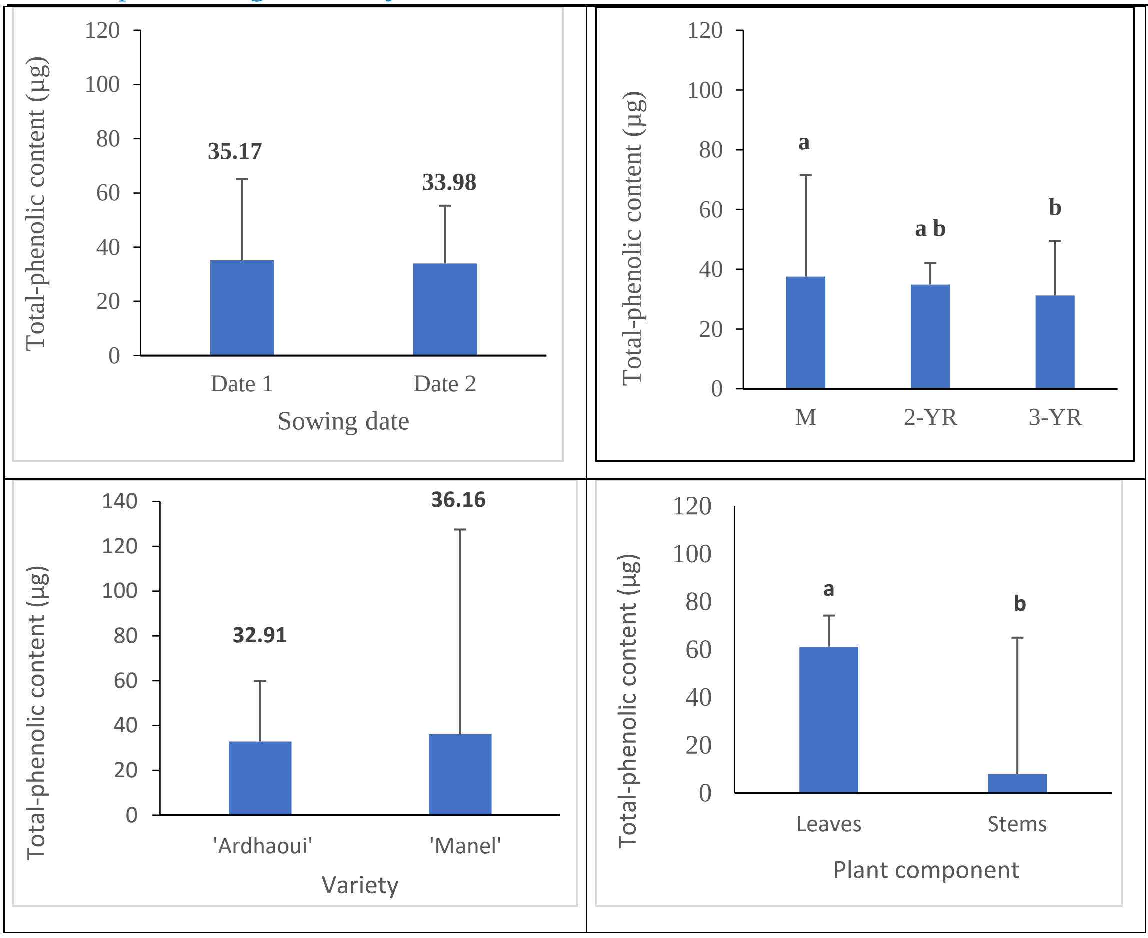

Figure 7: Effect of tillage method, water regime, sowing date, and rotation on total-phenolic

(µg of gallic acid equivalent per gram of dry tissue) content of two barley varieties ('Ardhaoui', 'Manel'). ((M: monoculture,2-YR: biennial rotation,3-YR: triennial rotation). Error bars denote the standard error. Bars having different letters are significantly different at p = 0.05 based on Fisher's protected LSD test

For this growing season, no significant association was found between the agronomic parameters and TP content in barley, despite significant variation in TP among plant components. Continued research over multiple seasons could provide further insight into these relationships.

CONCLUSION

Over the past decade, global warming in the Boulifa-Kef region has been evident, with an average annual temperature increase of 0.16°C per year. Its impact results in a more pronounced water deficit from the start of barley grain filling. The total phenolic content of the leaves proves to be an effective bioindicator of water stress, highlighting the resilience of barley under CA compared to Co. The study shows that Co is more stressful for barley in semi-arid environments, as evidenced by the higher total phenolic content and lower yields under Co. To mitigate the effects of climate change in semi-arid regions, it is recommended to adopt CA, supplemental irrigation, and biennial legume-based rotations, as well as drought-tolerant varieties such as "Ardhaoui," to improve barley productivity and resilience.

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Authors' contributions
Conceptualization: Oussama Oueslati
Data curation: Oussama Oueslati, Olfa Somrani
Methodology: Oussama Oueslati, Mohsen Rezgui
Supervision: Oussama Oueslati, Mohsen Rezgui
Writing – original draft: Olfa Somrani, Oussama Oueslati, Mohsen Rezgui, Houcin Bchini, Haithem Bahri, Mohamed Annabi
Writing – review & editing: Oussama Oueslati, Mohsen Rezgui, Houcin Bchini, Salem Marzougui

Conflicts of Interest
The author has no relevant financial or non-financial interests to disclose.

Ethics Approval
This field-based study did not involve humans or animals. All laboratory experiments were performed in accordance with institutional, national, and international guidelines for laboratory safety and biosafety.

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