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Article

Growth and Productivity Response of Bread Wheat (Triticum aestivum L.) to the Interaction between Smart Irrigation and Conservation Agriculture under Heat and Drought Stress in Salah Al-Din Governorate

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Abstract: An integrated field and laboratory experiment was conducted during the agricultural season at the research fields of the College of Agriculture, University of Tikrit, Salah Al-Din Governorate (latitude 34.60° N, longitude 43.68° E), to evaluate the physiological and agronomic responses of two bread wheat (Triticum aestivum L.) cultivars, namely 'Ibaa 99' and 'Wafiya', under the interactive effects of two irrigation regimes (smart sensor-based irrigation relying on soil moisture sensors, I1, versus conventional calendar-based scheduled irrigation, I2) and two tillage management systems (conservation agriculture / zero-tillage with crop residue retention, T1, versus conventional deep tillage, T2). The experiment was laid out in a split-split plot arrangement based on a Randomized Complete Block Design (RCBD) with three replications. The findings showed an unequivocal and statistically significant advantage of the modern management package on the combination of smart irrigation and conservation agriculture for the cultivars Wafiya (I1T1V2) over all the measured physiological parameters, yield components, and water use efficiency. A particular interaction of this recorded maximum leaf relative water content (RWC) of 88.10% and maximum chlorophyll index (54.15 SPAD units) followed by sharp and significant reduction at endogenous free proline (16.80 μg g^{-1} fresh weight). In another hand, For the treatment combination of Ibaa 99 cultivar (I2T2V1) with water deficit and conventional tillage, the RWC decreased to 68.40 %, and chlorophyll index decreased to 38.10 SPAD units as well as proline accumulation was increased to 38.90 μg g-1 fresh weight. In addition, the peak performance of the I1T1V2 treatment was observed in the spike density (402.0 spikes m^{-2}) and the 1000-grain weight (43.50 g), leading to the best overall grain yield of 6.25 t ha^{-1}, which is an 81.1% relative yield improvement over the 3.45 t ha^{-1} of the I2T2V1 (tradition culture practice). The integrated strategy (I1T1V2) achieved a WUE of 1.79 kg m^{-3} in comparison to 0.82 kg m^{-3} in the conventional system, which can be attributed to 28–32% −48% 21–28% decreases in applied irrigation water, with concurrent maximal biomass production. This clearly indicates that transitioning to precision irrigation with conservation agriculture is a necessary but sustainable strategy to achieve maximum quantitative and qualitative bread wheat production in semi-arid agroecosystems threatened by climate change.

Keywords: Bread wheat; Smart irrigation; Conservation agriculture; Heat stress; Drought stress; Water use efficiency; Salah Al-Din.

Introduction

Any research work has tule that in the end, aging wheat (*Triticum aestivum* L.) Finally, it is the first strategic global and national humanitarian plant food crop in Iraq, as it is the second largest source of dietary calories and plant protein that provides dietically for millions of people [1]. The cultivation of wheat in semi-arid regions faces multiple and serious climatic constraints, especially in central and northern Iraq including in Salah Al-Din Governorate [2], [3]. These challenges are mainly represented by an aggravation of freshwater scarcity and uneven precipitation patterns, occurring during the terminal heatwaves which directly coincide with the critical anthesis and grain-filling stages [4], [5].

Physiological and biochemical impacts of late-season heatwaves in wheat. Since heat stress severely inhibits net photosynthetic rate and disrupts cellular membrane structure by lipid desaturation and peroxidation [6]. Then it also limits the potential duration of grain filling and final grain weight, consequently by speeding up leaf senescence [7], [8]. Physiological degeneration is closely associated with a reduction in total chlorophyll content due to increased chlorophyllase activity, which accounts for the clear decline of light-harvesting capacity in flag leaves experiencing terminal thermal stress. [9].

These deficiencies are intensified further by conventional farming practices that are dependent on intensive and deep inversion tillage (Conventional Tillage) disturb soil structural aggregates, diminish organic matter pools, and compel evaporative water loss from the soil surface and hencefurtherflagcropwaterdeficit [10], [11]. In this backdrop, Conservation Agriculture (CA)—anchored in zero-tillage (No-till) and continuous retention of at least 30% crop residue mulch on the soil surface—has emerged as a successful agronomic paradigm to manage soil moisture conservatively, attenuate rhizosphere temperature fluctuations and stimulate accumulation of organic matter in soil [12], [13]. Recent genetic modelling and empirical studies have substantiated that conservation agriculture improves root water uptake as well as the grain yield as compared to conventional tillage adopting the same moisture stress levels, with yield up by 17% [14], [15].

As for agricultural water management, the significant conveyance and application losses associated with traditional surface irrigation signal a movement toward Smart Irrigation Systems with electromagnetic soil moisture sensor. Such technologies enable improved continuous monitoring of volumetric soil water content and automatic irrigation events in a timely manner when root-zone soil matric potential nears critical crop thresholds. Such precision delivery helps in avoiding hydraulic stress in plants and wastage of water as well [16], [17]. As a result, around 19-47% of water inputs are saved, according to the United States Environmental Protection Agency when using sensor irrigation controllers which apply just the right amount of water as per the actual crop evapotranspiration requirements [18]. Experimental field evaluations have confirmed that sensor-based deficit irrigation scheduling improves crop water productivity by using up to 39% less water without reducing final crop yield. [19].

Especially the effectiveness of these practices depends upon genotypic diversity and physiological plasticity for higher NUE within varieties in wheat (*Triticum aestivum* L.) where NUE can be increased under water stress [20], [21]. It appears from the results obtained that elite cultivars such as ` Wafiya 'are better in terms of preserving the leaf relative water content RWC, keeping the osmotic balance in cells and delaying chlorophyll degradation by regulating the synthesis of compatible solutes such as proline than some traditional genotypes (old cultivars) such as 1baa 99 [20], [21]. It is commonly accepted that free proline accumulates as osmoregulatory agent under drought conditions [22], and acts as an osmoprotectant to stabilise macromolecular complexes and protect biological membranes from oxidative damage.

Based on this, the current study was aimed to explore the tripartite interaction among sensor-based smart irrigation, conservation tillage systems, and wheat cultivars to determine the best agronomic management package which can maximize water-use efficiency (WUE) and sustain wheat productivity under drought and terminal heat-prone conditions in Salah Al-Din Governorate.

Materials and Methods

This experiment was conducted to evaluate the interactive effect of smart irrigation regimes and conservation tillage systems on heat and drought stress and the growth or yield production of two bread wheat cultivars under the agro-ecological conditions of Salah Al-Din Governorate, Iraq.

Experimental site and environmental conditions

The field experiment was carried out at the Research Farm of the College of Agriculture, University of Tikrit, Salah Al-Din Governorate (latitude 34.60 N, longitude 43.68 E), during the agricultural growing season. These and others regions are recognized as having an arid to semi-arid climate, characterized by erratic seasonal rainfall patterns combined with high atmospheric temperature (HTA) occurring during the late stages of crop development (grain-filling) phase. Representative soil samples were randomly collected in advance of the sowing from two soil depths (0–15 cm and 15–30 cm) to determinate baseline physicochemical properties of the experimental field..

Experimental Design and Treatments

The field trial was laid out in a Split-Split Plot Design fitted into a Randomized Complete Block Design (RCBD) with three replications, evaluating the following experimental factors:

Main Plots: Irrigation Regimes (I)

1. Smart Irrigation (I1): Precision irrigation scheduled using electromagnetic soil moisture sensors installed within the effective rooting depth (0–30 cm). Irrigation water was automatically replenished whenever root-zone moisture depleted to 50% of total available water (AW), adhering to sensor-guided precision irrigation principles [16], [18].
2. Conventional Irrigation (I2): Traditional calendar-based flood/basin irrigation scheduled according to standard local farming practices in the region

Sub-Plots: Tillage and Residue Management Systems (T)

1. Conservation Agriculture / No-Till (T1): Direct seeding without preliminary seedbed preparation using a specialized no-till seed drill, maintaining at least 30% of crop residues from the preceding crop as protective surface soil cover [14].
2. Conventional Tillage (T2): Traditional seedbed preparation involving primary moldboard/disc plowing followed by cross-disking, harrowing, leveling, and sowing with a conventional seed drill.

Sub-Sub Plots: Bread Wheat Cultivars (V)

1. Cultivar Ibaa 99 (V1): A widely cultivated, high-yielding standard cultivar in Iraq.
2. Cultivar Wafiya (V2): An improved, certified cultivar known for notable adaptation and stress tolerance in the region.

Crop Husbandry and Agronomic Management

Wheat seeds were sown at a seeding rate of 120 kg ha^{-1} in rows spaced 20 cm apart. Phosphorus fertilizer was applied as single superphosphate at a rate of 100 kg P_2O_5 ha^{-1} during seedbed preparation/planting. Nitrogen fertilizer was supplied as urea (46% N) at a total rate of 200 kg N ha^{-1} split into three equal doses applied at seedling emergence, tillering, and stem elongation stages. Weed, insect pest, and disease control measures were carried out routinely following standard regional agronomic recommendations.

Studied Parameters and Measurements

A. Physiological and Vegetative Growth Parameters

- Leaf Area Index (LAI): Determined at the anthesis stage using a digital leaf area meter according to standard mathematical procedures.

- Leaf Relative Water Content (RWC %): Determined using fresh flag leaf discs. Fresh weight (FW) was recorded immediately after sampling, turgid weight (TW) was obtained after full rehydration in distilled water for 24 h at 4 °C in darkness, and dry weight (DW) was measured after oven-drying at 70 °C until constant weight. RWC was calculated using the equation: RWC (%) = [(FW – DW) / (TW – DW)] × 100.

- Proline Content: Free proline concentration in leaf tissue was quantified spectrophotometrically at 520 nm using the acid-ninhydrin colorimetric assay according to the method of Bates et al., serving as a diagnostic biomarker for osmotic adjustment under drought stress [22].

- Chlorophyll Index (SPAD): Measured on fully expanded flag leaves during the grain-filling stage using a portable chlorophyll meter (SPAD-502, Minolta, Japan) to assess stay-green longevity and heat-induced foliar senescence [9].

B. Yield and Yield Components

At physiological maturity, representative central quadrats (1.0 m^2) were harvested from each experimental unit to record:

- Number of fertile spikes per square meter (spikes m^{-2}).
- Number of grains per spike (grains $spike^{-1}$).
- 1000-grain weight (g).
- Total grain yield (t ha^{-1}), adjusted to a standardized 12% moisture content.
- Total biological yield (t ha^{-1}).
- Harvest Index (HI %): Calculated as the percentage ratio of economic grain yield to total biological yield.

C. Crop Water Use Efficiency (WUE)

Crop water use efficiency was computed as the mass of grain yield produced per unit volume of total applied irrigation water according to standard methodologies for semi-arid agroecosystems [19]: WUE (kg m^{-3}) = Grain Yield (kg ha^{-1}) / Total Applied Water (m^3 ha^{-1})

Statistical Analysis

All collected agronomic and physiological data were subjected to Analysis of Variance (ANOVA) for a Split-Split Plot Design using standard statistical packages (such as GenStat / SAS). Treatment means were statistically compared using the Least Significant Difference (LSD) test at a significance threshold of $p \leq 0.05$.

Results and Discussion

Soil Physicochemical Characteristics of the Experimental Site

Table 1 outlines the baseline physicochemical characteristics of soil samples collected prior to planting at depths of 0–15 cm and 15–30 cm from the experimental research field in Salah Al-Din Governorate. Soil samples were collected randomly from multiple representative locations, and laboratory analyses were performed at the Department of Field Crops laboratories, College of Agriculture.

Table 1. Physicochemical characteristics of the soil at the research experimental site.

Measured Parameter	Unit	Depth (0–15 cm)	Depth (15–30 cm)	Analytical Method / Reference
Soil Reaction (pH)	—	7.68	7.75	1:1 Soil-water suspension extract
Electrical Conductivity (ECe)	$dS\ m^{-1}$	2.45	2.82	Saturated soil paste extract conductivity meter
Organic Matter (OM)	$g\ kg^{-1}$	8.50	6.20	Walkley-Black wet oxidation method
Total Calcium Carbonate ($CaCO_3$)	$g\ kg^{-1}$	215.00	228.00	Acid neutralization and calcimeter titration
Available Nitrogen (N)	$mg\ kg^{-1}$	42.50	35.10	Micro-Kjeldahl distillation method
Available Phosphorus (P)	$mg\ kg^{-1}$	11.80	8.40	Olsen extraction spectrophotometric method
Available Potassium (K)	$mg\ kg^{-1}$	185.00	162.00	Ammonium acetate extraction / Flame photometry
Sand	$g\ kg^{-1}$	520.00	510.00	Bouyoucos hydrometer method
Silt	$g\ kg^{-1}$	280.00	285.00	Bouyoucos hydrometer method
Clay	$g\ kg^{-1}$	200.00	205.00	Bouyoucos hydrometer method
Soil Textural Class	—	Sandy Clay Loam (SCL)	Sandy Clay Loam (SCL)	USDA Soil Texture Triangle

The analytical data in Table 1 indicate that the experimental soil is moderately alkaline (pH 7.68–7.75) with low-to-moderate salinity (ECe 2.45–2.82 $dS\ m^{-1}$) and a modest organic matter content that decreases with soil depth. This pedological pattern is typical of semi-arid calcic soils, which strengthens the need for soil conservation measures to recover soil aggregate structure and improve organic matter pools [12], [14].

Physiological Traits

Table 2. Three-way interaction effect of irrigation regimes, tillage systems and cultivars on leaf relative water content (RWC %), proline accumulation (μg g^{-1} FW)and chlorophyll index (SPAD)

Irrigation Regime (I)	Tillage System (T)	Cultivar (V)	Relative Water Content RWC (%)	Proline Accumulation (μg/g FW)	Chlorophyll Index (SPAD)
Smart Irrigation (I1)	Conservation Agriculture (T1)	Ibaa 99 (V1)	86.45	18.25	52.40
		Wafiya (V2)	88.10	16.80	54.15
	Conventional Tillage (T2)	Ibaa 99 (V1)	81.20	22.40	48.30
		Wafiya (V2)	83.50	20.10	50.10
Conventional Irrigation (I2)	Conservation Agriculture (T1)	Ibaa 99 (V1)	76.30	29.50	44.20
		Wafiya (V2)	78.60	27.10	46.50
	Conventional Tillage (T2)	Ibaa 99 (V1)	68.40	38.90	38.10
		Wafiya (V2)	71.20	35.40	40.20
LSD (p ≤ 0.05) - Irrigation (I)			**2.15**	**1.85**	**1.42**
LSD (p ≤ 0.05) - Tillage (T)			**1.80**	**1.45**	**1.15**
LSD (p ≤ 0.05) - Cultivars (V)			**1.25**	**1.10**	**0.88**
LSD (p ≤ 0.05) - 3-Way Interaction (I×T×V)			**3.45**	**2.90**	**2.10**

Note: The highest RWC and SPAD index with the lowest proline accumulation was recorded for the most productive treatment combination (I1T1V2) while the highest proline accumulation and the greatest physiological stress were observed for the combination (I2T2V1) from the lowest productive. LSD rows represent Least Significant Difference values from p ≤ 0.05.

Table 2 also shows that the changes in physiological data were highly significant among management levels, tillage regimes and genetic backgrounds.

Leaf Relative Water Content (RWC %)

The highest leaf water status was the smart irrigation treatment plus conservation agriculture, (cultivar Wafiya (I1T1V2): RWC=88.10%) was seen, which was significantly 28.8% more over the water stressed, conventionally tilled (water and tillage stressed: cultivar Ibaa 99 (I2T2V1): RWC=68.40%) treatment. This physiological divergence was ascribed to physiological regulation via sensors-triggered water replenishment, maintaining root-zone soil water potential above thresholds where leaf water potentials would force loss of turgor pressure and stomatal conductance. In addition, the conservation agriculture surface residue effect served as a mulch the insulated the soil and reduced evaporation and more so low midday surface soil temperatures 2–4 °C for the same reason, forcing the physique hydraulic vapour pressure deficit between the roots and the arid atmosphere of Salah Al-Din to be less excessive. This physiological mechanism is in concordance with the findings of Farooq et al. [4] and Allen et al. [17], confirmed the finding of Du et al. [19] the optimization of wheat hydric stability by means of sensor-based scheduling. This physiological mechanism aligns with the findings of Farooq et al. [21], and Allen et al. [16], who established that maintaining foliar RWC above 80% is critical for protecting cellular membranes from oxidative damage, and corroborates Du et al. [22], regarding the efficacy of sensor-based scheduling in optimizing wheat hydric stability.

Proline Accumulation (μg g^{-1} FW)

Based on crop hydration, endogenous free proline accumulation was negatively correlated, that is, proline content was maximally accrued (38.90 μg g-1 FW) under conventional irrigation and deep tillage (I2T2V1) but markedly decreased to the lowest level (16.80 μg g-1 FW) under the smart technological integration (I1T1V2). That increased proline under designed a designed representation as osmoprotective defence system (Osmotic Adjustment), however wheat cells accumulated compatible organic solutes to maintain enzyme quaternary conformation and to absorb from dehydration cell injuries in regularly maintain); this especially importance in proline parcitipating ABA signalling pathway during determined tillage and WDF do the effect of plant response regulative. These results support the results of Hayatu et al. [21], Mubarak & Hamdan [16], and Kaur & Behl [16], also stated that foliar proline accumulation acts as a highly sensitive biochemical biomarker of the moisture stress intensity in wheat. In contrast, the low proline levels observed in these treatments (smart irrigation and no-till) corroborate the absence of severe physiological stress and plant water homeostasis stability.

Chlorophyll Index (SPAD)

The I1T1V2 treatment clearly prevailed, keeping the highest index of chlorophyll (54.15 SPAD units) in relation to the traditional treatment (I2T2V1) that with 38.10 SPAD units. The severe decrease of chlorophyll content with conventional irrigation and bare soil tillage is attributed to pronounced upregulation of catabolic enzymes (chlorophyllase) and an overproduction of reactive oxygen species (ROS), which causes photo-oxidative degradation of the thylakoid membrane, leading to premature flag leaf senescence [9], [20]. This observed pattern is consistent with Talukder et al. [7], who noted that transient heat stress severely curtails flag leaf chlorophyll pools, and Djanaguiraman et al. [6], who reported that thermal stress promotes membrane lipid peroxidation and chloroplast disassembly. Conversely, conservation agriculture combined with real-time sensor irrigation stabilized foliar nitrogen reserves and prolonged the functional stay-green duration throughout the grain-filling period.

Agronomic Yield Components and Water Use Efficiency

Table 3. Effect of irrigation regimes, tillage systems, cultivars, and their three-way interaction on spike density (spikes m^{-2}), 1000-grain weight (g), grain yield (t ha^{-1}), and water use efficiency (kg m^{-3}).

Irrigation Regime (I)	Tillage System (T)	Cultivar (V)	Spike Density (spikes m^{-2})	1000-Grain Weight (g)	Grain Yield (t ha^{-1})	Water Use Efficiency (kg m^{-3})
Smart Irrigation (I1)	Conservation Agriculture (T1)	Ibaa 99 (V1)	385.0	41.80	5.85	1.68
		Wafiya (V2)	402.0	43.50	6.25	1.79
	Conventional Tillage (T2)	Ibaa 99 (V1)	360.0	38.90	5.15	1.47
		Wafiya (V2)	375.0	40.20	5.48	1.57
Conventional Irrigation (I2)	Conservation Agriculture (T1)	Ibaa 99 (V1)	335.0	36.10	4.32	1.03
		Wafiya (V2)	348.0	37.80	4.65	1.11
	Conventional Tillage (T2)	Ibaa 99 (V1)	295.0	31.40	3.45	0.82
		Wafiya (V2)	310.0	33.10	3.78	0.90
LSD ($p \leq 0.05$) - Irrigation (I)			**12.4**	**1.15**	**0.22**	**0.08**
LSD ($p \leq 0.05$) - Tillage (T)			**9.8**	**0.92**	**0.18**	**0.06**
LSD ($p \leq 0.05$) - Cultivars (V)			**7.5**	**0.68**	**0.12**	**0.04**
LSD ($p \leq 0.05$) - 3-Way Interaction (I×T×V)			**18.2**	**1.82**	**0.35**	**0.11**

Note: The maximum grain yield and water use efficiency was obtained with treatment I1T1V2, significantly greater than the traditional farming baseline (I2T2V1). Rows with the same letter differ statistically (LSD values at $p \leq 0.05$).

The yield components as well as the final agronomic productivity described in Table 3 directly reflect the favorable physiological and hydric conditions experienced by the wheat under optimized management.

Spike Density and 1000-Grain Weight

Highly significant superior in spike density/area (402.0 spikes m^{-2}) followed by 1000-grain weight (43.50 g) was recorded in treatment I1T1V2. Enhanced spike density has a biological basis related to increased survival of tillers and reduced tiller abortion occurring between the jointing and stem elongation phases due to uninterrupted access to moisture in the root-zone. In addition, the improved grain filling and final weight at individual level is due to a continued flow of photoassimilates (mainly sucrose) from functional flag leaves to the developing grain sinks, as there wasnot exposure to terminal stress. This agrees with Kassam et al. [10] and remains inline with Talukder et al. [7]. to individual grain weight to pre-anthesis and syn-anthesis thermal shocks.

Total Grain Yield (t ha^{-1})

The product combination which resulted in the highest grain yield of 6.25 t ha^{-1} was both the elite and the locally adapted high-yielding wheat varieties (I1) magic wheat elite and magic wheat traditional, and mixed layering and mixed cultivation (T1) and mixed layering (V2) in both years and resulted in a significant yield increase of 81.1% compared to traditional farming baseline (I2T2V1) of 3.45 t ha^{-1}. Such large yield differences are caused by the interaction of an unconsolidated, moisture-holding rhizosphere from zero-tillage residue management and smart timing of water delivery through smart sensors. This run-off was well correlated with data during the flowering and milk/dough stages, for the critical yield-determining phenophases, which eliminated the temporary moisture stress (Kumar et al. in conservation systems; Recent advances in understanding root water uptake and crop productivity. [14], [15].

Water Use Efficiency (WUE)

At the I1T1V2 interaction level, the fruit crop water use efficiency (WUE) reached the highest level (1.79 kg m^{-3}), while the WUE was only 0.82 kg m^{-3} in the conventional practice (I2T2V1). This doubling in on-farm water productivity is driven by two synergistic mechanisms; an increase in total economic yield and a direct reduction of the total applied irrigation depth by 28–32% due to smart sensor automation and reduced soil surface evaporation under residue mulch. These data corroborate the findings by Mubarak & Hamdan [16] for the feasibility of sensor-guided precision irrigation in arid regions and are in close agreement with the empirical observations reported by Du et al. [19], who documented more than 38% improvement in wheat water use efficiency using soil-moisture-guided irrigation scheduling in similar semi-arid regions.

Conclusions

This study demonstrates that the integration of sensor-based smart irrigation and zero-tillage conservation agriculture provides robust physiological protection to bread wheat under terminal heat and drought stress in semi-arid environments like Salah Al-Din Governorate, maintaining leaf RWC above 88%, preserving chlorophyll pigments (54.15 SPAD units), and suppressing stress-induced proline accumulation (16.80 μg g^{-1} FW). This modern technological package significantly enhances agronomic performance, achieving a peak grain yield of 6.25 t ha^{-1} in the cultivar Wafiya—an 81.1% increase over traditional calendar-based flood irrigation and deep tillage practices (3.45 t ha^{-1})—while more than doubling crop water use efficiency to 1.79 kg m^{-3} and reducing total applied irrigation water by 28–32%. Based on these findings, it is recommended to scale up and adopt this integrated management system (smart sensor irrigation + zero-tillage residue management) across wheat production schemes in Salah Al-Din and similar agro-ecological zones, prioritize high-yielding stress-tolerant cultivars like Wafiya in breeding and crop diversification programs, incorporate endogenous proline and SPAD index as early selection biomarkers for abiotic stress resilience, and expand future research into long-term rhizosphere microbial dynamics, nitrogen cycling, and advanced photosynthetic parameters such as photosystem II photochemical efficiency (F_v/F_m) under conservation management [8].

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