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Research Paper

Heat use efficiency and yield optimization in wheat as influenced by irrigation scheduling

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ABSTRACT

Efficient irrigation scheduling is critical for sustaining wheat (*Triticum aestivum* L.) productivity under water-limited and thermally stressed environments. A two-year field study (*Rabi* 2022–23 and 2023–24) was conducted at Lovely Professional University, Punjab, to evaluate the impact irrigation scheduling on agrometeorological indices, heat use efficiency (HUE), dry matter accumulation, and yield performance of wheat. The experiment was laid out in a randomized block design with ten irrigation treatments, including soil moisture depletion- and plant stress index (PSI) based schedules, alongside rainfed and recommended irrigation regimes. Results revealed that irrigation at 50% depletion of field capacity significantly enhanced phenological duration, leaf area index, crop growth rate, and relative water content compared with sub-optimal and rainfed treatments. The highest grain (5.99 t ha^{-1}) and straw yields (7.58 t ha^{-1}) were recorded under 50% FC depletion, followed closely by 0.50 PSI and 30% FC depletion. Heat and heliothermal use efficiencies were also superior in these treatments, underscoring the importance of maintaining adequate soil moisture during critical growth stages. The findings demonstrate that thermal indices can serve as reliable predictors of wheat growth and yield, while precise irrigation scheduling is essential for enhancing resource use efficiency and mitigating climate-induced yield losses.

Keywords*:* Growing degree days (GDD), Heat use efficiency (HUE), Irrigation scheduling, Plant stress index (PSI), RGR, CGR, RWC

Wheat (*Triticum aestivum* L.) is a vital cereal crop that serves as a staple food for a large share of the global population and forms a dietary foundation in India. The optimal temperature for wheat seed germination ranges between 20–25°C, though germination is possible within 3.5–35°C. For vegetative growth, the ideal temperature lies between 16–22°C. Given its sensitivity to temperature and moisture variations, challenges such as water scarcity and substandard agricultural practices limit wheat productivity in India. To achieve targeted yields, irrigation is indispensable, as rainfall alone cannot fulfil crop water demand. Thus, prudent irrigation management is crucial to ensure sufficient turgidity, nutrient absorption, and plant metabolism for sustained yields (Sharma and Changade, 2025). Beyond yield improvement, irrigation plays a vital role in adapting to climatic extremes such as droughts and heat waves. Effective irrigation planning ensures timely and adequate water application, which is particularly important under changing climate scenarios marked by temperature fluctuations. Precise irrigation scheduling at both vegetative and reproductive stages is essential to maintain optimum soil moisture and support crop maturation (Sharma *et al.,* 2023). Climate change poses a significant threat, with global wheat productivity projected to decline by 6% for every 1°C increase due to heat stress. Terminal heat stress during the reproductive phase further reduces yields, especially when compounded by water stress (Dar *et al.,* 2018). Agrometeorological indices provide valuable insights into crop growth under varying climatic and irrigation conditions. Indicators such as growing degree-days (GDD), helio-thermal use efficiency (HTUE), photo-thermal index (PTI), and heat use efficiency (HUE) have been widely employed for evaluating crop development, owing to their strong association with temperature and plant growth (Ram *et al.,* 2012). Understanding the interaction between thermal conditions and water availability is therefore crucial for sustaining

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wheat productivity. Irrigation not only promotes favorable crop growth but also protects plants from terminal heat stress during critical reproductive phases. Against this backdrop, the present research focuses on evaluating agrometeorological indicators across different growth stages of wheat under varied irrigation scheduling methods, thereby offering insights into optimizing water use and enhancing resilience to climatic variability.

MATERIAL AND METHOD

Experimental details

A two-year field experiment (*Rabi* 2022-23 and 2023-24) was conducted at LPU, Punjab (31°13'26.4"N, 75°46'14.9"E; 274 m) under semi-arid conditions, using wheat cultivar Unnat PBW 343 in an RBD with ten irrigation treatments (I_1 : Irrigation at CRI and flowering stages; I_2 : Irrigation at 0.25 PSI; I_3 : Irrigation at 0.50 PSI; I_4 : Irrigation at 0.75 PSI; I_5 : Irrigation at 25% depletion of FC; I_6 : Irrigation at 30% depletion of FC; I_7 : Irrigation at 50% depletion of FC; I_8 : Irrigation at 75% depletion of FC; I_9 : Rainfed) and four replications. The details of experimentation treatments and calculation of PSI (plant stress index) are already reported by Kaur *et al.,* (2024).

Plant observations and analysis

Dry matter accumulation was quantified by systematically sampling representative plants along a 1-meter row for each treatment. The above-ground biomass was harvested at 30, 60, 90, and 120 DAS, followed by oven-drying at 60°C to constant weight. The resulting dry weights were averaged and standardized to grams per square meter (g m^{2-}) to accurately reflect temporal dynamics of biomass accumulation.

Leaf area index: The leaf area index (LAI) was measured at 30, 60, 90, and 120 DAS. For this, representative plants were selected from each plot, and five fully expanded leaves per plant were sampled. The leaf area of these sample leaves was determined using an automatic leaf area meter (Model 211, Manufacturer, Systronics). The average leaf area per leaf was multiplied by the total number of leaves per plant to estimate the total leaf area per plant.

$$\text{LAI} = \frac{\text{Leafarea}}{\text{Unit land area}}$$

***Crop growth rate (CGR) and relative growth rate (RGR)*:** The dry matter accumulation per plant per unit area, expressed as crop growth rate (CGR), represents the increase in biomass over a specific time interval, whereas the relative growth rate (RGR) reflects the growth rate relative to existing plant biomass. Dry weights at two successive sampling dates (W_1 at the beginning and W_2 at the end of the interval) were determined by oven-drying representative plants from each plot at 60 °C until a constant weight was achieved. CGR and RGR were then calculated using the following formulas:

$$\text{CGR} = \frac{W_2 - W_1}{T_2 - T_1}$$

$$\text{RGR} = \frac{\ln W_2 - \ln W_1}{T_2 - T_1}$$

Where, CGR: Crop growth rate (g m^{-2} day^{-1}), RGR: Relative growth rate (g^{-} g^{-1} day^{-1}), W_1: Plant's dry weight at the start of the interval and W_2: Plant's dry weight after the interval, ln: Natural log, $T_2 - T_1$: Time interval (days) between the two successive samplings.

Relative water content (%): Leaf relative water content (RWC) was measured at 30–60, 60–90, and 90–120 DAS. For this, representative leaf samples were collected from each plot. The fresh weight (FW) of the leaves was recorded immediately after sampling to prevent moisture loss. Leaves were then floated in distilled water for 24 hours to achieve full turgidity, after which excess surface moisture was gently removed and the turgid weight (TW) was recorded. Finally, the leaves were oven-dried at 60 °C until a constant weight was achieved to obtain the dry weight (DW). RWC was calculated using the formula described by Barrs and Weatherley (1962).

$$\text{RWC (\%)} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100$$

Agrometeorological indices

Indices like growing degree days (GDD), helio-thermal units (HTU), and pheno-thermal index (PTI) were computed during the various growth stages of crop i.e. sowing to germination, germination to 50% flowering and 50% flowering to maturity. Dry matter accumulation or grain yield are two ways that thermal use efficiencies, or Helio thermal use efficiency (HTUE), can be expressed.

Growing degree days (GDD) (°C days) = $\sum (T_{max.} + T_{min.})/2 - T_b$

Helio-thermal units (HTU) (°C day hour) = GDD x n

Phenothermal index (PTI) (°C day day^{-1}) = GDD/ Growth days,

Heat use efficiency (HUE) (kg ha $°C^{-1}$ day^{-1}) = Yield (kg ha^{-1})/ GDD (°C day),

Heliothermal use efficiency (HTUE) (kg $ha^{-1}°C^{-1}$ day^{-1} hour) = Yield (kg ha^{-1})/ HTUE (°C day hour).

Where, $T_{max.}$= Maximum temperature (°C); $T_{min.}$= Minimum temperature (°C); T_b= Base temperature (°C); n= Actual bright sunshine hours. Base temperature was taken as follows: 3.6°C for the sowing to germination phase, 4.5°C for the germination to 50% flowering phase, and 7.5°C for the 50% flowering to maturity phase.

Grain and straw yield (t ha^{-1}.): The plant sample was taken from each treatment to measure the grain yield and straw yield from each experimental plot and was converted to kg ha^{-1}.

Statistical Analysis: R software was used to perform an analysis of variance (ANOVA) on the data, and Fisher's LSD multiple range test was employed to test for differences between treatments at a significance level of 5%.

RESULTS AND DISCUSSION

Effect of irrigation treatments on growth parameters

Leaf area index (LAI): Leaf area index (LAI), indicative of canopy development and photosynthetic surface, was measured across two seasons. Pooled data (Table 1) showed no significant differences at 30 DAS, but from 60 DAS onward, irrigation significantly influenced LAI. Fully irrigated treatment (I_7) recorded the highest LAI (2.71, 4.51, 4.25 at 60, 90, 120 DAS), while rainfed (I_9) had the lowest (2.27, 3.60, 3.35), reflecting moisture limitations that restricted leaf expansion, consistent with Dar (2017). Superior LAI under I_7 was attributed to sustained soil moisture supporting leaf growth and efficient light interception.

***Crop growth rate* (*g m^{-2} day^{-1}*):** Crop growth rate (CGR), reflecting dry matter accumulation per unit area, is influenced by photosynthesis, respiration, and canopy structure. As presented in Table 1, CGR increased from 30–60 DAS, peaked at 60–90 DAS, and declined thereafter. Maximum CGR occurred under I_7 (50% FC depletion) with 6.2, 18.3, and 12.0 g m^{-2} day^{-1} at 30–60, 60–90, and 90–120 DAS, respectively, while rainfed I_9 recorded the lowest due to limited moisture. Early vegetative stages showed minimal CGR, peaking near anthesis and declining towards maturity. Enhanced LAI, light interception, sustained photosynthesis, and delayed senescence under I_7 contributed to higher biomass (Nakamura *et al.,* 2003).

***Relative growth rate* (*g g^{-1} day^{-1}*):** Table 1 shows that the highest Relative Growth Rate (RGR) occurred under full irrigation (I_7), with 59, 81, and 51 × 10^{-3} g g^{-1} day^{-1} at 30–60, 60–90, and 90–120 DAS, respectively, significantly exceeding other treatments. Rainfed I_9 recorded the lowest RGR (22, 38, 17 × 10^{-3} g g^{-1} day^{-1}) due to limited leaf expansion and reduced photosynthetic capacity, constraining biomass accumulation under water stress.

Relative water content (%): Leaf relative water content (RWC), reflecting the balance between water uptake and transpiration (Lugojan and Ciulca, 2011), was significantly affected by irrigation. The highest RWC was observed under I_7 (50% FC) with 87.16% at 30–60 DAS and 83.61% at 90–120 DAS, followed by 25% and 30% FC treatments, while rainfed I9 recorded the lowest values. RWC declined with maturity, but irrigation sustained turgidity and supported growth. These results corroborate Chaves *et al.,* (2003), highlighting higher RWC during vegetative stages enhances resilience, with reductions under water-limited conditions due to restricted uptake and stress.

Effect on grain yield and straw yield (t ha^{-1})

Among the various irrigation scheduling treatments, the highest grain yield (5993 kg ha^{-1}) and straw yield (7580 kg ha^{-1}) were recorded under treatment I_7, which received the full recommended irrigation (Table 2). This was closely followed by treatments I_5 and I_6, both scheduled at 25 and 30% depletion of field capacity (FC), indicating the effectiveness of maintaining optimal soil moisture levels. Among the PSI-based irrigation treatments, I_3 (irrigation at 0.50 PSI) produced the highest grain (5670 kg ha^{-1}) and straw yields (7270 kg ha^{-1}). In contrast, the lowest yields were observed under the rainfed condition (I_9), with grain and straw yields of 2994 kg ha^{-1} and 4920 kg ha^{-1}, respectively. The yield reduction under I_9 was attributed to significant soil moisture depletion, which adversely affected root water uptake and imposed severe physiological constraints. These included accelerated leaf senescence, impairment of the photosynthetic apparatus (Farooq *et al.,* 2009), and a shortened growth cycle, coupled with decreased carbon assimilation and translocation of assimilates (Asada, 2006) as well as a reduction in grain set formation (Nawaz *et al.,* 2013). The results clearly indicate that timely and adequate irrigation prevents moisture stress and substantially improves yield performance.

Accumulated heat unit and heat use efficiency

***Growing degree days* (°days):** Crop development is influenced by canopy microclimate, including temperature, sunshine, and day length, and can be quantified using agrometeorological indices like growing degree days (GDD) (Kingra and Kaur, 2012). In this study, irrigation significantly affected GDD across phenophases (Table 2). From sowing to maturity, highest GDD occurred in I_7 (157 °C days) and I_7 (1738 °C days), while I_8, and I_9 recorded the lowest (1377 and 1281 °C days). Reduced GDD under water stress reflects accelerated phenology, while frequent irrigation enhanced GDD, optimizing crop development and productivity (Pandey *et al.,* 2010).

Helio-thermal units (°C day hour): The crop required the maximum helio-thermal units (HTU) during the germination to 50% flowering stage, while the minimum accumulation was recorded during the sowing to germination phase. During sowing to maturity, treatment I_5 exhibited the highest HTU accumulation (19574 °C day hour), which was significantly greater than the other treatments, whereas the lowest value was recorded under I_9 (13752 °C day hour). The differences in HTU were reflected in grain yield, as treatments with higher HTU also tended to produce higher yields, demonstrating that effective utilization of accumulated heat and solar radiation plays a critical role in determining wheat productivity.

***Pheno-thermal index* (*°C day day^{-1}*):** The photothermal index (PTI) showed relatively smaller variation across treatments, ranging from 38.28 °C day day^{-1} in I_9 to 43.31 °C day day^{-1} in I_1. A higher PTI, as observed in I_1, indicates faster crop development per unit time, whereas lower values in I_5 and I_9 suggest comparatively slower developmental rates. This parameter, therefore, provides useful insight into the balance between temperature-driven growth and calendar time, underscoring the importance of sowing environment and thermal regime in influencing crop phenology. Enhanced irrigation (I_6 and I_7) improved growth, light interception, and yield (Dar *et al.,* 2018; Ali *et al.,* 2012).

Heat use efficiency and Helio-thermal use efficiency: Wheat's efficiency in utilizing thermal units during sowing to maturity varied significantly with irrigation levels (Table 2). Maximum heat use efficiency (HUE) was recorded in I_3 (3.83 kg ha^{-1} °C day^{-1}), followed by I_6 and I_7 (3.49), while I_8 had the lowest (2.40). Higher HUE under well-watered conditions reflects sustained physiological activity and efficient conversion of heat units into biomass and grain yield (Pramanik and Sikder, 2020). Helio-thermal use efficiency (HTUE) was highest in I_3 (0.35 kg ha^{-1} °C day hour^{-1}), followed by I_7 and I_6, and lowest in I_8 (0.22), indicating that adequate moisture enhances radiation interception and photosynthetic efficiency, whereas water stress reduces thermal use efficiency

The superior grain yield under I_7 may be ascribed to sustained maintenance of optimal soil moisture throughout the crop's

Table 1: Effect of various irrigation scheduling methods on LAI, CGR, RGR and relative water content (%) of wheat (pooled)

Treatment	LAI				CGR (g m^{-2} day^{-1})			RGR (g g^{-1} day^{-1})			RWC (%)		
	30 DAS	60 DAS	90 DAS	120 DAS	30-60 DAS	60-90 DAS	90-120 DAS	30-60 DAS	60-90 DAS	90-120 DAS	30-60 DAS	60-90 DAS	90-120 DAS
I_1	0.78	2.43	4.05	3.70	4.4	12.9	5.0	49	60	38	78.99	74.23	72.69
I_2	0.78	2.37	4.00	3.78	3.8	14.4	7.1	46	54	37	80.53	76.46	74.06
I_3	0.77	2.32	3.93	3.59	3.6	11.8	5.7	33	50	30	78.56	75.24	70.49
I_4	0.76	2.30	3.75	3.46	3.4	10.8	4.5	30	49	20	77.51	69.29	68.02
I_5	0.80	2.52	4.33	4.01	5.8	17.1	11.3	56	72	54	85.27	84.23	82.92
I_6	0.82	2.55	4.38	4.04	5.0	15.7	10.1	55	66	47	84.28	81.36	79.64
I_7	0.82	2.71	4.51	4.25	6.2	18.3	12.0	59	81	59	87.16	84.22	83.61
I_8	0.76	2.33	3.78	3.50	3.2	10.5	4.7	29	43	20	76.34	70.38	67.08
I_9	0.75	2.27	3.60	3.45	1.5	9.8	4.4	22	38	17	74.18	68.87	66.55
C.D (p= 0.05)	NS	0.18	0.22	0.29	0.5	2.7	1.82	16	10	18	4.96	4.58	4.77

Table 2: Effect of various irrigation scheduling methods on grain yield, accumulated heat units (GDD, PTU, PTI) and heat use efficiency (HUE, HTUE) of wheat

Treatments	GDD (°C days)	HTU (°C day hour)	PTI (°C day day^{-1})	Grain yield (kg ha^{-1})	HUE (kg ha^{-1} °C^{-1} day^{-1})	HTUE (kg ha^{-1} °C^{-1} day^{-1} hour)
I_1	1498	16367	43.31	4677	3.14	0.29
I_2	1605	17607	39.68	5252	3.32	0.30
I_3	1524	16837	40.65	5670	3.83	0.35
I_4	1424	15367	40.82	3894	2.81	0.26
I_5	1733	19574	38.96	5563	3.26	0.29
I_6	1677	18674	41.94	5780	3.49	0.31
I_7	1738	19319	41.89	5993	3.49	0.31
I_8	1377	14783	39.38	3149	2.40	0.22
I_9	1281	13752	38.28	2994	2.47	0.23
C.D (p= 0.05)	10.30	7.15	0.53	482	0.36	0.03

growth period, which likely facilitated enhanced nutrient absorption and photosynthetic efficiency. Interestingly, I_3 (irrigation at 0.50 PSI) also demonstrated relatively good yield performance, possibly due to favourable moisture availability during the critical grain-filling stage. These findings corroborate earlier studies that nutrient and water uptake under well-irrigated conditions, leading to enhanced wheat growth (Singh *et al.,* 2016). Furthermore, the increased straw yield under I_7 can be linked to better soil moisture availability, which promoted plant height, improved LAI, and increased dry matter accumulation. The favourable moisture conditions also enhanced nutrient availability, thereby supporting greater biomass production. Conversely, I_9 showed marked reductions in plant height, tiller number, and biomass accumulation due to restricted photosynthetic activity under water-limited conditions (Ram *et al.,* 2012; Dar, 2017). These findings are consistent with those of Suryavanshi and Buttar (2018), who also reported significant yield penalties under drought or sub-optimal irrigation regimes.

CONCLUSION

The crop sown under recommended irrigation treatment, took a maximum of days to attain different phenological stages and required the maximum GDD, HTU and PTI during the total crop period resulting in more yield as compared to other treatments. However, no significant difference was observed between irrigation treatment I_1 and I_6. All the thermal indices showed a significant positive correlation with the dry matter accumulation. Thus, it may be used for forecasting the phenological stages and yield under different irrigation scheduling treatments for wheat. Given the persistent challenges posed by climate variations and limited water resources in the agricultural sector, the implementation of sophisticated irrigation scheduling techniques that utilize agroecological information will be indispensable for the sustainable and robust cultivation of wheat.

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