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Effect of irrigation scheduling on growth, yield, and water use efficiency and economics in wheat (*Triticum aestivum* L.)

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ABSTRACT

A field experiment was conducted during the Rabi season of 2025–26 at the Agricultural Research Farm, Suresh Gyan Vihar University, Jaipur, to evaluate the effect of irrigation scheduling on growth, yield components, water use efficiency, and economics in wheat (*Triticum aestivum* L.) variety RAJ-1482. The experiment was laid out in a Randomized Block Design with six treatments comprising progressive increases in the number of irrigations (T_1 : one irrigation at 25 DAS; T_2 – T_6 : two to six irrigations at successive critical growth stages) and four replications. Plant height increased significantly with irrigation, ranging from 74.3 cm (T_1) to 96.79 cm (T_6), while effective tillers per plant increased from 3.34 (T_1) to 5.28 (T_6). Grain yield increased progressively with irrigation frequency up to T_4 , after which T_4 , T_5 , and T_6 recorded statistically at-par yields, with T_6 achieving the highest numerical grain yield of 4,855.5 kg/ha. Water use efficiency exhibited an inverse relationship with irrigation frequency, declining from 30.08 kg/ha-mm (T_1) to 12.89 kg/ha-mm (T_6). Economic returns increased substantially with irrigation, with T_6 recording the highest gross returns (₹1,77,019/ha), net returns (₹1,28,111/ha), and benefit-cost ratio (2.62), closely followed by T_5 . Under controlled field trial conditions, a strong positive and highly significant correlation ($r = 0.826$, $p < 0.001$) was observed between irrigation frequency and grain yield. These findings suggest that while yield plateaus beyond four irrigations, additional irrigation applications substantially enhance economic returns, indicating that optimal irrigation scheduling should balance both yield and economic objectives in wheat cultivation.

Keywords: Irrigation scheduling, Wheat, Water use efficiency, Grain yield, Economics, Growth parameters, Correlation analysis

1. Introduction

Wheat, scientifically known as *Triticum aestivum* L., is one of the most important food crops in India. It plays a key role in ensuring food security and supporting the income of people in rural areas. India is the second-largest producer of wheat in the world, with annual production ranging between 113 to 122 million tonnes over an area of 31 to 33 million hectares. However, the average yield remains around 3.6 tonnes per hectare (ISRO, 2025).

The study conducted in the area of Eastern Rajasthan features a semi-arid climate marked by low and erratic rainfall (averaging 500–700 mm annually) alongside high evapotranspiration rates that surpass 1,500 mm per year. Achieving optimal wheat productivity under these conditions requires supplemental irrigation. Irrigation not only ensures adequate soil moisture but also influences nutrient availability, root development, and the expression of genetic potential for growth and yield (Prajapat *et al.*, 2020; You *et al.*, 2022) [1, 2].

Despite the critical importance of irrigation, determining the optimal number and timing of irrigations remains a challenge for farmers and agronomists. Insufficient irrigation hampers crop development and lowers yields, whereas over-irrigation raises production expenses, depletes groundwater, and can worsen waterlogging and salinization (Molden, 2007) [3]. Furthermore, water use efficiency (WUE), defined as the crop biomass or yield produced per unit of water applied, is crucial for sustainable agriculture in water-scarce regions (You *et al.*, 2022) [2].

Recent studies have shown that optimizing irrigation timing during critical growth stages substantially impacts both wheat yield and water use efficiency. Applying irrigation at the crown root initiation, tillering, jointing, and flowering stages has been demonstrated to optimize both productivity and water use efficiency (Khan *et al.*, 2025; Ma *et al.*, 2025) [4, 5].

Against this background, the present investigation was undertaken with the objectives of: (i) evaluating the effect of varying irrigation schedules on growth parameters in wheat; (ii) assessing the influence of irrigation schedules on yield attributes and grain yield; (iii) analyzing the impact of irrigation schedules on water use efficiency and economic returns; and (iv) determining the correlation between irrigation frequency and grain yield under controlled field trial conditions.

2. Materials and Methods

2.1 Experimental site and design

A field experiment was conducted during the Rabi season of 2025–26 at the Agricultural Research Farm of Suresh Gyan Vihar University, Jaipur (26°48'37.6"N 75°51'31.4"E, elevation 390 m). The soil was silt loam in texture with pH 8.25, electrical conductivity 1.42 dS/m, and organic carbon 0.23%. The experimental design was a Randomized Block Design (RBD) with six treatments and four replications (24 plots). Each plot measured 4 m × 3 m. Wheat variety RAJ-1482 was sown on 17 November 2025 at 100 kg/ha with 21 cm row spacing. The recommended fertilizer dose (120:60:40 kg N:P₂O₅:K₂O/ha) was applied at sowing, with nitrogen split-applied at sowing and tillering.

2.2 Treatment details and observations

Six irrigation treatments comprised progressive increases in the number of irrigations at critical growth stages: T₁: one irrigation at 25 DAS (crown root initiation); T₂: two irrigations at 25 and 45 DAS (tillering); T₃: three irrigations at 25, 45, and 65 DAS (jointing); T₄: four irrigations at 25, 45, 65, and 85 DAS (flowering); T₅: five irrigations at 25, 45, 65, 85, and 105 DAS (milk stage); T₆: six irrigations at 25, 45, 65, 85, 105, and 120 DAS (dough stage). Each irrigation applied 60 mm depth via conventional method, bringing soil moisture to field capacity.

Growth parameters (plant height and number of tillers per plant) were recorded at each critical irrigation stage and at harvest from five randomly selected and tagged plants per plot. Yield attributes were determined at harvest: number of effective tillers per plant and number of grains per spike were counted on the five tagged plants, spikes per m² were counted in a 1 m² area, and test weight was determined from 1,000 grains. The entire plot was harvested on 25th March 2026; grain and straw yields were recorded at 14% moisture content and expressed in kg/ha. The harvest index was calculated as the ratio of grain yield to biological yield (%). Water use efficiency (WUE, kg/ha-mm) was calculated as grain yield divided by total water input (rainfall + irrigation). Economic parameters including cost of cultivation, gross returns, net returns, and benefit-cost (B:C) ratio were computed based on prevailing market prices.

Experimental data were statistically analyzed using ANOVA appropriate to RBD. Treatment means were compared using critical difference (CD) at 5% probability. Pearson correlation analysis was performed to determine the relationship between irrigation frequency and grain yield. All analyses were conducted using SPSS version 27.0.

3. Results and Discussion

3.1 Growth parameters

3.1.1 Plant height

Plant height increased significantly with each additional irrigation throughout the crop growth period. At 25 DAS (crown root initiation), plant heights were uniform across all treatments, ranging from 14.2 to 15.03 cm, with no significant differences observed (CD = NS). However, from 45 DAS onwards, the effects of irrigation became evident and progressively enhanced plant height at successive growth stages. At harvest (128 DAS), plant heights reached 74.3, 82.95, 88.38, 96.55, 96.63, and 96.79 cm for T₁ through T₆, i.e. showing a significant linear increase with additional irrigations, respectively, with CD (5%) = 8.23 cm (Table 1). The effect plateaued beyond T₄, indicating that soil moisture saturation beyond a certain threshold provides no further enhancement in plant height.

Similar findings were reported by Kumar *et al.* (2023) [6], who observed progressive increases in wheat plant height from 68.5 cm (one irrigation) to 88.4 cm (four irrigations) in the Indo-Gangetic Plains. The plateau in plant height beyond four irrigations suggests that additional water does not further increase height, likely due to an increase in reproductive growth.

3.1.2 Number of tillers per plant

Tiller production exhibited a similar pattern to plant height, with negligible differences among treatments at early growth stages (25 and 45 DAS). By 65 DAS (jointing stage), clear differentiation among treatments became apparent, with T₃, T₄, T₅, and T₆ recording significantly higher tiller counts (4.62–4.71 tillers/plant) compared to T₁ and T₂ (4.11–4.55 tillers/plant). The number of tillers per plant at harvest were 3.75, 4.23, 4.70, 5.53, 5.50, and 5.55 for T₁ through T₆, respectively, with CD (5%) = 0.35 (Table 2).

Khan *et al.* (2025) [4] similarly observed that irrigation at critical stages increased wheat tillers from 3.2 (rainfed) to 5.8 (four irrigations). The absence of significant differences in effective tillers between T₅ and T₆ suggests that beyond four irrigations, additional water does not substantially improve tiller viability, possibly due to increased lodging risk and tiller mortality.

3.2 Yield attributes

All yield attributes were significantly improved by additional irrigations. Effective tillers per plant (tillers bearing grain-producing spikes) showed a similar trend, increasing from 3.34 (T₁) to 5.28 (T₆), with CD (5%) = 0.55. Notably, no significant difference in effective tillers was observed between T₅ and T₆, indicating yield plateau beyond four irrigations. The number of spikes per m² increased progressively from 178.8 (T₁) to 304.5 (T₆), with CD (5%) = 27.39. Similarly, the number of grains per spike showed a significant increase from 31.2 (T₁) to 46.8 (T₆), with CD (5%) = 3.14. Test weight (1000-grain weight) increased marginally but significantly from 39 g (T₁) to 42 g (T₆), with CD (5%) = NS (Table 3).

Ma *et al.* (2025) [5] demonstrated that irrigation at flowering stage specifically enhanced grain number per spike in winter wheat. The modest improvement in test weight suggests that irrigation's primary benefit resides in producing greater numbers of reproductive structures rather than increasing individual grain size, indicating that grain-filling conditions were generally adequate across most irrigation schedules.

3.3 Grain yield, straw yield and harvest index

Grain yield increased progressively and significantly with each additional irrigation from T₁ to T₄. Grain yields were 2304, 2905, 3728, 4614, 4722, and 4855 kg/ha for T₁ through T₆, respectively, with CD (5%) = 338.47. The yield increase from T₁ to T₄ represented a substantial improvement, a gain of considerable practical significance. However, the yield increment from T₄ to T₆ was minimal clearly indicating that beyond four irrigations, grain yield does not increase significantly (Table 4).

Straw yield followed a similar pattern, increasing from 3390 kg/ha (T₁) to 6181 kg/ha (T₆), with T₄, T₅ and T₆ showing at-par straw yields. The harvest index (grain yield/biological yield) showed a relatively stable increase across treatments, ranging from 40.4% to 44% indicating that additional irrigation does not substantially alter the partitioning of photosynthates between grain and straw (Table 4).

Kumar *et al.* (2023) [6] reported similar patterns, with maximum wheat yields achieved at three to four well-timed irrigations, beyond which further irrigation frequency provided diminishing returns. Prajapat *et al.* (2020) [1] reported wheat yields of 2.3 t/ha (one irrigation) to 3.5 t/ha (four irrigations) under semi-arid eastern Rajasthan conditions, closely paralleling the current results.

3.4 Water use efficiency

Water use efficiency (WUE) exhibited a marked inverse relationship with irrigation frequency. The total water input (rainfall + irrigation) was 76.6, 136.6, 196.6, 256.6, 316.6, and 376.6 mm for T₁ through T₆, respectively. Water use efficiency values were 30.08, 21.27, 18.96, 17.98, 14.92, and 12.89 kg/ha-mm for T₁ through T₆, respectively, with CD (5%) = 2.85 kg/ha-mm. Water use efficiency was highest under T₁ (38.08 kg ha⁻¹ mm⁻¹), which received the lowest irrigation amount (76 mm) (Table 5). Although increased irrigation improved grain production, the increase in yield was not proportional to

the additional irrigation water applied, resulting in a progressive decline in WUE with increasing irrigation levels.

Molden (2007) [3] explained this phenomenon as a consequence of the law of diminishing marginal returns: as soil moisture approaches saturation, the marginal productivity of additional water declines sharply because subsequent water beyond the plant's evapotranspiration requirement is lost as non-beneficial evaporation or percolation. **You et al. (2022)** [2] reported similar WUE patterns in winter wheat, with maximum WUE of 32.5 kg/ha-mm under rainfed conditions declining to 14.8 kg/ha-mm under a six-irrigation schedule.

3.6 Effect of irrigation scheduling on economics

The cost ratio improved from 0.96 (a loss-making proposition) to 2.62 under T_6 , with T_4 and T_5 (2.58 and 2.59) statistically at par with T_6 . This indicates that despite its lower WUE, T_6 remained the most profitable treatment because the value of the additional grain yield far outweighed the marginal cost of the extra irrigation (Table 6). These findings are consistent with **Kumar et al. (2023)** [6], who reported that irrigation scheduling close to full crop water requirement maximized net returns and benefit–cost ratio in wheat, even though the highest water-use efficiency was recorded under comparatively lower irrigation levels.

Table 1. Effect of irrigation scheduling on plant height (cm) at different growth stages

Treatment	25 DAS	45 DAS	65 DAS	85 DAS	At Harvest
T ₁	14.20	27.80	52.75	72.70	74.3
T ₂	15.03	28.91	59.05	80.84	82.95
T ₃	14.33	28.48	59.2	86.93	88.38
T ₄	14.13	28.20	59.50	89.27	96.55
T ₅	15.0	29.03	59.88	89.33	96.63
T ₆	14.68	28.80	60.53	89.50	96.79
SEm±	0.45	0.85	1.54	2.70	2.73
CD (5%)	NS	NS	4.65	8.15	8.23
CV (%)	6.22	5.93	4.27	6.38	6.12

Table 2. Effect of irrigation scheduling on number of tillers per plant

Treatment	25 DAS	45 DAS	65 DAS	85 DAS	At Harvest
T ₁	1.40	3.65	4.11	4.35	3.75
T ₂	1.41	3.80	4.55	5.14	4.23
T ₃	1.29	3.78	4.62	5.52	4.70
T ₄	1.37	3.63	4.67	5.55	5.53
T ₅	1.41	3.78	4.69	5.58	5.50
T ₆	1.42	3.67	4.71	5.60	5.55
SEm±	0.06	0.15	0.13	0.14	0.12
CD (5%)	NS	NS	0.39	0.44	0.35
CV (%)	8.51	7.93	5.63	5.55	4.79

Table 3. Effect of irrigation scheduling on yield attributes at harvest

Treatment	Effective Tillers/Plant	Spikes/m ²	Grains/Spike	Test Weight (g)
T ₁	3.34	178.75	31.20	39.0
T ₂	3.91	206.80	34.98	40.0
T ₃	4.50	229.18	38.93	40.8
T ₄	5.25	297.98	46.00	41.5
T ₅	5.24	301.80	46.43	41.8
T ₆	5.28	304.45	46.80	42.0
SEm±	0.18	9.09	1.04	1.38
CD (5%)	0.55	27.39	3.14	NS
CV (%)	8.06	7.18	5.12	6.77

Table 4. Effect of irrigation scheduling on grain yield, straw yield, and harvest index

Treatment	Grain Yield (kg/ha)	Straw Yield (kg/ha)	Harvest Index (%)
T ₁	2304.25	3390.33	40.44
T ₂	2905.50	4035.40	41.86
T ₃	3728.00	4985.15	42.81
T ₄	4614.50	5994.55	43.50
T ₅	4722.00	6082.38	43.70
T ₆	4855.50	6181.33	44.00

(continued on next page)

Treatment	Grain Yield (kg/ha)	Straw Yield (kg/ha)	Harvest Index (%)
SEm±	112.29	155.01	0.19
CD (5%)	338.47	467.25	0.58
CV (%)	5.83	6.07	0.91

Table 5. Effect of irrigation scheduling on water use efficiency (kg/ha-mm)

Treatment	Total Water (mm)	WUE (kg/ha-mm)
T ₁	76.6	30.08
T ₂	136.6	21.27
T ₃	196.6	18.96
T ₄	256.6	17.98
T ₅	316.6	14.92
T ₆	376.6	12.89
SEm±	—	0.94
CD (5%)	—	2.85
CV (%)	—	9.77

Table 6. Effect of irrigation scheduling on Economics

Treatment	Cost (₹/ha)	Gross Returns (₹/ha)	Net Returns (₹/ha)	B:C Ratio
T ₁	44908.00	88119.18	43211.18	0.96
T ₂	45708.00	108956.10	63248.10	1.39
T ₃	46508.00	138066.35	91558.35	1.97
T ₄	47308.00	169313.45	122005.45	2.58
T ₅	48108.00	172791.38	124683.38	2.54
T ₆	48908.00	177019.43	128111.43	2.52
SEm±	—	4180.03	4180.03	0.09
CD (5%)	—	125999.97	125999.97	0.27
CV (%)	—	5.87	8.76	9.03

3.7 Correlation analysis: irrigation frequency and grain yield

Pearson correlation analysis revealed a strong positive and highly significant correlation between irrigation frequency (number of irrigations) and grain yield under controlled field trial conditions: $r = 0.826$ ($p < 0.001$, $n = 24$). This correlation coefficient represents a strong positive linear relationship, demonstrating that approximately 68.2% of the variation in grain yield ($R^2 = 0.682$) could be explained by irrigation frequency alone under controlled field conditions. Each additional irrigation at the prescribed critical growth stages progressively increased grain yield in a highly predictable manner, validating contemporary irrigation management theory and the importance of precise irrigation scheduling for maximizing wheat productivity. Khan *et al.* (2025) [4] and You *et al.* (2022) [2] have similarly established strong correlations ($r > 0.80$) between irrigation frequency and wheat yield in semi-arid environments, confirming the applicability of this relationship across diverse agro-climatic zones.

4. Conclusion

This field experiment demonstrates that irrigation scheduling significantly influences wheat growth, yield, water use efficiency, and economics. The strong correlation ($r = 0.826$) between irrigation frequency and grain yield under controlled conditions validates the importance of strategic irrigation scheduling. Plant height and tiller production increased progressively with irrigation, yielding an improvement in grain yield from T₁ to T₄. However, diminishing returns beyond four irrigations (T₄) suggest an optimization point exists. Water use efficiency exhibited an inverse relationship with irrigation frequency, highlighting the trade-off between maximizing absolute yield and maximizing water productivity.

Economic analysis demonstrated that four well-timed irrigations at critical growth stages (25, 45, 65, and 85 DAS) provide optimal re-

turns (₹122,005/ha net returns, B:C ratio 2.58), balancing productivity, water conservation, and economic viability. This recommendation is particularly relevant for groundwater-scarce regions facing rising irrigation costs. Future research should validate these findings across multiple seasons and locations to establish robust recommendations for irrigation management in wheat under diverse agro-climatic and socio-economic conditions.

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