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Comparative evaluation of irrigation schedules and hydrogel formulations for enhancing growth and nutrient uptake of wheat

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Abstract

Water scarcity and inefficient irrigation scheduling remain principal constraints to wheat productivity in India. A field experiment was conducted during the *Rabi* season of 2020-21 at Sabour, Bhagalpur, Bihar, in a split-plot design replicated thrice, to evaluate the combined effects of three irrigation schedules (I₁: one irrigation at the crown root initiation, CRI; I₂: two irrigations at CRI and boot leaf stage; I₃: three irrigations at CRI, late jointing and milking stage) as the main-plot factor and five hydrogel treatments (Eco Sarovar, Vedic, Vaaridhar G1 and Nano hydrogel, plus an untreated control) as the sub-plot factor on growth and nutrient uptake of wheat. Three irrigations significantly increased plant height, number of tillers m⁻², leaf area index (LAI), dry matter accumulation and nitrogen, phosphorus, and potassium uptake over a single irrigation, while remaining statistically at par with two irrigations for most traits at later growth stages. Among hydrogels, Nano hydrogel (20 kg ha⁻¹) consistently outperformed all other treatments and the control, increasing plant height, tiller number and dry matter accumulation at harvest by 8.9, 31.9 and 25.4%, respectively, over the control, and elevating total nitrogen, phosphorus and potassium uptake by 32.9, 31.9 and 25.3%, respectively. Eco Sarovar and Vedic hydrogels produced intermediate, statistically comparable responses, whereas Vaaridhar G1 performed only marginally above the control. Irrigation × hydrogel interactions were non-significant for all traits, indicating that hydrogel benefits were additive and consistent across irrigation regimes. Multi-trait visualization (percentage-increase-over-control and standardized heat-map analyses) confirmed Nano hydrogel as the superior treatment across nearly all measured traits. These findings demonstrate that superabsorbent hydrogel amendment, particularly at the nano scale, can partially compensate for restricted irrigation and improve resource-use efficiency in wheat production under semi-arid, sub-tropical field conditions.

Keywords: Hydrogel, irrigation scheduling, wheat, dry matter accumulation, nutrient uptake, split-plot design, crop growth rate

1. Introduction

Wheat is the second most important staple cereal after rice in India, underpinning both national food security and rural livelihoods across the region. Wheat occupied an area of 31.83 million hectares with a production of 113.29 million tonnes and a productivity of 3559 kg/ha (MoA & FW, 2023-24). Wheat productivity is tightly coupled to the timing and adequacy of irrigation, since the crop is largely grown on residual soil moisture supplemented by a limited number of irrigations during the winter (*Rabi*) season. Annual per capita water availability in India fell from over 5,000 m³ in the 1950s to below 1,450 m³ today, pushing large parts of the country below the international water-stress benchmark of 1,700 m³ per capita (Rajanna *et al.*, 2022) ^[16]. India faces critical groundwater depletion driven heavily by agriculture, which consumes 80% to 90% of the country's available freshwater (Roy *et al.*, 2019) ^[17]. Erratic and declining rainfall, groundwater depletion, and rising pump-irrigation costs have intensified the need for management strategies that either improve water-use efficiency or reduce the number of irrigations needed to sustain yield. Against this backdrop, soil-applied superabsorbent hydrogels have attracted growing agronomic interest as a low-cost, field-deployable technology to buffer soil moisture availability during critical crop-growth stages (Agbna *et al.*, 2025) ^[2].

Hydrogels are three-dimensional, cross-linked hydrophilic polymer networks capable of absorbing and retaining water at many times their own dry weight, and of releasing this water gradually to the surrounding rhizosphere as the soil dries (Saini *et al.*, 2023) [18]. Beyond their function as water reservoirs, hydrogels modify soil physical structure by reducing bulk density and increasing porosity, particularly in coarse-textured soils, and can improve aggregate stability and soil aeration through repeated swelling–shrinkage cycles (Wang *et al.*, 2026) [23]. In addition to improving soil moisture retention, hydrogels can reduce nutrient leaching by 20–30%, thereby promoting nutrient conservation and potentially enhancing soil fertility (Kebede *et al.*, 2022) [11]. Despite this accumulating evidence, most published trials have evaluated a single hydrogel product against an untreated control, leaving open the question of how different commercially available hydrogel formulations differing in polymer chemistry, particle scale and recommended application rate compare with one another when tested side by side under a common irrigation gradient. Therefore, the present study was undertaken to evaluate the effect of three irrigation schedules and four hydrogel formulations, together with an untreated control, on growth parameters of wheat cv. HD-2967 and nutrient uptake in grain and straw

2. Materials and Methods

2.1 Experimental site and climate

The experiment was conducted during the winter (rabi) season of 2020-21 at the college farm of Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India, located in the middle Gangetic plain (Agro-climatic Zone IIIA of southern East Bihar) at 25°50' N latitude, 87°19' E longitude and 52.73 m altitude above mean sea level. The site experiences a sub-tropical climate with hot, dry summers, moderate rainfall and cold winters; during the 2020-21 crop season, weekly minimum and maximum temperatures ranged from 7.7 to 19.9°C (29 January–4 February) and 24.8 to 36.1°C (9–15 April), respectively. Total rainfall received during the crop period was only 0.40 mm, against a normal of 56.0 mm, so that crop water supply was almost entirely determined by the imposed irrigation treatments. The experimental soil was sandy loam in texture, neutral in P^H, and contained 0.50% organic carbon, 179.38 kg available nitrogen/ha (Subbiah and Asija, 1956) [20], 23.52 kg available P₂O₅/ha (Olsen *et al.*, 1954) [14], and 193.00 kg available K₂O/ha (Jackson, 1973) [10].

2.2 Treatment details

The field trial was laid out in a split-plot design replicated thrice. Three irrigation schedules were assigned to main plots: I₁, one irrigation at the crown root initiation (CRI) stage; I₂, two irrigations at CRI and the boot leaf stage; and I₃, three irrigations at CRI, late jointing and the milking stage. Four hydrogel treatments: T₁, Eco Sarovar hydrogel (7.5 kg ha⁻¹); T₂, Vedic hydrogel (7.5 kg ha⁻¹); T₃, Vaaridhar G1 hydrogel (2.5 kg ha⁻¹); T₄, Nano hydrogel (20 kg ha⁻¹); and T₅, an untreated control (no hydrogel), formed the sub-plot factor, giving 15 main-plot × sub-plot treatment combinations. Wheat variety HD-2967 was used as the test cultivar, and the recommended fertilizer dose of 150:60:40 kg N: P₂O₅: K₂O ha⁻¹ was applied through urea, diammonium phosphate and muriate of potash.

2.3 Growth parameters

Plant height (cm) was recorded on five randomly selected, tagged plants per plot at 30, 60 and 90 days after sowing (DAS) and at harvest, measured from the base to the tip of the plant using a meter scale, and averaged per plot. The number of tillers m⁻² was

counted at three randomly selected locations per plot at the same growth stages and averaged. Leaf area index (LAI) was measured directly at 30, 60 and 90 DAS using a ceptometer (AccuPAR LP-80, Decagon Devices Inc., Pullman, WA, USA) at three randomly selected locations per plot. Total dry matter accumulation (g m⁻²) was determined destructively from a 25-cm row-length sample cut from the third row of each plot at 30, 60 and 90 DAS and at harvest; samples were sun-dried and then oven-dried at 60 ± 5 °C to constant weight. Crop growth rate (CGR, g m⁻² day⁻¹) was calculated for the intervals 0–30, 30–60, 60–90 DAS and 90 DAS–harvest using the classical formula of Watson (1947) [24]:

$$CGR = \frac{(W_2 - W_1)}{(t_2 - t_1)}$$

where W₁ and W₂ are dry matter accumulation (g m⁻²) at times t₁ and t₂, respectively.

2.4 Plant sample analysis and nutrient uptake

At harvest, grain and straw samples from each plot were oven-dried for 48 h at 60 ± 5°C, ground in a Willey mill and passed through a 30-mesh sieve for chemical analysis. Nitrogen content was determined following digestion with concentrated H₂SO₄ and H₂O₂ in the presence of a catalyst mixture, using the modified Kjeldahl method (Piper, 1966) [15]. Phosphorus content was estimated after di-acid digestion by the vanadomolybdate-phosphoric yellow colour method (Jackson, 1973) [10], read spectrophotometrically. Potassium content was determined on the same di-acid digest using a flame photometer (Jackson, 1973) [10]. Nutrient uptake (kg ha⁻¹) in grain and straw was calculated using the formula below, and total uptake was obtained by summing grain and straw uptake.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \frac{\text{Nutrient concentration (\%)}}{100} \times \text{Yield (kg ha}^{-1}\text{)}$$

2.5 Statistical analysis and data visualization

All data were subjected to analysis of variance appropriate to the split-plot design, with irrigation levels as the main-plot factor and hydrogel treatments as the sub-plot factor, replicated thrice. Treatment means were compared using the critical difference (CD) at P = 0.05; where the F-test was non-significant, treatment effects were reported as non-significant (NS) as described by Gomez and Gomez (1984) [7]. In addition to the standard analysis of variance, treatment-mean data for all recorded traits were used to construct a series of complementary visualizations including temporal growth-trajectory line plots, stacked bar charts for grain/straw nutrient partitioning, a percentage-increase-over-control summary chart, and standardized (z-score) heat map to facilitate multi-trait comparison among the five hydrogel treatments. All these figures were generated in Python using Matplotlib (Hunter, 2007) [9] and NumPy (Harris *et al.*, 2020) [8] at a resolution of 300 dpi.

3. Results

3.1 Growth parameters

3.1.1 Plant height

Data on plant height at different growth stages are presented in Table 1. Irrigation levels significantly influenced plant height at 90 DAS and at harvest but not at 30 or 60 DAS. Three irrigations (I₃) produced the tallest plants at harvest, 7.17 and 2.58% taller than under one (I₁) and two (I₂) irrigations, respectively, and I₃ was statistically at par with I₂. Hydrogel treatments significantly affected plant height at all stages except 30 DAS. Nano hydrogel

(T₄) consistently produced the tallest plants, exceeding the untreated control by 16.37, 9.31 and 8.90% at 60 DAS, 90 DAS and harvest, respectively, while control plants (T₅) remained shortest throughout. The irrigation × hydrogel interaction was non-significant at all stages.

Table 1: Effect of irrigation regimes and hydrogel formulations on plant height (cm) of wheat at successive growth stages

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Irrigation levels (main-plot factor)				
I ₁ (1 irrigation)	23.08	52.26	90.62	93.92
I ₂ (2 irrigations)	23.04	52.25	94.18	98.12
I ₃ (3 irrigations)	23.20	55.73	95.74	100.65
SEm±	0.43	1.24	0.99	1.07
CD (P=0.05)	NS	NS	4.00	4.31
Hydrogel treatments (sub-plot factor)				
T ₁ Eco Sarovar	23.16	54.79	94.54	98.43
T ₂ Vedic	23.21	54.79	94.48	98.59
T ₃ Vaaridhar G1	22.62	51.76	91.70	95.94
T ₄ Nano hydrogel	23.73	56.87	97.57	101.58
T ₅ Control	22.81	48.87	89.26	93.28
SEm±	0.29	0.74	0.46	0.42
CD (P=0.05)	NS	2.18	1.35	1.22
I × T	NS	NS	NS	NS

3.1.2 Number of tillers

Number of tillers m⁻² (Table 2) increased sharply from 30 to 60 DAS and then declined progressively to harvest. Irrigation level significantly affected tiller number at 90 DAS and at harvest, where I₃ exceeded I₁ and I₂ by 10.53 and 7.04%, respectively. Hydrogel treatments significantly influenced tiller number at all stages except 30 DAS, with Nano hydrogel (T₄) again superior to all other treatments; tiller number under T₄ exceeded the control by 12.69, 28.11 and 31.88% at 60 DAS, 90 DAS and harvest, respectively. The irrigation × hydrogel interaction remained non-significant throughout.

Table 2: Effect of irrigation regimes and hydrogel formulations on number of tillers (m⁻²) of wheat at successive growth stages

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Irrigation levels (main-plot factor)				
I ₁ (1 irrigation)	131.41	335.88	288.41	277.23
I ₂ (2 irrigations)	131.24	331.49	307.66	286.26
I ₃ (3 irrigations)	131.73	336.98	326.41	306.42
SEm±	1.26	1.29	3.20	4.73
CD (P=0.05)	NS	NS	12.56	19.08
Hydrogel treatments (sub-plot factor)				
T ₁ Eco Sarovar	131.85	334.54	311.61	293.54
T ₂ Vedic	131.76	335.91	314.94	296.15
T ₃ Vaaridhar G1	130.49	325.07	290.18	271.60
T ₄ Nano hydrogel	132.74	359.44	348.63	329.99
T ₅ Control	130.46	318.95	272.12	250.22
SEm±	0.62	1.68	2.73	2.41
CD (P=0.05)	NS	4.91	7.98	7.07
I × T	NS	NS	NS	NS

3.1.3 Leaf area index

Leaf area index rose sharply between 30 and 60 DAS irrespective

of treatment (Table 3). Irrigation level significantly affected LAI at 60 and 90 DAS, with I₃ recording the highest LAI (4.56) at 90 DAS, statistically at par with I₂. Hydrogel treatments significantly influenced LAI at 60 and 90 DAS; the maximum LAI at 90 DAS (4.59) was recorded with Nano hydrogel, significantly higher than the control (4.29), while T₁ and T₂ were statistically at par with one another at 60 DAS. Interaction effects were non-significant at all stages.

Table 3: Effect of irrigation regimes and hydrogel formulations on leaf area index of wheat at successive growth stages

Treatment	30 DAS	60 DAS	90 DAS
Irrigation levels (main-plot factor)			
I ₁ (1 irrigation)	0.783	2.453	4.295
I ₂ (2 irrigations)	0.783	2.454	4.553
I ₃ (3 irrigations)	0.782	2.501	4.556
SEm±	0.004	0.006	0.021
CD (P=0.05)	NS	0.024	0.081
Hydrogel treatments (sub-plot factor)			
T ₁ Eco Sarovar	0.783	2.482	4.527
T ₂ Vedic	0.786	2.483	4.534
T ₃ Vaaridhar G1	0.777	2.450	4.398
T ₄ Nano hydrogel	0.791	2.500	4.589
T ₅ Control	0.778	2.430	4.292
SEm±	0.004	0.007	0.010
CD (P=0.05)	NS	0.021	0.030
I × T	NS	NS	NS

3.1.4 Total dry matter accumulation

Total dry matter accumulation increased progressively with crop age under all treatments (Table 4). Irrigation level significantly affected dry matter accumulation at all stages except 30 DAS; maximum accumulation at harvest (971.50 g m⁻²) occurred under I₃, statistically at par with I₂ (901.41 g m⁻²). Hydrogel treatments significantly affected dry matter accumulation at all stages except 30 DAS, with Nano hydrogel producing 25.42% greater accumulation at harvest than the untreated control. Irrigation × hydrogel interaction was non-significant at all stages.

Table 4: Effect of irrigation regimes and hydrogel formulations on total dry matter accumulation (g m⁻²) of wheat at successive growth stages

Treatment	30 DAS	60 DAS	90 DAS	At harvest
Irrigation levels (main-plot factor)				
I ₁ (1 irrigation)	92.70	298.92	559.26	789.17
I ₂ (2 irrigations)	93.00	309.92	648.63	901.41
I ₃ (3 irrigations)	93.02	335.09	673.55	971.50
SEm±	0.84	5.96	11.99	27.74
CD (P=0.05)	NS	24.02	48.34	111.85
Hydrogel treatments (sub-plot factor)				
T ₁ Eco Sarovar	92.50	318.08	633.43	900.61
T ₂ Vedic	92.84	320.79	641.39	910.47
T ₃ Vaaridhar G1	92.78	302.11	597.82	853.70
T ₄ Nano hydrogel	93.37	342.33	689.73	985.92
T ₅ Control	93.05	289.90	573.36	786.10
SEm±	0.31	2.73	6.72	10.08
CD (P=0.05)	NS	8.02	19.74	29.59
I × T	NS	NS	NS	NS

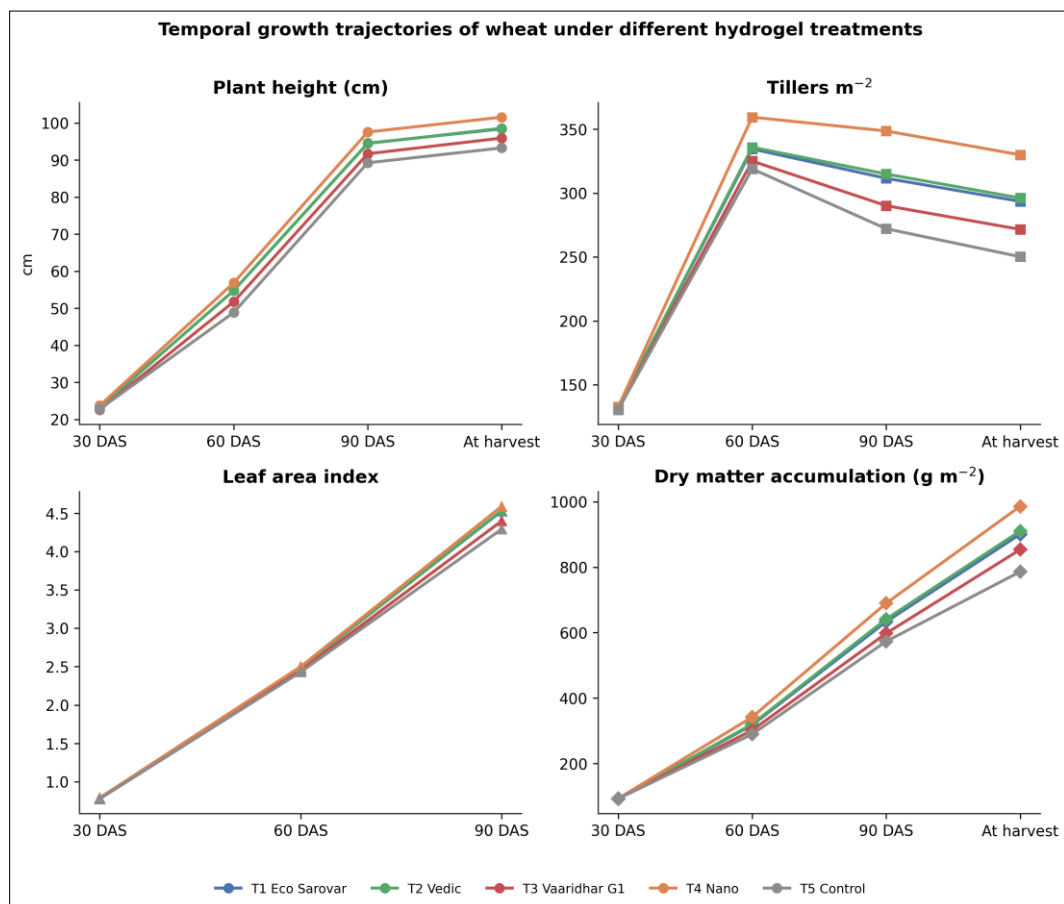


Fig 3: Temporal growth trajectories of wheat plant height, tiller number, leaf area index and dry matter accumulation under five hydrogel treatments (T₁–T₅), recorded at 30, 60, 90 DAS and at harvest.

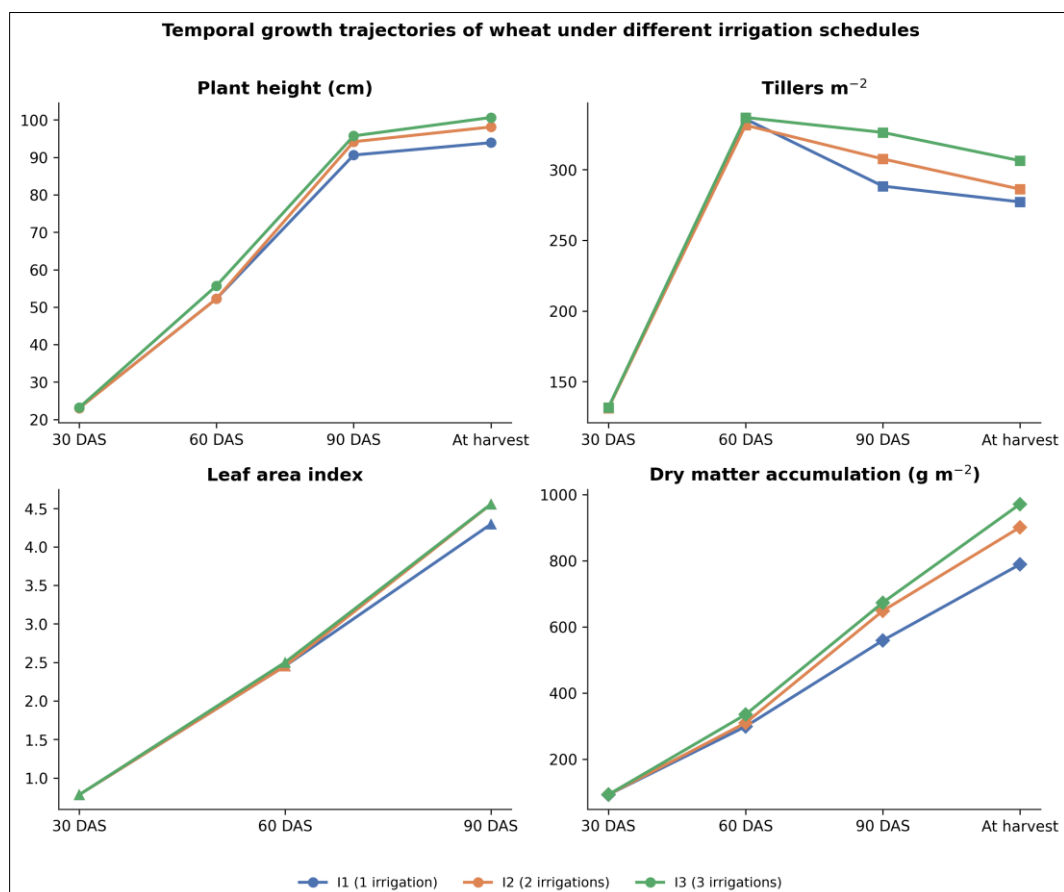


Fig 4: Temporal growth trajectories of wheat plant height, tiller number, leaf area index and dry matter accumulation under three irrigation schedules (I₁–I₃), recorded at 30, 60, 90 DAS and at harvest

3.1.5 Crop growth rate

Crop growth rate increased progressively to a peak during the 60–90 DAS interval before declining toward harvest (Table 5). Irrigation level significantly influenced CGR at all intervals except 0–30 DAS; the highest CGR during 60–90 DAS was recorded under I_2 (11.29 g m⁻² day⁻¹), statistically at par with I_3 (11.28 g m⁻² day⁻¹), while during 90 DAS–harvest, I_3 recorded the

significantly highest CGR. Hydrogel treatments significantly influenced CGR at all intervals except 0–30 DAS, with Nano hydrogel recording the highest CGR at every interval (8.30, 11.58 and 7.40 g m⁻² day⁻¹ during 30–60, 60–90 and 90 DAS–harvest, respectively), significantly superior to all other treatments and the control. No significant irrigation × hydrogel interaction was detected.

Table 5: Effect of irrigation regimes and hydrogel formulations on crop growth rate (g m⁻² day⁻¹) of wheat across phenological intervals

Treatment	0–30 DAS	30–60 DAS	60–90 DAS	90 DAS–Harvest
Irrigation levels (main-plot factor)				
I_1 (1 irrigation)	3.09	6.88	8.68	5.75
I_2 (2 irrigations)	3.10	7.23	11.29	6.32
I_3 (3 irrigations)	3.10	8.07	11.28	7.45
SEm±	0.03	0.18	0.21	0.25
CD (P=0.05)	NS	0.72	0.83	1.00
Hydrogel treatments (sub-plot factor)				
T_1 Eco Sarovar	3.08	7.52	10.51	6.68
T_2 Vedic	3.09	7.60	10.69	6.73
T_3 Vaaridhar G1	3.09	6.98	9.86	6.40
T_4 Nano hydrogel	3.11	8.30	11.58	7.40
T_5 Control	3.10	6.56	9.45	5.32
SEm±	0.01	0.08	0.11	0.17
CD (P=0.05)	NS	0.24	0.32	0.51
$I \times T$	NS	NS	NS	NS

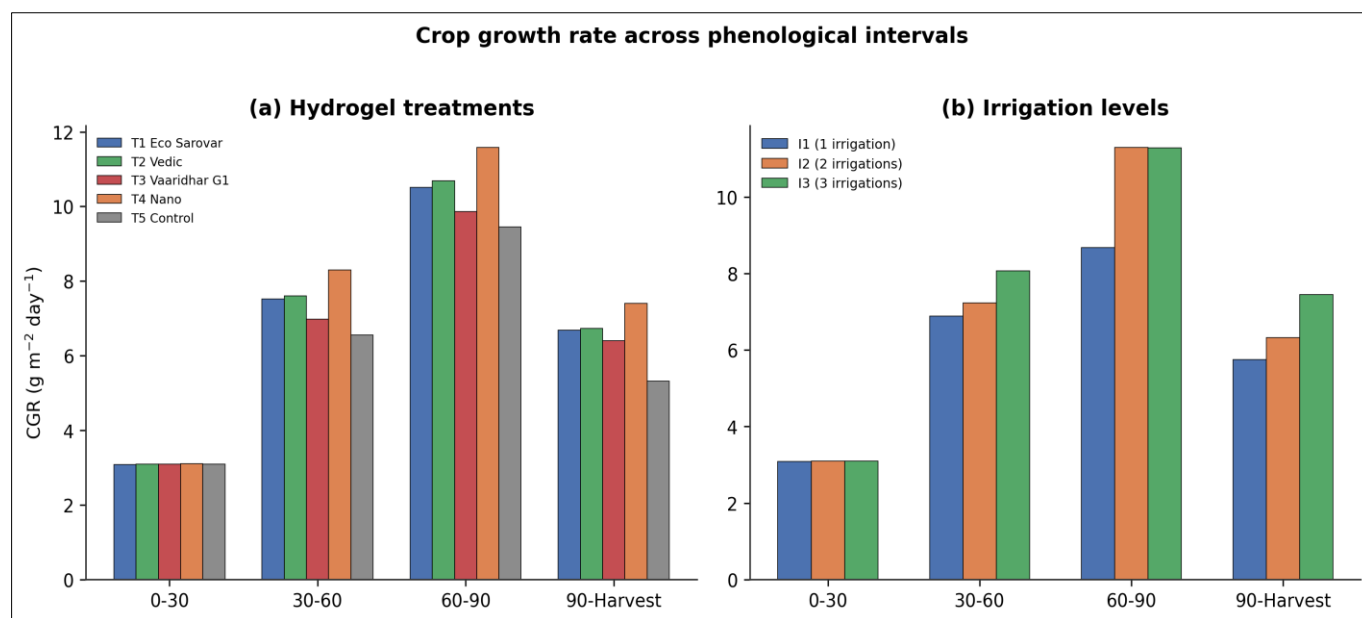


Fig 5: Crop growth rate (CGR) of wheat across four phenological intervals (0–30, 30–60, 60–90 DAS and 90 DAS–harvest) under (a) five hydrogel treatments and (b) three irrigation schedules.

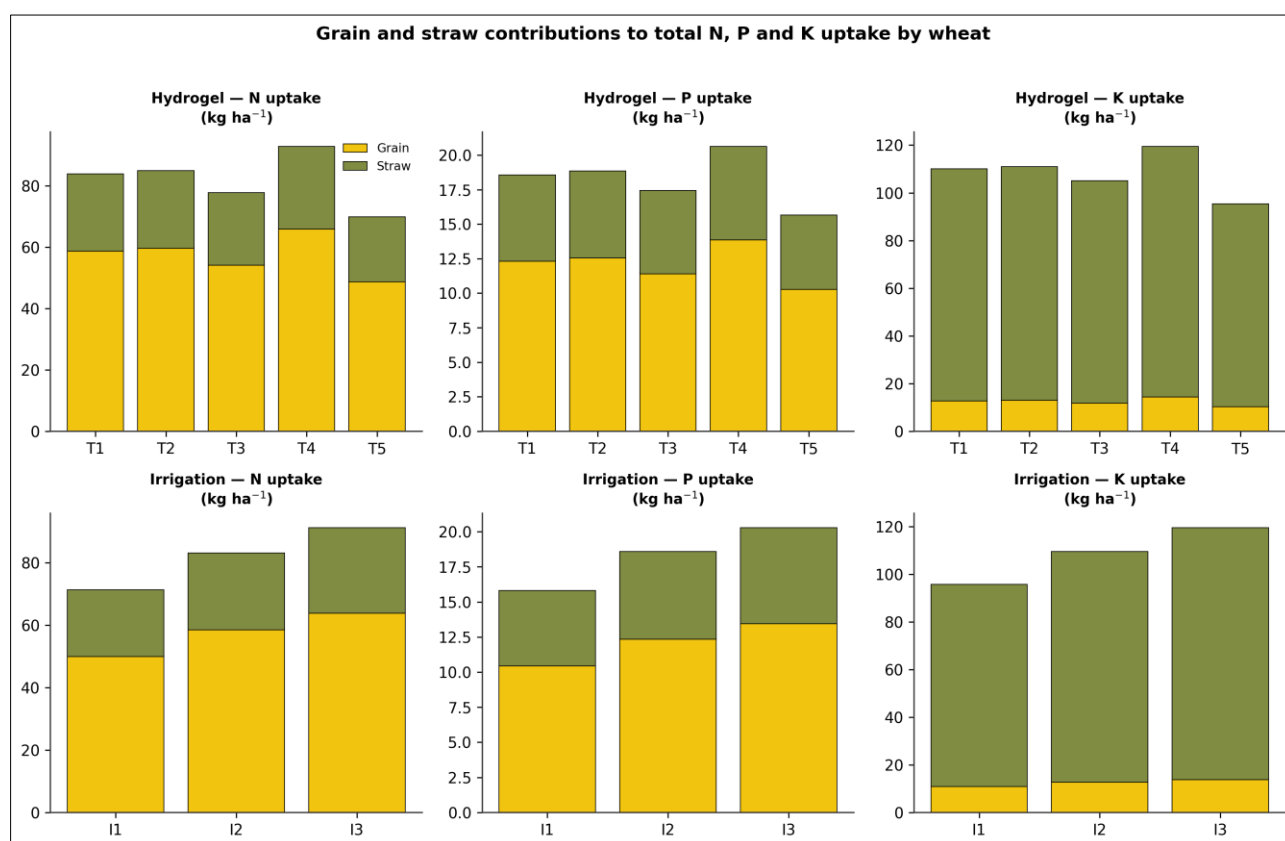
3.2 Plant sample analysis and nutrient uptake

Nitrogen, phosphorus and potassium uptake in grain, straw and total are summarized in Table 6. Nutrient uptake for all three elements increased consistently with increasing irrigation frequency. Nitrogen, phosphorus and potassium uptake by wheat was higher with three irrigations (I_3), but it was statistically at par

with I_2 for all three nutrients. Nano hydrogel recorded 32.95, 31.88 and 25.29% higher N, P and K uptake over the control and was statistically comparable with Vedic hydrogel for straw nitrogen uptake. Irrigation × hydrogel interactions were non-significant for nitrogen, phosphorus and potassium uptake in both grain and straw.

Table 6: Effect of irrigation regimes and hydrogel formulations on nitrogen, phosphorus and potassium uptake (kg ha^{-1}) by wheat grain and straw

Treatment	N Grain	N Straw	N Total	P Grain	P Straw	P Total	K Grain	K Straw	K Total
Irrigation levels (main-plot factor)									
I ₁ (1 irrigation)	49.94	21.34	71.28	10.44	5.37	15.80	10.82	84.82	95.64
I ₂ (2 irrigations)	58.41	24.68	83.09	12.35	6.23	18.57	12.72	96.77	109.49
I ₃ (3 irrigations)	63.79	27.44	91.23	13.44	6.86	20.30	13.76	105.78	119.54
SEm $\pm$	2.17	0.94	3.11	0.46	0.23	0.66	0.52	2.97	3.47
CD (P=0.05)	8.77	3.78	12.52	1.85	0.91	2.67	2.08	11.97	13.97
Hydrogel treatments (sub-plot factor)									
T ₁ Eco Sarovar	58.65	25.23	83.88	12.30	6.27	18.56	12.75	97.36	110.11
T ₂ Vedic	59.61	25.36	84.97	12.55	6.30	18.85	12.99	98.05	111.04
T ₃ Vaaridhar G1	54.08	23.66	77.73	11.40	6.03	17.42	11.76	93.29	105.04
T ₄ Nano hydrogel	65.89	26.99	92.88	13.85	6.79	20.64	14.36	105.17	119.53
T ₅ Control	48.67	21.20	69.86	10.28	5.38	15.65	10.32	85.08	95.40
SEm $\pm$	1.09	0.40	1.48	0.23	0.11	0.34	0.30	1.56	1.84
CD (P=0.05)	3.21	1.78	4.34	0.68	0.32	1.00	0.87	4.58	5.39
I $\times$ T	NS	NS	NS	NS	NS	NS	NS	NS	NS

**Fig 6:** Grain and straw contributions to total nitrogen, phosphorus and potassium uptake by wheat under five hydrogel treatments (top row) and three irrigation schedules (bottom row).

3.3 Multi-trait visualization of treatment performance

The percentage-increase-over-control summary for hydrogels (Figure 7) and the corresponding percentage-increase-over-single-irrigation summary for irrigation schedules (Figure 8) quantify the relative efficacy of each treatment level across all measured traits simultaneously. Nano hydrogel delivered the largest relative gain for every trait among hydrogel treatments, followed by Vedic and Eco Sarovar, which performed similarly to one another, while Vaaridhar G1 provided only a modest improvement over the control; among irrigation schedules, three irrigations (I₃) produced the largest relative gain over a single irrigation for every trait, with two irrigations (I₂) delivering roughly half of that gain, reflecting a diminishing-returns pattern as irrigation frequency increased.

The standardized (z-score) heat maps (Figures 9 and 10) provide an integrated, multi-trait view of treatment performance for each factor separately. Nano hydrogel (T₄) and three irrigations (I₃) schedule independently maximized all agronomic and nutrient uptake traits. Notably, T₄ elicited the highest comparative efficacy across all parameters (z-scores ranging from +1.00 for LAI to +1.40 for tillers m^{-2}), whereas the control (T₅) uniformly suppressed trait development ($z = -1.28$ to -1.46). Furthermore, trait performance scaled positively with water availability, the I₃ regime secured peak standardized scores ($z = +0.59$ to $+1.10$), while the moisture-restricted single-irrigation (I₁) regime resulted in pronounced, systemic deficits across all measured indices ($z = -0.85$ to -1.15).

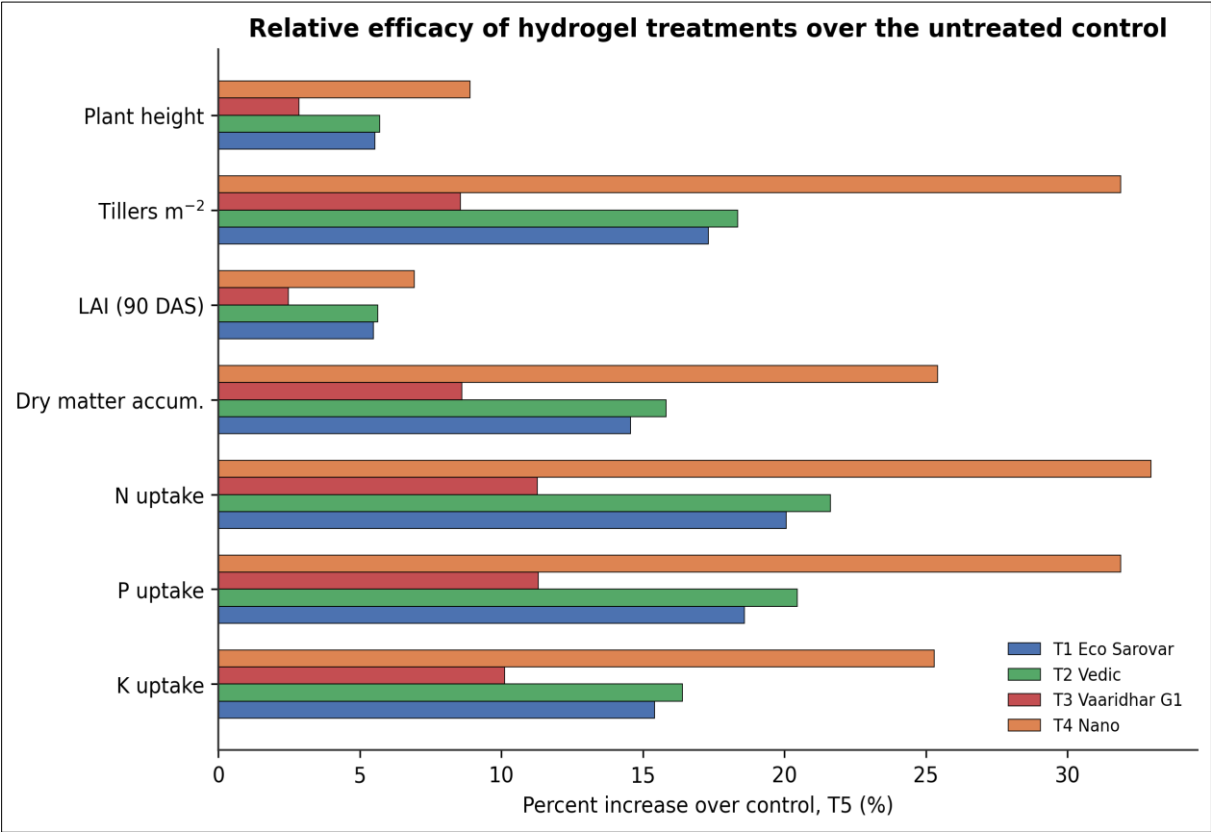


Fig 7: Percentage increase in plant height, tiller number, leaf area index, dry matter accumulation, and nitrogen, phosphorus and potassium uptake under hydrogel treatments T₁–T₄ relative to the untreated control (T₅ = 0% reference line), at the final recorded growth stage.

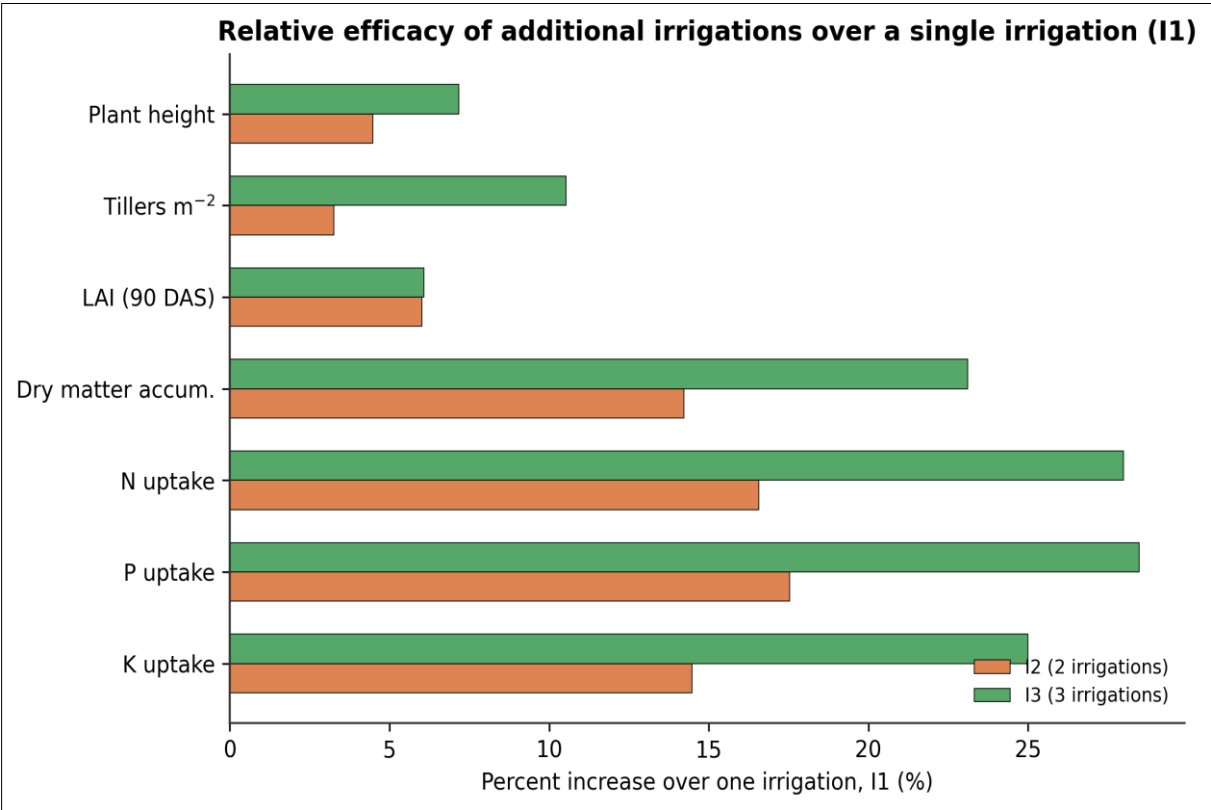


Fig 8: Percentage increase in plant height, tiller number, leaf area index, dry matter accumulation, and nitrogen, phosphorus and potassium uptake under two and three irrigations (I₂, I₃) relative to a single irrigation (I₁ = 0% reference line), at the final recorded growth stage.

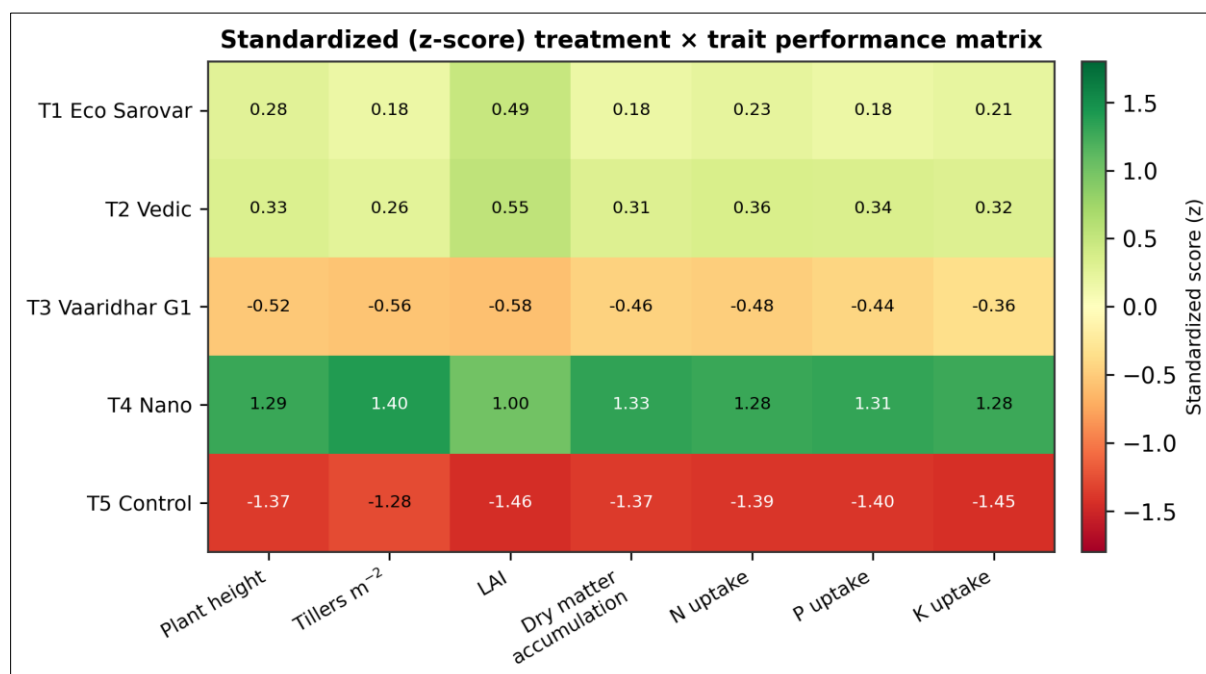


Fig 11: Standardized (z-score) heat map of hydrogel treatment × trait performance, summarizing the relative standing of each hydrogel treatment across all seven final-stage traits. Positive (green) values indicate above-average performance and negative (red) values indicate below-average performance relative to the five-treatment mean.

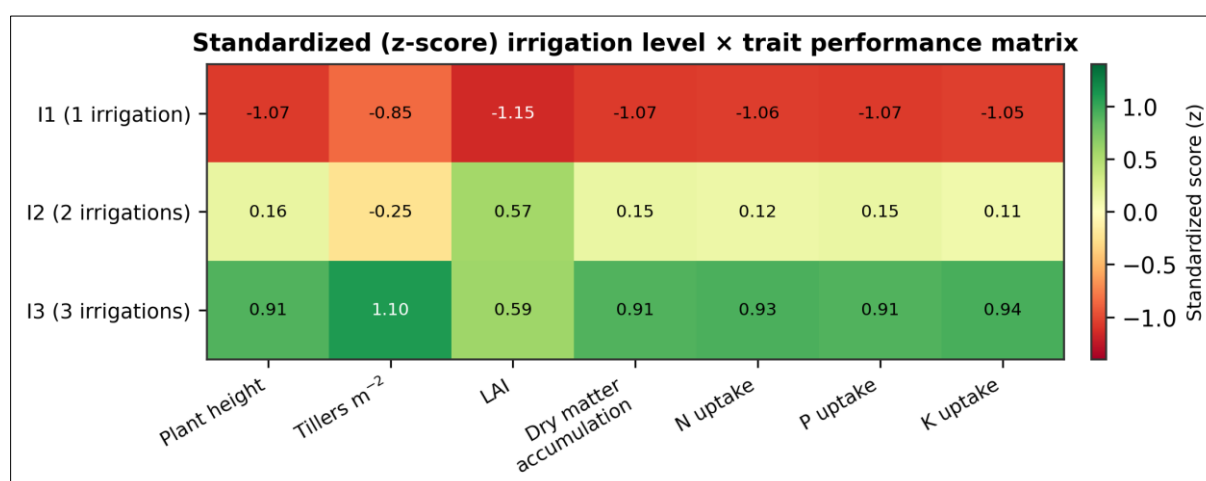


Fig 12: Standardized (z-score) heat map of irrigation level × trait performance, summarizing the relative standing of each irrigation schedule across all seven final-stage traits, relative to the three-level mean.

4. Discussion

Growth parameters

Plant height and Number of tillers m⁻² at 90 DAS and at harvest was significantly improved by three irrigations at CRI, late jointing and the milking stage likely reflect better utilization of applied water across three critical growth stages, consistent with Buttar *et al.* (2018) [4], Kumar *et al.* (2019) [12], Tripathi *et al.* (2023) [21], and Gupta *et al.* The highest LAI at 60 and 90 DAS recorded under three irrigations, statistically at par with two irrigations at 90 DAS and significantly superior to one irrigation, consistent with Singh *et al.* (2017) [19], Gupta *et al.* (2025) and Tripathi *et al.* (2023) [21]. Dry matter accumulation increased with three irrigations and statistically at par with two irrigations most plausibly reflecting sufficient water supply across three critical growth stages under I₃, in line with Kumar *et al.* (2019) [12], Tripathi *et al.* (2023) [21] and Gupta *et al.* (2025). Two and three irrigations produced statistically comparable CGR at 60–90 DAS, while three irrigations were superior during 90 DAS–harvest, consistent with Singh *et al.* (2017) [19], Kumar *et al.* (2019) [12] and

Gupta *et al.*

Nano hydrogel (20 kg ha⁻¹) recorded significantly greater plant height at 90 DAS and at harvest than the control, plausibly reflecting greater moisture availability within the root zone of hydrogel-treated plots, consistent with Roy *et al.* (2019) [17], Tripathi *et al.* (2023) [21] and Gupta *et al.* (2025). The number of tillers m⁻² at 60, 90 DAS and at harvest was higher with nano hydrogel, supported by the findings of Dar and Ram (2017) [5], Gupta *et al.* (2025) and Tripathi *et al.* (2023) [21]. Significantly higher LAI at 90 DAS was recorded with nano hydrogel than the control, in agreement with El-Karamany *et al.* (2015) [6], Singh *et al.* (2017) [19], Tripathi *et al.* (2023) [21] and Gupta *et al.* Total dry matter accumulation was significantly superior with Nano hydrogel, plausibly reflecting more available root-zone moisture and more efficient utilization of applied water for photosynthesis and nutrient uptake, consistent with Kumar *et al.* (2019) [12] and Tripathi *et al.* (2023) [21]. Nano hydrogel recorded significantly higher CGR at 30–60, 60–90 and 90 DAS–harvest, in agreement with Singh *et al.* (2017) [19] and Kumar *et al.* (2019) [12].

Nutrient uptake

Nutrient uptake (N, P and K) by the crop was significantly increased with three irrigations, which was statistically comparable with two irrigations, most likely because additional irrigation events promote greater mass-flow and diffusion of nutrients to the root surface. Similar results were reported by Tyagi *et al.* (2015) ^[22], Singh *et al.* (2017) ^[19] and Kumar *et al.* (2024) ^[13].

Nano hydrogel recorded significantly higher N, P, and K uptake by plant than all other treatments and the control, plausibly reflecting prolonged moisture availability and reduced leaching losses of water and nutrients, consistent with Singh *et al.* (2017) ^[19], Bisen *et al.* (2018) ^[3] and Abd-Eladl (2018) ^[1]. This pattern is also consistent with the broader agronomic literature on hydrogel-mediated controlled nutrient release, in which sustained soil moisture and reduced nutrient leaching are repeatedly identified as the principal mechanisms underlying improved crop nutrient status under hydrogel amendment (Wang *et al.*, 2026) ^[23].

5. Conclusion

Under the sandy-loam, sub-tropical field conditions of the middle Gangetic plain, both irrigation scheduling and hydrogel amendment significantly influenced the plant growth, dry matter accumulation, crop growth rate and nutrient uptake of wheat cv. HD-2967, with three irrigations at CRI, late jointing and milking stage generally statistically at par with two irrigations for most traits at later growth stages. Among the hydrogel formulations evaluated, Nano hydrogel (20 kg ha⁻¹) was consistently and significantly superior to Eco Sarovar, Vedic and Vaaridhar G1 hydrogels as well as to the untreated control across nearly every trait measured, a pattern corroborated by complementary multi-trait visualizations (percentage-increase and standardized heat-map analyses). The absence of a significant irrigation × hydrogel interaction for any trait indicates that the benefit of hydrogel amendment, and of Nano hydrogel in particular, was additive across irrigation regimes. These findings support the integration of nanocomposite hydrogel amendment into wheat production packages in water-limited environments as a practical means of improving crop growth and nutrient-use efficiency, while underscoring the need for further multi-location and multi-season trials, together with a formal economic (cost:benefit) evaluation, before broad-scale recommendation.

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