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Effect of hydrogel and nutrient management on wheat (*Triticum aestivum* L.) productivity under limited irrigation conditions

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Abstract
The study titled "Effect of hydrogel and nutrient management on wheat (*Triticum aestivum* L.) productivity under limited irrigation conditions" The study took place at the Agricultural Research Farm of R.B.S. College in Bichpuri, Agra (U.P) during the *Rabi* seasons of 2021-22 and 2022-23. The research employed a split plot design, the study includes four distinct irrigation levels as the primary plot treatments: I_0 (no irrigation), I_1 (a single irrigation at the CRI stage), I_2 (irrigation twice at the CRI and boot leaf stages), and I_3 (irrigation three times at the CRI, booting leaf, and milking stages). Additionally, six hydrogel and nutrient management levels were used as sub plot treatments: HNM_1 (75% NPK without hydrogel), HNM_2 (75% NPK with hydrogel @ 2.5 kg/ha), HNM_3 (75% NPK with hydrogel @ 5.0 kg/ha), HNM_4 (100% NPK without hydrogel), HNM_5 (100% NPK with hydrogel @ 2.5 kg/ha), and HNM_6 (100% NPK with hydrogel @ 5.0 kg/ha). Each of the 24 treatment combinations was replicated three times. The results revealed that the irrigation levels, (I_3) three irrigations (CRI, booting, and milking stages) produced the maximum grain yield (41.96 q ha^{-1}), biomass (102.24 q ha^{-1}), and straw yield (60.28 q ha^{-1}). Similarly, among nutrient management practices, the application of HNM_6 (100% NPK with hydrogel @ 5.0 kg/ha) recorded the maximum grain yield (43.16 q ha^{-1}) and biomass yield (105.86 q ha^{-1}), indicate the synergistic effect of hydrogel in enhancing soil moisture retention, nutrient uptake, and tiller survival in moisture stress condition.

Keywords: Wheat, *Triticum aestivum* L., hydrogel, nutrient management, irrigation scheduling

Introduction

Wheat is staple food of approximately 23 per cent population of the world. Twenty per cent energy is achieved through wheat at global level. Among food grains wheat is the richest source of protein and it stands at second place after pulses. In general wheat contains carbohydrate (70%), protein (12%), lipid (2%), vitamins & minerals (2% each) and crude (Archna, *et al.*, 2023) [2]. It is an important winter cereal contributing about 35 per cent of the total food grain production in India. Wheat straw is an important source of fodder for a large animal population in India. (Kumar *et al.*, 2019) [4]. In India, wheat is the second most important cereal crop after rice covering an area of 34.15 million hectares. Total annual production of wheat in India is 113.29 million tonnes with the productivity of 3.61 tonnes per hectare during 2023-24. India witnessed an all-time high wheat production during the year 2023-24. India is the second largest wheat producer (approximately 12.60 per cent world's wheat production) and consumer after China. (Kumar *et al.*, 2025) [5].

The limited availability of water resources in arid and semi-arid regions poses a significant challenge to sustainable agriculture, with drought stress projected to cause up to a 30% reduction in global crop production by 2025. (Singh *et al.*, 2024) [11]. The sensitive growth stages of wheat to water stress are from stem elongation to booting, followed by anthesis, and grain-filling. Crop yield linearly increased with an increase in evapo-transpiration. Water and fertilizer plays a vital role in crop production management. An application of only 1st irrigation increases the yield of wheat by more than 40%, whereas 2 to 3 irrigation with proper water and fertilizer management practices increase wheat yield by 50-100%. Water should be utilized for optimum and economic yield. In general six irrigation at a different stages like CRI, tillering, jointing, booting, milking and grain formation in the wheat crop one given for better yield while wheat receiving four irrigations at crown root initiation, maximum tillering stage, boot stage and milky also stage maintained taller plants, more tillers per unit area, dry matter accumulation, leaf area index, net assimilation ratio, crop growth rate and relative growth rate over two and three irrigations at crown root initiation and boot stage and crown root initiation, boot stage (Shivani *et al*., 2003) [7].

Hydrogel is basically a water absorbing polymer, which are classified as crosslinked, absorb aqueous solutions through hydrogen bonding with water molecules. Agricultural hydrogels are referred to as water retention granules because they swell to many times their original size when they come in contact with water. It has been widely proposed over the last 40 years for agricultural use with the aim to ameliorate water availability for plants, by increasing water holding properties of growing media (soils or soilless substrates). Most of the area of India is located in arid and semiarid regions, more efficient use of water is essential in the field of agriculture. The application of hydrogel in arid and semi arid regions improve soil properties, increases the water holding capacity of the soil, enhance of the soil water retention, improving irrigation efficiency, increasing the growth of various crops, and enhancement water productivity of the crop. It also provides a conductive atmosphere for the better growth of roots in well–drained soils and ultimately increases yield (Waleed Abobatta 2018) [1].

Materials and Methods

The field experiment was carried out during *Rabi* season of 2021-22 and 2022-23 at Agricultural Research Farm, Department of Agronomy, R.B.S. College, Bichpuri, Agra (U.P.). The research farm is situated at about 11 km to the west of Agra on Agra-Bharatpur Road at latitude of 27º 02' N and longitude of 77º 09' E with an elevation of 163.4 m above the mean sea level. This region falls under south-western semi-arid zone of Uttar Pradesh. The wheat variety known as 'HD 2967' was introduced by ICAR-IARI, New Delhi, for the North-Western Plains Zone in 2011. During both seasons of experimentation, it was sown at a seed rate of 100 kg/ha. The seeds were planted in rows spaced 20 cm apart and at a depth of 4-5 cm in furrows created by Kudali. The variables involved in this study were four distinct irrigation levels as the primary plot treatments: I_0 (no irrigation), I_1 (a single irrigation at the CRI stage), I_2 (irrigation twice at the CRI and boot leaf stages), and I_3 (irrigation three times at the CRI, booting leaf, and milking stages) and six hydrogel and nutrient management levels were used as sub plot treatments *viz*. HNM_1 (75% NPK without hydrogel), HNM_2 (75% NPK with hydrogel @ 2.5 kg/ha), HNM_3 (75% NPK with hydrogel @ 5.0 kg/ha), HNM_4 (100% NPK without hydrogel), HNM_5 (100% NPK with hydrogel @ 2.5 kg/ha), and HNM_6 (100% NPK with hydrogel @ 5.0 kg/ha) thus, in all 24 treatment combinations were compared in a “split plot design” with three replications. Crop response to the treatments was measured in term of various parameters, *viz*., Ear length (cm), Number of spikes (m^{-2}), Length of spike (cm), Number of grains $spike^{-1}$, Test weight (g) Biological yield (q/ha), Grain yield (q/ha), Straw yield (q/ha) and Harvest index (%). Nitrogen, phosphorus, and potassium fertilizers were administered as urea, DAP, and muriate of potash at the rates of 150, 60, and 40 kg/ha, respectively. The entire amount of phosphorus and potassium, along with half of the nitrogen, was applied during sowing, while the remaining nitrogen was added after the first irrigation.

Results and Discussion

Yield attributes: Effect of irrigation levels on yield attributes

The data presented in Table 1 showed that ear length of wheat was significantly influenced by different irrigation levels during both the years as well as on pooled basis. During year 2021-22, the maximum ear length (8.80 cm) was recorded with I_3 (four irrigations), which was statistically superior to all other irrigation levels, followed by I_2 (three irrigations) with 8.37 cm. The treatment I_1 (two irrigations) produced a moderate ear length of 7.74 cm, while the lowest ear length (7.07 cm) was observed under I_0 (no irrigation). A similar result was observed in during year 2022-23, where the maximum ear length of 8.86 cm was obtained with (four irrigations), followed by 8.44 cm with I_2, 7.91 cm with I_1 (two irrigations), and the minimum ear length of 7.17 cm with I_0 (no irrigation). On pooled analysis of two years, the maximum ear length (8.83 cm) was recorded under I_3 (four irrigations), which was statistically at par with I_2 (three irrigations) 8.41 cm, while significantly higher than I_1 (two irrigations) 7.83 cm and I_0- no irrigation (7.12 cm). The number of spikelets per spike was significantly affected by different irrigation levels during both the years and in pooled results. In year 2021-22, the maximum spikelets per spike (25.60) were recorded under I_3 (four irrigations), which remained statistically superior over the rest of the treatments, followed by I_2 (three irrigations) with 25.35. The treatment I_1 (two irrigations) produced a moderate of 24.29 spikelets per spike, whereas the minimum spikelets per spike (22.19) was observed under I_0 (no irrigation). A similar result was noted in year 2022–23, where the highest number of spikelets per spike (25.67) was obtained with I_3, followed by I_2 (25.47) and I_1 (24.46), while the lowest number of spikelets per spike (22.43) was recorded under I_0 (no irrigation). On a pooled basis of two years, the maximum spikelets per spike (25.63) were found with I_3 (four irrigations), which was at par with I_2 (three irrigations) 25.41 but significantly superior over I_1 (two irrigations) 24.38 and I_0 (no irrigation) 22.31.

The number of grains per spike in wheat was significantly influenced by different irrigation levels during both the years 2021-22 and 2022-23 as well as on pooled basis. In year of 2021–22, the highest number of grains per spike (37.30) was recorded with I_3 (four irrigations), which was statistically superior to all other treatments. This was followed by I_2 (three irrigations) with 36.79 grains per spike, while I_1 (two irrigations) produced 35.19 grains per spike. The lowest number of grains per spike (32.05) was observed under I_0 (no irrigation). A similar result were observed during year 2022-23, where the maximum number of grains per spike (37.44) was obtained with I_3 (four irrigations), followed by I_2 (three irrigations) 36.92 and I_1 (two irrigations) 35.32, whereas the minimum number of grains per spike (32.34) was again recorded under I_0 (no irrigation). On pooled result over two years, the maximum number of grains per spike (37.37) was obtained with I_3 (four irrigations), which was at par with I_2 (three irrigations) 36.85 but significantly superior to I_1 (two irrigations) 35.26 and I_0- no irrigation (32.20). The number of ears per m² area of wheat was significantly affected by different irrigation levels during both years and in pooled mean. In year of 2021-22, the maximum number of ears per m^2 (109.39) was observed with I_3 (four irrigations), which remained statistically superior over all other treatments. This was followed by I_2 (three irrigations) with 107.49 and I_1 (two irrigations) with 101.55 number of ears per m², whereas the minimum value (94.62) was obtained under I_0 (no irrigation). In year of 2022-23, the highest number of ears per m² (109.84) was recorded under I_3 (four irrigations), followed by 107.98 under I_2 (three irrigations) and 102.08 under I_1 (two irrigations), while the lowest umber of ears per m² (95.39) was noted with I_0 (no irrigation). On pooled analysis, the maximum number of ears per m² (109.61) was observed with I_3 (four irrigations), which was statistically at par with I_2 (three irrigations) 107.74, but significantly higher than I_1 (two irrigations), 101.81 and I_0 (no irrigation) 95.01.

Table 1: Effect of Irrigation levels and hydrogel with nutrient management on Yield attributes of wheat

Treatments	Ear length (cm)			Spikelet's per spike			Number of grains per spike			Number of ears per m² area			Grain weight (g) per spike			1000-grain weight (g)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
Irrigation levels																		
I_0	7.07	7.17	7.12	22.19	22.43	22.31	32.05	32.34	32.20	94.62	95.39	95.01	1.43	1.46	1.44	37.98	37.83	37.91
I_1	7.74	7.91	7.83	24.29	24.46	24.38	35.19	35.32	35.26	101.55	102.08	101.81	1.56	1.59	1.57	39.65	39.71	39.68
I_2	8.37	8.44	8.41	25.35	25.47	25.41	36.79	36.92	36.85	107.49	107.98	107.74	1.63	1.66	1.64	41.39	41.62	41.50
I_3	8.80	8.86	8.83	25.60	25.67	25.63	37.30	37.44	37.37	109.39	109.84	109.61	1.67	1.70	1.69	41.91	42.19	42.05
S.Em+	0.151	0.158	0.101	0.483	0.478	0.315	0.787	0.736	0.499	2.440	2.348	1.567	0.027	0.032	0.019	0.963	0.825	0.587
CD (P = 0.05)	0.522	0.547	0.312	1.672	1.655	0.970	2.723	2.548	1.537	8.443	8.123	4.830	0.094	0.110	0.060	3.334	2.856	1.809
Hydrogel+ Nutrient management																		
HNM_1	7.21	7.32	7.27	22.88	22.96	22.92	32.82	32.99	32.91	96.12	96.86	96.49	1.44	1.46	1.45	38.76	38.96	38.86
HNM_2	7.56	7.66	7.61	23.18	23.36	23.27	34.12	34.35	34.24	99.45	100.45	99.95	1.52	1.55	1.54	39.23	39.33	39.28
HNM_3	7.89	7.96	7.93	23.89	24.00	23.95	34.92	35.12	35.02	102.14	102.89	102.52	1.55	1.60	1.58	39.48	39.52	39.50
HNM_4	8.10	8.19	8.15	24.65	24.88	24.77	35.65	35.81	35.73	103.65	104.00	103.83	1.61	1.64	1.63	40.10	40.19	40.15
HNM_5	8.45	8.59	8.52	25.45	25.68	25.57	36.55	36.62	36.59	107.74	108.14	107.94	1.63	1.68	1.66	41.13	41.28	41.21
HNM_6	8.76	8.85	8.81	26.10	26.16	26.13	37.95	38.15	38.05	110.48	110.59	110.54	1.67	1.69	1.68	42.68	42.75	42.72
S.Em+	0.131	0.134	0.107	0.520	0.526	0.403	0.831	0.849	0.647	2.514	2.557	1.964	0.030	0.038	0.026	0.747	0.801	0.625
CD (P = 0.05)	0.374	0.383	0.301	1.485	1.503	1.135	2.375	2.426	1.820	7.186	7.307	5.529	0.087	0.110	0.074	2.135	2.289	1.759

The grain weight per spike was significantly influenced by different irrigation levels during both years and in pooled analysis. In the year 2021-22, the maximum grain weight per spike (1.67 g) was observed with I_3 (four irrigations), which was statistically superior to the other treatments. This was followed by I_2 (three irrigations) with 1.63 g, while I_1 (two irrigations) produced grain weight per spike of 1.56 g. The minimum grain weight per spike (1.43 g) was observed under I_0 (no irrigation). A similar result was evident in the year 2022–23, where the highest grain weight per spike (1.70 g) was obtained under I_3 (four irrigations), followed by 1.66 g under I_2 (three irrigations) and 1.59 g under I_1 (two irrigations), whereas the lowest grain weight per spike of 1.46 g was noted with I_0 (no irrigation).On pooled result across both years, the maximum grain weight per spike (1.69 g) was registered with I_3 (four irrigations), which was statistically at par (1.64 g) with I_2 (three irrigations) but significantly superior to I_1 (two irrigations) (1.57 g) and I_0 (no irrigation) (1.44 g). These findings are in close agreement with the reports of Lokendra *et al.* (2024) [6], Kumar *et al*. (2025) [5], and Singh *et al*., (2025) [8], who observed that assured irrigation during reproductive stages improved grain development and weight per spike in wheat. The 1000-grain weight of wheat was significantly influenced by different irrigation levels during both the years as well as in pooled analysis. In the year 2021-22, the highest 1000-grain weight (41.91 g) was obtained with I_3 (four irrigations), which was statistically superior over all other treatments. This was followed by I_2 (three irrigations) with 41.39 g, while I_1 (two irrigations) recorded 39.65 g. The lowest 1000-grain weight (37.98 g) was observed under I_0 (no irrigation). A similar result was recorded in the year 2022-23, where the maximum 1000-grain weight (42.19 g) was noted with I_3 (four irrigations), followed by 41.62 g under I_2 (three irrigations) and 39.71 g under I_1 (two irrigations), whereas the minimum 1000-grain weight (37.83 g) was obtained under I_0 (no irrigation). On pooled result across two years, the highest 1000-grain weight (42.05 g) was registered with I_3 (four irrigations), which was statistically at par (41.50 g) with I_2 (three irrigations), but significantly superior to (39.68 g) I_1 (two irrigations) and (37.91 g) I_0 (no irrigation). These results are in agreement with the findings of Singh *et al.* (2023) [9] and Singh *et al.* (2024) [12], who reported that timely irrigation during grain filling enhanced kernel weight and improved test weight in wheat.

Hydrogel + Nutrient management

Application of hydrogel with nutrient management significantly enhanced ear length of wheat (Table 1). The highest ear length was recorded under HNM_6, measuring 8.76 cm in 2021-22 and 8.85 cm in 2022-23, with a pooled mean of 8.81 cm. This was followed by HNM_5 (8.45 and 8.59 cm; pooled 8.52 cm) and HNM_4 (8.10 and 8.19 cm; pooled 8.15 cm). Intermediate treatments HNM_3 and HNM_2 recorded pooled data of 7.93 cm and 7.61 cm, respectively. The minimum ear length was observed in HNM_1, with 7.21 cm in 2021–22 and 7.32 cm in 2022–23, giving a pooled data of 7.27 cm. Ear length increased by about 21% under HNM_6 compared with HNM_1, indicating that hydrogel application coupled with proper nutrient management improved soil moisture retention and nutrient uptake, thereby supporting ear elongation. Spikelets per spike also showed a clear response to hydrogel and nutrient management. Maximum spikelets per spike was recorded in HNM_6 (26.10 and 26.16; pooled 26.13), followed by HNM_5 (25.45 and 25.68; pooled 25.57) and HNM_4 (24.65 and 24.88; pooled 24.77). HNM_3 produced a pooled mean of 23.95 spikelets per spike, while HNM_2 and HNM_1 recorded lower of 23.27 and 22.92, respectively. The minimum spikelets per spike was observed in HNM_1 (22.88 in 2021-22 and 22.96 in 2022-23). The pooled results showed an increase of nearly 14% in spikelets per spike from HNM_1 to HNM_6, reflecting the role of hydrogel in maintaining favorable conditions for spike differentiation.

The highest number of grains per spike was produced under treatment HNM_6, with 37.95 grains in year 2021-22 and 38.15 in the year 2022-23, yielding a pooled result of 38.05. This was closely followed by treatments HNM_5 (36.59 pooled) and HNM_4 (35.73 pooled). Intermediate treatments HNM_3 and HNM_2 recorded pooled data of 35.02 and 34.24 grains per spike, respectively. The minimum grains per spike was noted in HNM_1, with 32.82 in the year 2021-22 and 32.99 in the year 2022-23 (pooled 32.91). Thus, HNM_6 improved grain number per spike by about 16% compared with HNM_1, suggesting that enhanced soil water retention from hydrogel facilitated better pollination and grain filling. The maximum number of ears per unit area was obtained under application of HNM_6, with 110.48 and 110.59 during both the years 2021-22 and 2022-23 of ears per unit area, giving a pooled result of 110.54 ears per unit area. This was followed by application of HNM_5 (107.94 pooled), HNM_4 (103.83), and HNM_3 (102.52). Moderate ears per unit area were noted in application of HNM_2 (99.95 pooled), while the minimum was recorded in application of HNM_1 (96.49 pooled). The pooled results indicated an increase of about 15% in ear density application of HNM_1 to HNM_6, highlighting that hydrogel improved tiller survival and ear emergence under better water and nutrient availability.

Grain weight per spike was highest in application of HNM_6 with recorded in (1.67 g) and (1.69 g) during both the year 2021-22 and 2022-23, yielding a pooled result of (1.68 g). This was followed by applications of HNM_5 (1.66 g pooled), HNM_4 (1.63 g pooled), and HNM_3 (1.58 g pooled). Application of HNM_2 recorded a pooled grain weight per spike of 1.54 g, while the lowest grain weight per spike was observed in application of HNM_1 (1.45 g). The improvement from application of HNM_1 to HNM_6 was about 16%, confirming that hydrogel improved assimilate translocation and retention of grain weight per spike. A similar result were observed for 1000-grain weight, with the maximum 1000-grain weight under application of HNM_6 (42.68 g in 2021-22 and 42.75 g in 2022-23; pooled 42.72 g). Application of HNM_5 recorded 41.21 g, while application of HNM_4 and HNM_3 produced 40.15 g and 39.50 g, respectively. Moderate 1000-grain weight was observed in application of HNM_2 (39.28 g), while the minimum 1000-grain weight was recorded in applications of HNM_1 (38.86 g). The pooled 1000-grain weight indicated an improvement of nearly 10% between applications of HNM_6 and HNM_1, suggesting that hydrogel application not only increased grain number but also enhanced grain size. Similar findings have also been reported by Singhal *et al.*, (2023) [13], Singh *et al.*, (2024) [11], Lokendra *et el.*, (2024) [6] and Verma *et al.*, (2025) [14],

Yield

Irrigation levels

The data presented in Table 2 revealed that biomass yield (q ha^{-1}) of wheat was significantly influenced by irrigation levels during both years as well as in pooled analysis. In the year 2021-22, the maximum biomass yield (101.28 q ha^{-1}) was obtained under I_3 (four irrigations), which was significantly higher than the other irrigation levels. This was followed by I_2 (three irrigations) with 100.03 q ha^{-1}, while I_1 (two irrigations) recorded 92.15 q ha^{-1}. The lowest biomass yield (83.29 q ha^{-1}) was observed under I_0 (no irrigation). In 2022–23, a similar result was noted, where the highest biomass yield (103.21 q ha^{-1}) was recorded with I_3, followed by 100.05 q ha^{-1} under I_2, 92.32 q ha^{-1} under I_1, and the lowest 83.76 q ha^{-1} with I_0. On pooled basis of two years, the maximum biomass yield (102.24 q ha^{-1}) was recorded under I_3, which was statistically superior to I_2 (100.04 q ha^{-1}) but both remained significantly higher than I_1 (92.23 q ha^{-1}) and I_0 (83.52 q ha^{-1}). The consistent superiority of I_3 over the other irrigation regimes clearly demonstrated the beneficial effect of assured and timely irrigation at critical growth stages, which improved tiller survival, leaf area development, photosynthetic efficiency, and dry matter accumulation. Similar findings have also been reported by Kumar *et al.*, (2019) [4], Singh *et al.*, (2024) [12], Lokendra *et el.*, (2024) [6] and Singh *et al.* (2024) [11], with maximum biomass recorded under optimum irrigation compared to limited or no irrigation conditions.

The data in Table 2 revealed that (grain yield q ha^{-1}) of wheat was significantly affected by irrigation levels during both the years as well as in pooled results. In the year 2021–22, the maximum grain yield (41.43 q ha^{-1}) was recorded under I_3 (four irrigations), which was significantly superior to the other irrigation levels. This was followed by I_2 (three irrigations) with 40.36 q ha^1 and I_1 (two irrigations) with 36.53 q ha^{-1}, whereas the minimum yield (32.33 q ha^{-1}) was observed under I_0 (no irrigation). A similar result was recorded in 2022–23, where the highest grain yield (42.49 q ha^1) was obtained with I_3, followed by I_2 (40.47 q ha^1), I_1 (36.70 q ha^1), and the lowest (32.44 q ha^{-1}) with I_0. On pooled result across two years, the maximum grain yield (41.96 q ha^1) was recorded under I_3, which was at par with I_2 (40.42 q ha^{-1}) but both were significantly superior to I_1 (36.62 q ha^{-1}) and I_0 (32.39 q ha^1). The consistent superiority of I_3 and I_2 highlights the role of adequate irrigation in ensuring favorable moisture conditions during critical growth stages such as tillering, flowering, and grain filling, which enhanced spike development, grain setting, and ultimately grain yield. These results are in close agreement with the findings of Kumar *et al.*, (2025) [5], who reported that wheat grain yield increased significantly with higher irrigation frequency. Likewise, Singh *et al.* (2024) [11] confirmed that optimum irrigation scheduling enhances physiological processes and assimilate partitioning towards grains, resulting in higher grain yield compared to moisture-stressed conditions.

The straw yield of wheat was significantly influenced by different irrigation levels during both years as well as in pooled analysis. In the year 2021–22, the maximum straw yield (59.85 q ha^{-1}) was obtained under I_3 (four irrigations), which remained statistically superior over all other treatments. This was followed by I_2 (three irrigations) with 59.66 q ha^{-1} and I_1 (two irrigations) with 55.61 q ha^{-1}, while the lowest straw yield (50.96 q ha^{-1}) was recorded under I_0 (no irrigation). In the year 2022–23, a similar result was observed where the highest straw yield (60.72 q ha^{-1}) was noted under I_3, followed by I_2 (59.58 q ha^{-1}), I_1 (55.61 q ha^{-1}), and the lowest (51.32 q ha^{-1}) with I_0. On pooled analysis of two years, the maximum straw yield (60.28 q ha^{-1}) was recorded under I_3, which was statistically at par with I_2 (59.62 q ha^{-1}) but significantly superior to I_1 (55.61 q ha^{-1}) and I_0 (51.14 q ha^{-1}). The increase in straw yield under I_3 and I_2 could be attributed to better vegetative growth, enhanced tiller survival, and greater biomass accumulation due to assured soil moisture throughout the crop growth cycle. Similar findings were also reported by Kumar *et al.* (2019) [4], who noted that irrigation at critical stages of wheat enhanced tillering and stem elongation, leading to higher straw yields.

The data in Table 2 indicated that harvest index (%) of wheat was not significantly affected by different irrigation levels during either year or in pooled results, as the differences among treatments were statistically non-significant. However, a slight increasing result was evident with higher irrigation levels. In the year 2021–22, the maximum harvest index (40.89%) was observed under I_3 (four irrigations), followed closely by I_2 (40.33%) and I_1 (39.62%), while the minimum (38.80%) was recorded under I_0 (no irrigation). In 2022–23, the highest value (41.14%) was again noted with I_3, followed by I_2 (40.42%), I_1 (39.73%), and the lowest (38.71%) with I_0. On pooled result, the maximum harvest index (41.01%) was registered with I_3, which was statistically at par with I_2 (40.38%), while slightly higher than I_1 (39.68%) and I_0 (38.75%). Although the effect was non-significant, the result suggests that adequate irrigation favored a balanced partitioning of assimilates towards both grain and straw, leading to a relatively higher proportion of grain in total biomass. These findings corroborate the results of Singh *et al.* (2024) [12], who also observed that harvest index in wheat is relatively stable across irrigation levels, though marginal improvements occur with assured irrigation.

Table 2: Effect of Irrigation levels and hydrogel with nutrient management on biomass, grain and straw yield and harvest index of wheat

Treatments	Biomass (q ha^{-1})			Grain yield (q ha^{-1})			Straw yield (q ha^{-1})			Harvest index (%)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
Irrigation levels												
I_0	83.29	83.76	83.52	32.33	32.44	32.39	50.96	51.32	51.14	38.80	38.71	38.75
I_1	92.15	92.32	92.23	36.53	36.70	36.62	55.61	55.61	55.61	39.62	39.73	39.68
I_2	100.03	100.05	100.04	40.36	40.47	40.42	59.66	59.58	59.62	40.33	40.42	40.38
I_3	101.28	103.21	102.24	41.43	42.49	41.96	59.85	60.72	60.28	40.89	41.14	41.01
S.Em+	1.81	1.88	1.21	0.78	0.86	0.54	1.25	1.29	0.83	0.83	0.86	0.55
CD (P = 0.05)	6.25	6.50	3.72	2.70	2.96	1.65	4.33	4.45	2.56	NS	NS	NS
Hydrogel +Nutrient management												
HNM_1	83.59	84.41	84.00	33.12	33.62	33.37	50.47	50.79	50.63	39.56	39.76	39.66
HNM_2	91.68	92.28	91.98	36.56	36.96	36.76	55.12	55.32	55.22	39.82	39.98	39.90
HNM_3	93.06	93.40	93.23	36.89	37.01	36.95	56.17	56.39	56.28	39.58	39.56	39.57
HNM_4	92.80	93.56	93.18	36.98	37.10	37.04	55.82	56.46	56.14	39.79	39.58	39.69
HNM_5	98.41	99.20	98.81	39.49	40.10	39.80	58.92	59.10	59.01	40.07	40.35	40.21
HNM_6	105.57	106.14	105.86	42.95	43.36	43.16	62.62	62.78	62.70	40.62	40.78	40.70
S.Em+	1.79	1.43	1.30	0.71	0.64	0.55	0.95	0.98	0.80	0.83	0.82	0.65
CD (P = 0.05)	5.10	4.08	3.66	2.04	1.82	1.55	2.71	2.81	2.26	NS	NS	NS

Hydrogel and nutrient management (HNM)

The data in Table 2 revealed that biomass yield of wheat was significantly affected by different hydrogel and nutrient management (HNM) treatments during both the years and in pooled results. In the year 2021–22, the maximum biomass yield (105.57 q ha^{-1}) was obtained under HNM_6, which was significantly superior to all other treatments. This was followed by HNM_5 (98.41 q ha^{-1}) and HNM_3 (93.06 q ha^{-1}), whereas the lowest biomass yield (83.59 q ha^{-1}) was recorded by HNM_1. A similar result was observed in the year 2022–23, where HNM_6 registered the highest biomass (106.14 q ha^{-1}), followed by HNM_5 (99.20 q ha^{-1}) and HNM_4 (93.56 q ha^{-1}), while the lowest biomass (84.41 q ha^{-1}) was found with HNM_1. On pooled analysis, the maximum biomass yield (105.86 q ha^{-1}) was recorded under HNM_6, which was significantly superior to HNM_5 (98.81 q ha^{-1}), HNM_4 (93.18 q ha^{-1}) and HNM_3 (93.23 q ha^{-1}), while the minimum pooled biomass (84.00 q ha^{-1}) was recorded under HNM_1. The increase in biomass yield under HNM_6 and HNM_1 treatments can be attributed to the synergistic effect of hydrogel and nutrients, which maintained favorable soil–water relations during critical crop growth stages. Hydrogel acts as a water reservoir in the root zone, reducing evaporative losses and improving water-use efficiency, thereby promoting vigorous vegetative growth and tiller survival. Similar observations were made by Verma *et al*. (2025) [14], who noted that integrated nutrient management combined with hydrogel application promoted higher dry matter production.

The data in Table 2 showed that grain yield of wheat was significantly influenced by hydrogel+ nutrient management (HNM) treatments during both years and in pooled results. In the year 2021–22, the maximum grain yield (42.95 q ha^{-1}) was recorded under HNM_6, which was statistically superior to all other treatments. This was followed by HNM_5 (39.49 ha^{-1}) and HNM_4 (36.98 q ha^{-1}), while the lowest grain yield (33.12 q ha^{-1}) was observed under HNM_1. A similar result was observed in the year 2022–23, where the maximum grain yield (43.36 q ha^{-1}) was recorded under HNM_6, followed by HNM_5 (40.10 q ha^{-1}) and HNM_4 (37.10 q ha^{-1}), whereas the minimum grain yield (33.62 q ha^{-1}) was recorded under HNM_1. On pooled analysis, the maximum grain yield (43.16 q ha^{-1}) was obtained under HNM_6, which was significantly superior to HNM_5 (39.80 q ha^{-1}) and HNM_4 (37.04 q ha^{-1}), while the lowest pooled grain yield (33.37 q ha^{-1}) was recorded under HNM_1. The consistent superiority of HNM_6 across both years can be attributed to the improved soil moisture retention capacity of hydrogel in conjunction with balanced nutrient availability, which provided favorable growth conditions during critical stages such as flowering and grain filling. Hydrogel application reduces moisture stress during reproductive stages, improves nutrient uptake efficiency, and ensures sustained photosynthetic activity, thereby enhancing grain productivity. These findings are supported by (Archna, *et al.*, 2023) [2], who observed that hydrogel application in wheat improved soil water status and significantly increased grain yield.

The data in Table 2 revealed that straw yield of wheat was significantly influenced by different hydrogel and nutrient management (HNM) treatments during both the years as well as in pooled analysis. In the year 2021-22, the maximum straw yield (62.62 q ha^{-1}) was recorded with HNM_6, which was statistically superior to all other treatments. This was followed by HNM_5 (58.92 q ha^{-1}) and HNM_4 (55.82 q ha^{-1}), while the lowest straw yield (50.47 q ha^{-1}) was noted under HNM_1. In 2022-23, a similar result was observed, with the highest straw yield (62.78 q ha^{-1}) obtained under HNM_6, followed by HNM_5 (59.10 q ha^{-1}) and HNM_4 (56.46 q ha^{-1}), whereas the minimum straw yield (50.79 q ha^{-1}) was recorded under HNM_1. On pooled analysis of two years, the maximum straw yield (62.70 q ha^{-1}) was obtained under HNM_6, followed by HNM_5 (59.01 q ha^{-1}) and HNM_4(56.14 q ha^{-1}), while the lowest pooled straw yield (50.63 q ha^{-1}) was recorded with HNM_1. The consistent superiority of HNM_6 clearly demonstrates that the combined effect of hydrogel and nutrient management created favorable soil moisture conditions and enhanced nutrient uptake, which promoted better vegetative growth, tiller survival, and ultimately higher straw yield. These findings are in line with Kumar *et al.* (2019) [4], Singh *et al.*, (2022) [10] and Islamuddeen, *et al.*, (2022) [3] who reported that hydrogel application improved soil water retention and enhanced straw yield of wheat.

The data in Table 2 revealed that harvest index (%) of wheat was not significantly affected by hydrogel and nutrient management (HNM) treatments during both the years as well as in pooled analysis, though minor variations were observed. In the year 2021–22, the maximum harvest index (40.62%) was recorded with HNM_6, followed by HNM_5 (40.07%) and HNM_2 (39.82%), while the minimum harvest index (39.56%) was obtained under HNM_3. In year of 2022-23, a similar result were observed, where the highest harvest index (40.78%) was registered under HNM_6, followed by HNM_5 (40.35%) and HNM_2 (39.98%), whereas the lowest (39.56%) was noted with HNM_3. On pooled basis, the maximum harvest index (40.70%) was obtained with HNM_6, which was higher than HNM_5 (40.21%) and HNM_2 (39.90%), while the lowest harvest index (39.57%) was observed under HNM_3. Although the differences were statistically non-significant, the consistent improvement in harvest index under HNM_6 indicates that the combined use of hydrogel and nutrients promoted balanced partitioning of assimilates between grain and straw, thus enhancing the proportion of economic yield. Similarly, Kumar *et al.* (2025) [5] noted that the integrated application of hydrogel and nutrients did not drastically alter harvest index but maintained a favorable balance between grain and straw yields.

Conclusion

The conclusion of this study revealed that wheat productivity under limited irrigation conditions can be substantially improved through appropriate irrigation scheduling and hydrogel-based nutrient management. Among the treatments, three irrigations at CRI, booting, and milking stages (I_3) combined with 100% NPK and hydrogel @ 5.0 kg ha^{-1} (HNM_6) proved most effective, resulting in superior growth, yield attributes, and grain productivity. It can therefore be concluded that integrating optimum irrigation with hydrogel and balanced fertilization offers a practical and sustainable approach to enhance wheat yield and resource-use efficiency in semi-arid regions

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