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RESEARCH ARTICLE

Impact of hydrogel under different fertiliser and irrigation levels on growth, yield and its contributing traits of barley (*Hordeum vulgare* L.)

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Abstract

The application of polymeric hydrogel improved barley seed germination under low-quality irrigation water, indicating enhanced moisture availability during early growth. In dual-purpose barley systems, initial fodder harvesting did not adversely affect subsequent grain yield when crop management remained comparable to grain-only production. A field experiment was conducted during the rabi seasons of 2023–24 and 2024–25 at the research farm, Mandawa, Jhunjhunu district, Rajasthan, to study the effect of irrigation levels and hydrogel application under different fertiliser doses on the growth, yield and yield attributes of barley (cv. RD-2035). The experiment was carried out in a split-plot design (SPD) in 3 replications. The main plot consisted of 3 irrigation levels, while the subplots included 6 hydrogel-nutrient treatments (100, 70 and 50 % nitrogen, phosphorous and potassium (NPK) with and without hydrogel at 2.5 kg ha^{-1}). Hydrogel was applied in seed rows at sowing to enhance soil moisture retention. Growth and yield parameters such as plant height, tiller number, dry matter accumulation, flag leaf area and yield attributes were recorded at different stages of crop growth. The irrigation treatment (I_3) produced the tallest plants, maximum tillers, dry matter accumulation and highest grain, straw and biological yields, followed by irrigations (I_2). The irrigation (I_1) treatment recorded the lowest values for all parameters. Results indicated that irrigation levels significantly affected growth and yield attributes. Similarly, the combined application of hydrogel at 2.5kg ha^{-1} with 100 % NPK (H_2) resulted in significantly higher plant growth, spike length, number of grains per spike, test weight and overall productivity compared to other nutrient combinations. The improvement in grain yield due to hydrogel application was attributed to enhanced water and nutrient availability throughout the growth period. The study concludes that irrigation (I_3) with hydrogel application at 2.5 kg ha^{-1} and 100 % NPK (H_2) fertilisation effectively improves growth, yield attributes and water use efficiency of barley under semi-arid conditions of Rajasthan.

Keywords: barley; growth parameters; hydrogel; irrigation levels; NPK fertiliser; yield attributes

Introduction

Barley (*Hordeum vulgare* L.) is an important cereal crop globally, ranking after maize, wheat and rice in terms of both cultivated area and total production (1). Due to its low input requirements and ability to perform well under marginal conditions, barley is often referred to as a "poor man's crop". It is widely utilised for malting, livestock feed and human consumption. In addition to its agronomic importance, barley grains are rich in β-glucans, a soluble dietary fiber known for its role in lowering blood cholesterol levels and reducing the risk of cardiovascular diseases, thereby enhancing its nutritional and functional value (2).

Among cereal crops, barley exhibits exceptional adaptability and can be grown across a broader range of agro-ecological conditions than most other cereals, including extremes of latitude, longitude and high altitudes. Because of this wide ecological amplitude, it is frequently described as the most cosmopolitan cereal crop. Its tolerance to drought, salinity, alkalinity and low fertility soils further contributes to its suitability for cultivation on marginal and problematic lands, reinforcing its significance in resource-poor farming systems (3). In Rajasthan, barley is an important rabi season crop, occupying approximately 2.74 lakh ha, which accounts for about 8.23 % of the total rabi cereal area of the state and contributes nearly 7.46 % to the total rabi cereal production (4).

Barley grains possess considerable nutritional value. Each 100 g of grain contains approximately 10.6 g of protein, 2.1 g of fat, 64.0 g of carbohydrates, along with essential minerals and vitamins such as calcium (50.0 mg), iron (6.0 mg), vitamin B_1 (31.0 mg), vitamin B_2 (0.1 mg) and folate (50.0 µg), making it a valuable component of human and animal diets (5). Owing to its adaptability and diverse uses, barley is cultivated in almost all parts of the world. Major barley-producing countries include China, Russia, Germany, the USA, Canada, India, Turkey and Australia. In India, barley is primarily grown in Rajasthan, Uttar Pradesh, Madhya Pradesh, Haryana, Punjab, West Bengal and Bihar. The crop is cultivated over an area of about 0.62 million ha, with a production of 1.91 million tonnes and an average productivity of 3030 kg ha^{-1} (6). In Rajasthan, barley covers nearly 0.27 million ha with a productivity of 3324 kg ha^{-1}, which is higher than the national average (6). However, the realised yields remain considerably lower than the attainable yield potential of 45–50 q ha^{-1}, mainly due to water scarcity and nutritional stresses (7).

Although barley productivity can be enhanced through fertiliser application, excessive and imbalanced use of chemical fertilisers has emerged as a major constraint by adversely affecting soil health (8). Soil health deterioration, characterised by declining organic matter and nutrient imbalance, poses a serious threat to sustainable agriculture in India, particularly in less responsive soils with low organic carbon content (9). The indiscriminate use of inorganic fertilisers has highlighted the need for integrating organic sources such as farmyard manure, vermicompost, poultry manure and bio-fertilisers into crop production systems. However, organic manures alone are insufficient to meet the nutrient demand of high-yielding crops under present population pressure. Under these circumstances, the integrated use of organic manures with inorganic fertilisers has shown promising results in sustaining crop productivity, improving soil health and enhancing nutrient use efficiency (10).

In recent years, hydrogel amendments have gained attention as a potential tool for improving soil moisture retention and crop establishment, particularly under arid and semi-arid environments (11). Hydrogels exhibit rapid water absorption, with maximum swelling observed in distilled water, while increased salinity reduces their absorption capacity. The application of hydrogels has been reported to delay seedling wilting by 4–5 days compared to untreated soils, indicating improved moisture availability under stress conditions (12). Although hydrogel amendments enhance soil water availability and plant establishment, variations in crop response across soil types suggest the need for further investigation. Consequently, the use of polymeric hydrogels has expanded in agricultural production systems, particularly for improving the water-holding capacity of light-textured soils (13).

In the present study, the effect of polymeric hydrogel on the germination of barley seeds under low-quality irrigation water conditions was evaluated. In dual-purpose barley production systems, the crop is initially harvested for fodder and subsequently allowed to regenerate for grain production without compromising grain yield when managed similarly to a grain crop. For dual-purpose barley, the selection of suitable cultivars, optimum sowing time and appropriate stage of fodder harvesting are critical factors in ensuring the production of high-quality fodder along with satisfactory grain yield (14). In the present context, hydrogel application is particularly relevant, as it has been reported to reduce irrigation frequency across a wide range of crops, including cereals, pulses, vegetables and ornamental plants, thereby saving water, labour, time and irrigation costs (15).

Therefore, in view of the above considerations, a field experiment was conducted to evaluate the effects of different fertiliser regimes, irrigation levels and hydrogel application on the productivity of barley.

Materials and Methods

Experimental site

The field experiment was carried out during the rabi seasons of 2023–24 and 2024–25 at the research farm located at Mandawa in Jhunjhunu district, Rajasthan. Geographically, the experimental site is situated at 75°88′99″ E longitude and 26°81′17″ N latitude and falls under Agro-climatic Zone II A, known as the Transitional Plains of Inland Drainage Zone of Rajasthan.

Experimental details

The present investigation was conducted using a split-plot design (SPD) with 3 replications, comprising a total of 27 plots. The barley variety RD-2035 was sown at 22.5 cm row spacing with a seed rate of 100 kg ha^{-1}, using plots of 16 rows with a gross area of 18.0 m^2 and a net area of 15.75 m^2. A total of nine treatments were evaluated to assess the effects of different combinations of experimental factors (Table 1).

Table 1. Treatments details with their symbols

Treatment category	Treatment description	Symbol
Irrigation levels	1 irrigation	I_1
	2 irrigations	I_2
	3 irrigations	I_3
Hydrogel and nutrient levels	100 % NPK without hydrogel	H_1
	100 % NPK with 2.5 kg ha^{-1} hydrogel	H_2
	70 % NPK without hydrogel	H_3
	70 % NPK with 2.5 kg ha^{-1} hydrogel	H_4
	50 % NPK without hydrogel	H_5
	50 % NPK with 2.5 kg ha^{-1} hydrogel	H_6

Soil characteristics

The experimental soil was loamy sand in texture, comprising 84.3 % sand, 9.2 % silt and 6.5 % clay, with a bulk density of 1.52 mg m^{-3} and a porosity of 41.76 %. Chemically, the soil was alkaline (pH 8.20) with low organic carbon (0.21 %), low available nitrogen (132.73 kg ha^{-1}), medium phosphorous (19.92 kg ha^{-1}), high potassium (231.76 kg ha^{-1}) and low electrical conductivity (0.31 dS m^{-1}).

Characteristics of variety

The RD-2035 is a high-yielding dual-purpose barley variety developed from the cross RD-103 × PL-101 and was released and notified in 1994. The variety is medium tall, attaining a plant height of about 85–90 cm and is characterised by pigmented awn tips and internodes. Its grains are dirty yellow in colour, medium bold in size and uniformly developed. The RD-2035 is resistant to cereal cyst nematode and brown rust, contributing to its yield stability under biotic stress conditions. It is recommended for irrigated areas of the North-Western Plains Zone and is well suited to timely sown irrigated conditions. The variety matures within 120–125 days, produces grains with a test weight of 40–45 g and has an average yield potential of 50–55 q ha^{-1}.

Treatment application

Application of hydrogel

The hydrogel was thoroughly mixed with soil and applied at the time of sowing in a band along the seed rows, as per the respective treatments, at a rate of 2.5 kg ha^{-1}. Upon incorporation into the soil, the hydrogel absorbed and retained large quantities of water and gradually released the stored moisture, thereby improving soil moisture availability in the root zone.

Growth parameters

Plant height, plant population m^{-1} row length, dry matter accumulation, dry matter partitioning, total number of tillers, crop growth rate (CGR), relative growth rate (RGR) and flag leaf area. The CGR (g m^{-2} day^{-1}) between 25–50 DAS, 51–75 DAS, 76–90 DAS and 91 DAS to harvest stage was computed based on dry matter accumulation by using the following formula (16):

$$CGR = \frac{W_2 - W_1}{t_2 - t_1} \times \frac{1}{P}$$

Where, W_1 and W_2 are dry matter (g) at time t_1 and t_2 respectively and P represents ground area.

Relative growth rate (RGR)

Relative growth rate (g g^{1-} day^{-1}) is the growth rate relative to size. It is also called the exponential growth rate, or the continuous growth rate. The RGR was computed on the basis of dry matter accumulation by using the following formula (17):

$$RGR = \frac{\text{Log } W_2 - \text{Log } W_1}{t_2 - t_1}$$

Where, W_1 and W_2 are dry matter at times t_1 and t_2 respectively and log is natural log.

Flag leaf area

Ten plants were tagged in each plot of all replications for flag leaf area sampling. The average length and width of 10 plants from the main shoot in each plot were taken in the field with the help of a scale at 60 and 90 DAS. Thereafter, the length and width of each flag leaf were multiplied using the following equation (18):

$$\text{Flag leaf area } (cm^2) = \text{length (cm)} \times \text{width (cm)} \times 0.75$$

Yield and yield attributes

Grain yield, straw yield, biological yield, harvest index, number of effective tillers, ear length, number of grains per ear, weight of grains ear^{-1} and 1000-grains weight.

Statistical analysis

All the data were subjected to statistical analysis by using Microsoft Excel and SPSS software for testing the significance of variation in experimental results. Wherever the F value was found significant at the 5 % level of significance, the critical difference (CD) value was computed for making comparison among the treatment means. All these computations were carried out by a standard statistical procedure (19).

Results

Impact of hydrogel under different fertiliser and irrigation levels on growth attributes

Plant height (cm)

Data on plant height at different growth stages is presented in (Table 2 & Fig. 1). The maximum plant height was recorded from I_3 (3 irrigations), which was significantly superior to I_1 (1 irrigation) and I_2 (2 irrigations) at different growth stages expect at 30 DAS, where I_1 (1 irrigation) was significantly superior to I_3 (3 irrigations) at 30 DAS stage.

At all growth stages H_1 (2.5 kg hydrogel ha^{-1}) with 100 % nitrogen, phosphorous and potassium (NPK) recorded significantly higher number of tillers than rest of the treatments. At the 60 DAS stage, hydrogel soil application has more numbers of tillers compared to other stages. Moreover, the increment in plant height under hydrogel at 2.5 kg ha^{-1} along with I_3 (3 irrigations) at harvest stage was 28.5 % (2023–24) and 33.0 % (2024–25) over control.

Leaf area index

Data pertaining of leaf area index reveals that in general increased with advancement in growth stages till 90 DAS. Leaf area index differed significantly due to application of irrigation in both years (Table 3 & Fig. 2). Maximum leaf area index was recorded in I_3 (3 irrigations) and was significantly superior to I_2 (2 irrigations) and I_1 (1 irrigation) at all growth stages, except at 30 DAS where I_1 (1 irrigation) was significantly superior over H_1 (3 irrigations).

Crop fertilised with hydrogel at 2.5 kg ha^{-1} + 100 % NPK had significantly maximum leaf area index as compared to all other treatments, irrespective of the years and stages. However, application of 100 % NPK did resulted higher leaf area index over control while compared to application of 70 % NPK and 50 % NPK without hydrogel at all the stages during both the years. Moreover, the leaf area index under hydrogel at 2.5 kg ha^{-1} along with 100 % NPK at harvest stages was 3.10 (2023–24) and 3.04 (2024–25) at 90 DAS stage.

Table 2. Effect of Hydrogel under different doses of fertiliser and irrigation on plant height (cm) of barley

Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Irrigation levels								
I_1 (1 irrigation)	9.1	8.4	40.1	38.3	65.5	63.4	85.5	82.3
I_2 (2 irrigations)	9.7	9.3	54.2	50.1	80.3	77.7	98.4	97.4
I_3 (3 irrigations)	9.9	9.4	56.3	52.3	90.3	86.7	106.5	103.8
S Em ±	**0.11**	**0.11**	**0.34**	**0.32**	**0.46**	**0.44**	**0.65**	**0.75**
C.D. (p = 0.05)	**0.40**	**0.41**	**1.30**	**1.21**	**1.87**	**1.77**	**2.61**	**2.75**
Hydrogel × Fertiliser treatments								
H_1 (100 % NPK without hydrogel)	9.5	8.7	51.5	47.1	82.1	76.9	100.2	99.1
H_2 (100 % NPK + 2.5 kg/ha hydrogel)	10.2	9.5	54.7	49.7	86.6	83.4	104.9	103.2
H_3 (70 % NPK without hydrogel)	9.3	8.5	38.9	38.2	64.3	61.2	82.2	79.2
H_4 (70 % NPK + 2.5 kg/ha hydrogel)	9.6	9.1	52.4	47.6	84.5	79.6	102.5	99.2
H_5 (50 % NPK without hydrogel)	8.8	8.2	36.6	36.2	61.2	59.4	79.6	74.1
H_6 (50 % NPK + 2.5 kg/ha hydrogel)	9.1	8.9	47.2	44.6	81.3	76.2	90.5	85.6
S Em ±	**0.08**	**0.07**	**0.46**	**0.44**	**0.76**	**0.74**	**1.16**	**1.16**
C.D. (p = 0.05)	**0.21**	**0.22**	**1.45**	**1.35**	**2.30**	**2.16**	**3.45**	**3.45**

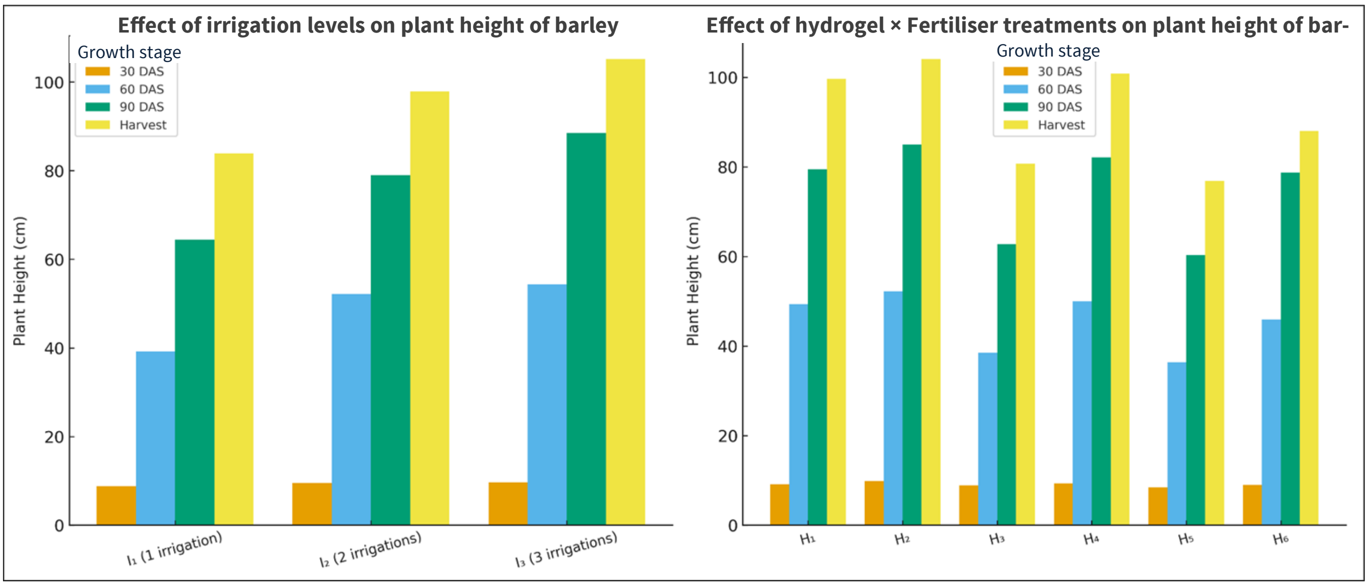

Fig. 1. Effect of hydrogel under different doses of fertiliser and irrigation on plant height (cm) of barley.

Table 3. Effect of hydrogel under different doses of fertiliser and irrigation at different crop growth stages on leaf area index of barley

Treatment	30 DAS		60 DAS		90 DAS	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Irrigation levels						
I_1 (1 irrigation)	1.29	1.22	2.94	2.80	2.70	2.58
I_2 (2 irrigations)	1.28	1.25	3.21	3.15	2.96	2.92
I_3 (3 irrigations)	1.24	1.27	3.50	3.58	3.15	3.23
S Em ±	**0.024**	**0.004**	**0.072**	**0.010**	**0.065**	**0.009**
C.D. (p = 0.05)	**NS**	**0.016**	**0.290**	**0.042**	**0.260**	**0.036**
Hydrogel × Fertiliser treatments						
H_1 (100 % NPK without hydrogel)	1.26	1.30	3.22	3.26	2.96	3.01
H_2 (100 % NPK + 2.5 kg/ha hydrogel)	1.33	1.31	3.37	3.33	3.12	3.05
H_3 (70 % NPK without hydrogel)	1.20	1.13	3.04	2.87	2.78	2.65
H_4 (70 % NPK + 2.5 kg/ha hydrogel)	1.24	1.25	3.19	3.20	2.92	2.93
H_5 (50 % NPK without hydrogel)	1.16	1.11	3.02	2.84	2.74	2.63
H_6 (50 % NPK + 2.5 kg/ha hydrogel)	1.19	1.23	3.17	3.16	2.86	2.87
S Em ±	**0.005**	**0.003**	**0.015**	**0.008**	**0.014**	**0.008**
C.D. (p = 0.05)	**0.017**	**0.010**	**0.045**	**0.026**	**0.042**	**0.024**

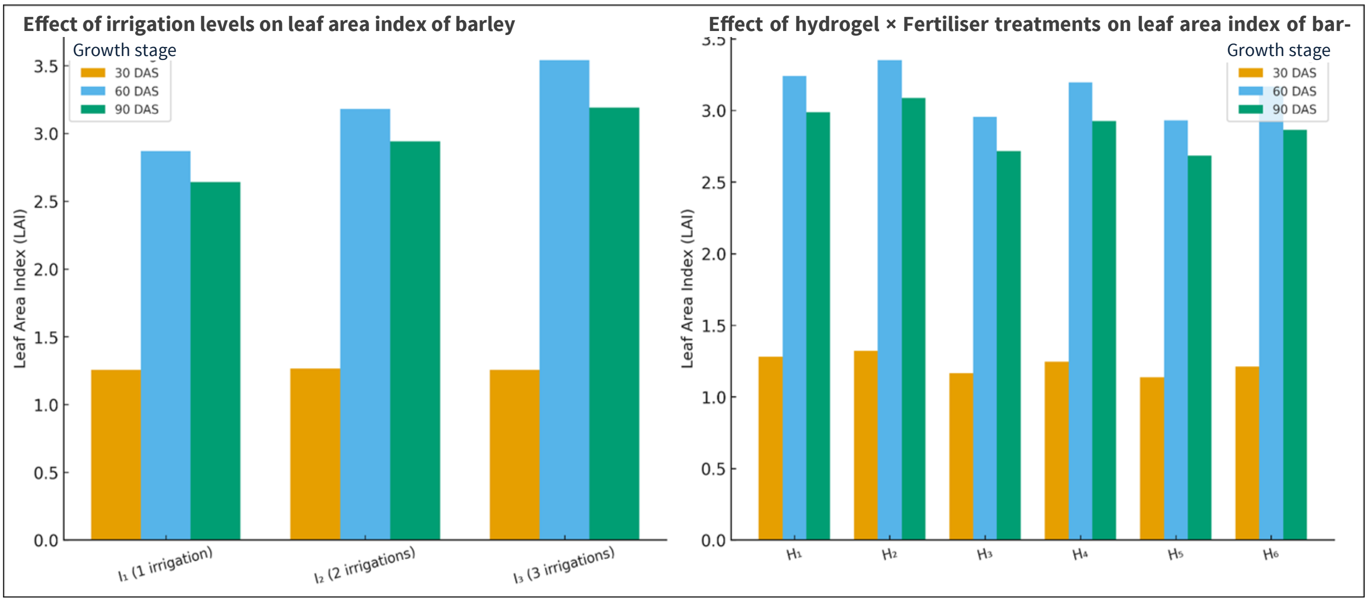

Fig. 2. Effect of hydrogel under different doses of fertiliser and irrigation on leaf area index of barley.

Dry matter accumulation (g m^{-1} row length)

Dry matter accumulation did exhibit significant effect of irrigation level and hydrogel with NPK fertilisers practices during both the years and at all the stages of crop growth. Dry matter accumulation increased progressively with advancement in crop age irrespective of the treatment (Table 4), however the rate of increase slowed down with age and it was lowest after 90 days stage during both the years. Under 1 irrigation being at par with 3 irrigations at 30 DAS during 2023–24 only was accumulated least mean dry matter at 30 DAS (8.1 g), 60 DAS (56 g), 90 DAS (100.6 g) and at harvest (120.4 g).

Control plot showed significant reduction in dry matter accumulation at all the stages than other treatments during both the years. However, use of hydrogel at 2.5 kg ha^{-1} along with 100 % NPK did recorded maximum dry matter accumulation as against

Table 4. Effect of hydrogel under different doses of fertiliser and irrigation on dry matter accumulation (g m^{-1} row length) of barley

Treatment	30 DAS		60 DAS		90 DAS		At harvest	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Irrigation levels								
I_1 (1 irrigation)	8.2	8.1	56.1	55.8	100.6	100.4	121.1	120.4
I_2 (2 irrigations)	9.1	9.1	63.4	63.3	116.8	116.7	162.1	161.0
I_3 (3 irrigations)	11.1	11.4	75.6	77.0	162.4	164.8	183.4	194.0
S Em ±	**0.3**	**0.2**	**1.3**	**0.8**	**3.6**	**2.6**	**6.2**	**4.9**
C.D. (P = 0.05)	**1.1**	**0.7**	**5.2**	**3.4**	**14.4**	**10.2**	**24.3**	**19.3**
Hydrogel × Fertiliser treatments								
H_1 (100 % NPK without hydrogel)	10.5	10.1	70.6	68.7	134.4	131.3	184.3	180.6
H_2 (100 % NPK + 2.5 kg/ha hydrogel)	12.1	11.8	75.7	74.5	147.3	145.1	194.1	198.1
H_3 (70 % NPK without hydrogel)	6.8	7.4	54.9	58.1	106.2	110.4	148.6	151.2
H_4 (70 % NPK + 2.5 kg/ha hydrogel)	8.2	8.5	61.4	63.5	117.6	121.8	160.2	165.5
H_5 (50 % NPK without hydrogel)	6.4	7.2	52.8	56.2	104.1	108.2	146.3	149.1
H_6 (50 % NPK + 2.5 kg/ha hydrogel)	8.1	8.3	58.2	61.6	114.5	119.6	158.1	163.4
S Em ±	**0.4**	**0.2**	**1.4**	**0.6**	**2.7**	**1.3**	**3.6**	**1.7**
C.D. (P = 0.05)	**1.0**	**0.5**	**4.2**	**2.1**	**8.0**	**3.8**	**11.2**	**5.1**

rest of the treatments irrespective of the years and stages. Moreover, application of hydrogel at 2.5 kg ha^{-1} alone had brought significant change over 100 % NPK and control at all the stages. At harvest stage, maximum dry matter m^{-1} row length was recorded with hydrogel at 2.5 kg ha^{-1} + 100 % NPK which was 33.2 % and 31.0 % compared to application of 70 % NPK and 50 % NPK during 2023–24 and 2024–25, respectively.

Impact of hydrogel under different fertiliser and irrigation levels on yield attributes

Yield attributes (effective tillers, spike length, number of spikelets spike^{-1}, number of grains spike^{-1} and test weight) did show significant effect of irrigation level, except number of spikelets spike^{-1} during 2023–24 and spike length during 2023–2024 and 2024–25. Nonetheless, moisture conservation practices had significantly influenced all the yield attributes during both the years. The interaction between irrigation levels and moisture conservation practices was non-significant (Table 5).

Effective tillers (m^{-2})

Crop raised with 1 irrigation at crown root initiation (CRI) stage condition had significantly lowest no. of effective tillers (280 and 265 m^{-2}) as against receiving 3 irrigations (362 and 342 m^{-2}) during first and second year, respectively. The next in the order were barley grown with 3 irrigations during both the years.

Combined application of hydrogel at 2.5 kg ha^{-1} with 100 % NPK did record maximum effective tillers (345 and 321 m^{2}) followed by 70 % NPK without hydrogel while significantly lowest effective tillers compare 50 % NPK without hydrogel (312 and 290 m^{-2}) and recorded during 2023–24 and 2024–25, respectively (Table 5).

Spike length

Crop raised with 1 irrigation at CRI stage condition did bear mean spike of less length (7.5 cm) as against receiving 3 irrigations (9.5 cm) and 2 irrigations (9.3 cm) with order change of 18.2 and 17.1 % during first and second year, respectively.

Combined application of hydrogel at2.5 kg ha^{-1} with 100 % NPK did recorded maximum spike length (10.22 and 9.83 cm) followed by 70 % NPK without hydrogel (7.45 and 7.25 cm) and recorded lowest effective tillers from 50 % NPK without hydrogel was recorded under control during 2023–24 and 2024–25, respectively (Table 5).

Number of spikelets spike^{-1}

Crop obtained 3 irrigations had highest number of spikelets spike^{-1} (13.52 and 12.23), while lowest number of spikelets spike^{-1} (10.56 and 10.33) was noted under crop obtained 1 irrigation during 2023–24 and 2024–25, respectively. The differences were however significant during 2023–24 only.

Crop fertilised with hydrogel at 2.5 kg ha^{-1} + 100 % NPK significantly maximum number of spikelets spike^{-1} as compared to all other treatments irrespective of the years. However, application of 100 % NPK being at par with hydrogel at 2.5 kg ha^{-1} resulted higher number of spikelets spike^{-1} over control during both the years (Table 5).

Number of grains spike^{-1}

Crop receiving 3 times irrigation did showed its superiority over other to record maximum number of grains spike^{-1} which was 41.25 (2023–24) and 38.84 (2024–25). However, lowest number of grains spike^{-1} did significantly recorded under crop obtaining 1 at CRI only irrigation as compared to all other treatments.

Table 5. Effect of hydrogel under different doses of fertiliser and irrigation on yield attributes of barley

Treatment	Effective tillers (m^2)		Spike length (cm)		No. of spikelets/spike		No. of grains/spike		Test weight (g)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Irrigation levels										
I_1 (1 irrigation)	280	263	7.5	7.4	10.5	10.3	25.4	24.6	35.31	35.25
I_2 (2 irrigations)	325	299	9.3	9.0	13.4	12.5	38.6	37.5	38.72	37.21
I_3 (3 irrigations)	364	341	9.5	9.1	13.5	12.2	41.2	38.8	40.18	38.45
S Em ±	**1.4**	**1.3**	**0.16**	**0.15**	**0.13**	**0.15**	**0.21**	**0.13**	**0.25**	**0.12**
C.D. (p = 0.05)	**4.1**	**3.7**	**NS**	**NS**	**0.56**	**NS**	**0.86**	**0.58**	**1.11**	**0.56**
Hydrogel × Fertiliser treatments										
H_1 (100 % NPK without hydrogel)	334	312	9.7	9.3	13.2	13.0	40.2	38.6	41.10	39.19
H_2 (100 % NPK + 2.5 kg/ha hydrogel)	345	321	10.2	9.8	14.8	13.6	42.4	40.4	42.44	40.56
H_3 (70 % NPK without hydrogel)	315	292	7.5	7.3	9.6	10.4	30.1	29.0	35.14	33.65
H_4 (70 % NPK + 2.5 kg/ha hydrogel)	321	301	9.4	9.1	13.0	12.2	38.2	36.6	38.86	36.85
H_5 (50 % NPK without hydrogel)	312	290	6.4	6.1	8.5	9.4	29.5	28.4	34.10	32.60
H_6 (50 % NPK + 2.5 kg/ha hydrogel)	318	300	8.3	8.2	11.5	10.2	36.6	34.3	37.80	35.80
S Em ±	**1.1**	**1.0**	**0.04**	**0.07**	**0.10**	**0.21**	**0.24**	**0.20**	**0.10**	**0.17**
C.D. (p = 0.05)	**3.1**	**3.0**	**0.18**	**0.25**	**0.35**	**0.66**	**0.73**	**0.60**	**0.32**	**0.56**

Combined application of hydrogel at 2.5 kg ha^{-1} + 100 % NPK recorded maximum number of grains $spike^{-1}$ which was significantly more over rest of the treatments, irrespective of the years. Though, application of hydrogel at 2.5 kg ha^{-1} + 100 % NPK significantly resulted higher number of grains $spike^{-1}$ over while compared to application of 70 % NPK and 50 % NPK without hydrogel during both the years. Moreover, significantly lowest number of grains $spike^{-1}$ (29.51 and 28.46) was recorded under the control during 2023–24 and 2024–25, respectively (Table 5).

Test weight (g)

Application of 3 irrigations and 1 irrigation recorded highest test weight of 41.19 and 39.46 g during 2023–24 and 2024–25 respectively. Moreover, lowest test weight of 36.32 and 35.26 g during 2023–24 and 2024–25, respectively was noted under crop obtained only 1 irrigation.

Crop receiving hydrogel at 2.5 kg ha^{-1} + 100 % NPK did significantly maximum test weight as compared to all other treatments irrespective of the years. However, application of hydrogel at 2.5 kg ha^{-1}+ 100 % NPK did also significantly result in higher test weight as against hydrogel at 2.5 kg ha^{-1} + 70 % NPK and hydrogel at 2.5 kg ha^{-1} + 50 % NPK control during both the years (Table 5).

Impact of hydrogel under different fertiliser and irrigation levels on yield

Yields viz., grain yield, straw yield, biological yield and harvest index did exhibit significant effect of irrigation level and moisture conservation practices during both the years (Table 6). However, harvest index was revealed nonsignificant hydrogel effect under different doses of fertiliser and irrigation practices during both the years. Moreover, the interaction between irrigation level and hydrogel practices was nonsignificant.

Grain yield/ha

Grain yield/ha increases with each successive increasing irrigation level significantly during both years. The increment was to the tune of 69.8 % (2023–24) and 70.4 % (2024–25) as against 1 irrigation. Though, wheat received 1 irrigation showed inferiority over other treatments to record least grain yield, irrespective of the years.

Crop grown without fertilisation obtained 35.6 % (2023–24) and 39.4 % (2024–25) lower grain yield/ha as compared with combined application of hydrogel at 2.5 kg ha^{-1}. Although, incorporation of hydrogel at 2.5 kg ha^{-1} along with 100 % NPK in Barley significantly recorded the highest grain yield over its individual component, irrespective of the years. Though, application of hydrogel at 2.5 kg ha^{-1} + 100 % NPK did significantly result higher grain yield over while compared to application of 70 and 50 % NPK without hydrogel during both the years.

Straw yield/ha

Barley grown with only of 1 irrigation recorded 28.6 and 29.1 % lower grain yield/ha during 2023–24 and 2024–25, respectively. The next in order was 3 time irrigation (at CRI, Tillering and Panicle emergence) which was significantly more over 1 time Although, wheat irrigated 4 times out yielded 3 times irrigation by 16.8 and 16.7 q/ha during first and second years, respectively.

Crop fertilised with hydrogel at 2.5 kg ha^{-1} + 100 % NPK obtained 64.97 q ha^{-1} (2023–24) and 63.09 q ha^{-1} (2024–25) straw yield/ha which was significantly higher over other, during both the years. Although, incorporation of hydrogel at 2. 5 kg ha^{-1}did at par with 100 % NPK while significantly superior over control in order to recorded maximum straw yields. Moreover, control did remain inferior over rest of its counterparts during both the years.

Biological yield/ha

Irrigation level had also resulted significant difference among themselves during both the years. Though, application of 3-times irrigation in barley did significantly recorded maximum biological yield (118.60 and 116.02 q ha^{-1}), while lowest biological yield (77.99 and 75.95 q ha^{-1}) was found under the crop received only 1 irrigation as compared with other irrigation levels during 2023–24 and 2024–25, respectively.

Crop grown 50 % NPK without hydrogel did significantly obtain lowest biological yield as compared with all other treatments. Moreover, combined application of hydrogel at 2.5 kg ha^{-1} along with 100 % NPK being at par had recorded highest biological yield as compared with 70 % NPK with 2.5 kg ha^{-1} hydrogel.

Harvest index

Barley crop received 1 irrigation did record least harvest index followed by 3 irrigations and 2 irrigations. Though, maximum harvest index was noted under the crop obtained 3 irrigations which was 45.43 and 45.44 during 2023–24 and 2024–25, respectively. Crop fertilised with hydrogel at 2.5 kg ha^{-1} + 100 % NPK did obtain maximum harvest index, it was followed by 70 and 50 % NPK. The difference was however nonsignificant during both the years.

Table 6. Effect of Hydrogel under different doses of fertiliser and irrigation on grain, straw and biological yield (q ha^{-1}) and harvest index (%) of barley

Treatment	Grain yield (q ha^{-1})		Straw yield (q ha^{-1})		Biological yield (q ha^{-1})		Harvest index (%)	
	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25	2023–24	2024–25
Irrigation levels								
I_1 (1 irrigation)	28.22	27.55	52.72	51.36	77.99	75.95	37.45	37.47
I_2 (2 irrigations)	43.72	42.63	58.71	57.21	101.45	98.81	43.54	43.55
I_3 (3 irrigations)	45.01	44.02	72.61	71.02	118.60	116.02	45.43	45.44
S Em ±	**0.31**	**0.46**	**0.58**	**0.67**	**0.86**	**1.11**	**0.11**	**0.17**
C.D. (p = 0.05)	**1.29**	**1.80**	**2.31**	**2.66**	**3.61**	**4.57**	**0.44**	**0.58**
Hydrogel × Fertiliser treatments								
H_1 (100 % NPK without hydrogel)	44.45	43.15	61.46	60.65	105.92	103.84	42.56	42.55
H_2 (100 % NPK + 2.5 kg/ha hydrogel)	46.96	45.60	64.97	63.09	111.94	109.70	42.58	42.56
H_3 (70 % NPK without hydrogel)	30.71	28.12	55.10	54.02	85.81	82.12	42.51	42.51
H_4 (70 % NPK + 2.5 kg/ha hydrogel)	42.30	41.42	58.52	58.34	101.82	99.76	42.53	42.51
H_5 (50 % NPK without hydrogel)	30.69	28.10	54.10	53.01	85.70	82.11	41.48	41.49
H_6 (50 % NPK + 2.5 kg/ha hydrogel)	42.28	41.40	57.51	57.33	101.71	99.74	41.52	41.50
S Em ±	**0.86**	**0.66**	**1.45**	**1.50**	**2.47**	**2.51**	**0.25**	**0.11**
C.D. (p = 0.05)	**2.95**	**3.01**	**4.37**	**4.48**	**7.45**	**7.59**	**NS**	**NS**

Discussion

Impact of hydrogel under different fertiliser and irrigation levels on growth attributes

Vegetative and reproductive growth of plants is governed by complex physiological and metabolic processes that are strongly influenced by environmental conditions and crop management practices. In the present investigation, different irrigation levels significantly influenced the overall growth performance of barley in terms of plant height, number of tillers and dry matter accumulation during both years of study. Plant height (Table 2) increased progressively with crop age and exhibited a rapid growth. The application of 3 irrigation levels recorded the maximum plant height, which was significantly superior to all other treatments. In contrast, plots receiving only 1 irrigation level showed a significant reduction in plant height at all growth stages, indicating the adverse effect of moisture stress on vegetative growth.

The number of tillers (Table 3) increased up to 60 DAS, after which a gradual decline was observed until harvest, mainly due to mortality of late-emerging tillers. The enhanced tillering under these treatments can be attributed to adequate moisture availability during the active tillering stage, which favours cell division and tiller initiation. Similar findings were reported earlier researchers, who emphasised that the efficiency of irrigation practices is largely dependent on soil water-holding capacity, irrigation water quality and inherent soil physical and chemical properties (20, 12).

Dry matter accumulation (Table 4), being a cumulative outcome of plant height and tiller production, was significantly affected by irrigation treatments. Higher dry matter accumulation was observed under 3 irrigation levels. The minimum dry matter accumulation at all growth stages was recorded in the control plots. These findings are in agreement with those of previous studies, reported that improved soil moisture availability through increased irrigation frequency enhanced nutrient uptake and physiological activity, resulting in higher biomass production (21, 22).

Impact of hydrogel under different fertiliser and irrigation levels on yield attributes and yield

Crop yield is governed by the source-sink relationship and represents the cumulative effect of various growth and yield-attributing characters such as spike length, number of spikelets per spike, number of grains per spike and test weight (1000-grain weight). Any factor influencing these components ultimately affects the economic yield of the crop. In the present study, the application of 3 irrigation levels resulted in a significant improvement in yield-attributing characters of barley compared to 2 irrigation levels. Three irrigation levels followed by 2 irrigation levels were superior to 1 irrigation level for all yield-attributing characters during both years of experimentation.

The application of different irrigation levels significantly increased grain, straw and biological yields of barley during both years. The highest grain, straw and biological yields were recorded under 3 irrigation levels, Harvest index was also significantly improved by the application of irrigation treatments during both years. Similar observations were reported previously (23). Furthermore, the combined application of organic manures and chemical fertilisers improved soil fertility and its inherent nutrient-supplying capacity, as also reported by previous researchers (24).

Among yield attributes, spike length, number of spikelets per spike, number of grains per spike and test weight were significantly influenced by different fertiliser doses and irrigation practices over the control during both years. The application of hydrogel at 2.5 kg ha^{-1} along with 100 % recommended NPK resulted in a significant increase in spike length. The maximum number of spikelets per spike was also recorded under the same treatment during both years. Similarly, the highest number of grains per spike (and test weight were observed under hydrogel at 2.5 kg ha^{-1} with 100 % NPK, which was significantly superior to the control during both years. There seems to be highly inconsistent effect of hydrogel on grain yield and its attributing characteristics (25, 26).

Conclusion

The study clearly demonstrated that irrigation levels exerted a significant impact on the growth, yield attributes and productivity of the crop during both years of experimentation. Among the treatments, 3 irrigations consistently produced the tallest plants, highest number of tillers, maximum dry matter accumulation and superior grain, straw and biological yields, followed by 2 irrigations. Future research should focus on optimising irrigation schedules in combination with hydrogel doses under varying soil and climatic conditions to enhance water-use efficiency and yield stability. Long-term studies on the residual effects of hydrogel, its biodegradation behaviour and economic viability across different cropping systems would provide deeper insights into sustainable resource management in arid and semi-arid regions. Exploring precision irrigation technologies and climate-resilient hydrogel formulations could further strengthen water conservation strategies and improve crop productivity under changing environmental conditions.

Authors' contributions

N carried out the experiment, recorded observations and analysed the data. HS conceptualised and supervised the research, participated in the study design, performed the statistical analysis and approved the final manuscript. SB, SC, SCS, PS, SJ and AAL contributed to conducting the experiment and assisted in editing, summarising and revising the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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