International Journal of Plant & Soil Science

Volume 38, Issue 8, Page 210-223, 2026; Article no.IJPSS.162851
ISSN: 2320-7035

Effect of Irrigation Regimes and Nitrogen Scheduling on Growth Attributes of Wheat (*Triticum aestivum* L.) under Semi-arid Conditions

Priyanka Shrivastava [a], Neetu [a], Shubham C. Salve [a] and Hoshiyar Singh [a*]

[a] *Department of Agronomy, Vivekananda Global University, Jaipur -303012, (Rajasthan), India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i86211

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/162851

Original Research Article

Received: 13/05/2026
Accepted: 18/07/2026
Published: 20/07/2026

Abstract

A field experiment was conducted during the *Rabi* season of 2024-25 at the Research Farm of Vivekananda Global University, Jaipur, Rajasthan, India, to evaluate the effects of irrigation regimes and nitrogen scheduling on the growth of wheat (*Triticum aestivum* L.). The experiment comprised nine treatment combinations involving three irrigation regimes, *viz.,* three irrigations (I_1), four irrigations (I_2), and five irrigations (I_3), and three nitrogen scheduling treatments, *viz.,* N_1 (50% basal + 50% at crown root initiation (CRI)), N_2 (50% basal + 25% at CRI + 25% at jointing stage) and N_3 (33.33% at each of the basal, CRI, and jointing stages). The treatments were evaluated in a split-plot design with three replications. Irrigation regimes and nitrogen scheduling had no significant effect on plant stand at 20 DAS and at harvest. However, both factors significantly influenced plant height and dry matter accumulation from 60 DAS onwards.

**Corresponding author: E-mail: hoshiyar.singh@vgu.ac.in;*

Cite as: *Shrivastava, P., Neetu, Salve, S. C., & Singh, H. (2026). Effect of Irrigation Regimes and Nitrogen Scheduling on Growth Attributes of Wheat (Triticum aestivum L.) under Semi-arid Conditions. International Journal of Plant & Soil Science, 38(8), 210–223. https://doi.org/10.9734/ijpss/2026/v38i86211*

Among the irrigation regimes, five irrigations (I_3) produced the maximum plant height (68.14, 83.06, and 87.58 cm at 60 DAS, 90 DAS, and harvest, respectively) and dry matter accumulation (145.81, 189.65 and 250.71 g m^{-1} row length at 60 DAS, 90 DAS and harvest, respectively). Similarly, nitrogen applied in three equal splits (N_3) recorded the highest plant height (67.32, 82.00 and 87.61 cm) and dry matter accumulation (146.00, 189.00 and 250.63 g m^{-1} row length) at the corresponding growth stages. The findings indicate that five irrigations and nitrogen applied in three equal splits at the basal, CRI, and jointing stages, considered as separate management effects, provided favourable conditions for sustained vegetative growth by improving plant height and biomass accumulation. These management practices may therefore be considered for enhancing wheat growth under semi-arid agro-ecological conditions.

Keywords: Irrigation regimes; nitrogen scheduling; dry matter accumulation; split nitrogen application; biomass accumulation.

1. Introduction

Wheat (*Triticum aestivum* L.; 2n = 6x = 42, AABBDD) is one of the most important cereal crops cultivated worldwide and serves as the principal staple food for nearly 35% of the global population. It belongs to the family Poaceae and is an allohexaploid species that originated through natural hybridization among three ancestral diploid species, resulting in broad genetic diversity and remarkable adaptability to diverse agro-climatic conditions (Shewry, 2009; Marcussen et al., 2014). Wheat grain is an excellent source of carbohydrates, proteins, dietary fibre, vitamins, and essential minerals, contributing nearly 20% of the calories and protein consumed by the world's population (Shiferaw et al., 2013; Paudel et al., 2024). Owing to its superior nutritional quality, processing characteristics, and wide adaptability, wheat plays a pivotal role in ensuring global food and nutritional security (Santhoshini et al., 2023). However, increasing climatic variability, shrinking natural resources and the growing demand for food necessitate the adoption of improved crop management strategies to sustain wheat productivity (FAO, 2024).

India is the second-largest producer of wheat after China and occupies a prominent position in the global wheat economy (Reddy et al., 2023). During 2023-24, wheat was cultivated on approximately 32.0 million hectares, producing over 113 million tonnes with an average productivity of around 3.5 t ha^{-1} (Directorate of Economics and Statistics, 2024). Among the wheat-growing states, Rajasthan contributes substantially to national production, where the crop is predominantly cultivated during the rabi season under irrigated conditions. However, wheat cultivation in the semi-arid regions of Rajasthan is frequently constrained by erratic rainfall, declining groundwater resources, rising temperatures, and inefficient nutrient management, which collectively restrict crop growth and biomass production (El-Shafei & Mattar, 2022). Under such environments, efficient utilisation of irrigation water together with balanced nutrient management has become indispensable for sustaining crop productivity and improving resource-use efficiency (Pradhan et al., 2014).

Among various agronomic inputs, irrigation and nitrogen are considered the two most influential factors governing wheat growth and development. Adequate soil moisture is essential for seed germination, crown root development, tiller formation, leaf expansion, photosynthesis, and assimilate translocation throughout the crop growth cycle. Moisture stress during critical phenological stages, particularly crown root initiation (CRI), jointing, flowering, and grain filling, adversely affects physiological processes by reducing cell expansion, stomatal conductance and photosynthetic activity, ultimately limiting biomass accumulation and crop growth (Kumar et al., 2015; El-Shafei & Mattar, 2022). Conversely, excessive irrigation may reduce water-use efficiency, increase nutrient losses through leaching and elevate production costs. Therefore, optimising irrigation scheduling has become an effective strategy for maximising crop growth while conserving increasingly scarce irrigation water resources (Ankit et al., 2024).

Nitrogen is the most yield-limiting nutrient in wheat because it is an essential constituent of chlorophyll, amino acids, nucleic acids, and proteins that regulate plant metabolism and growth (Kumari et al., 2023). Continuous nitrogen availability during active vegetative growth promotes chlorophyll synthesis, leaf-area development, tillering, and dry-matter accumulation, whereas inadequate or poorly synchronised nitrogen application substantially reduces nitrogen-use efficiency and plant growth (Fageria & Baligar, 2005; Ladha et al., 2005). Split application of nitrogen synchronised with crop demand has been reported to improve nitrogen recovery, minimize losses through volatilisation and leaching, and enhance biomass production compared with conventional nitrogen application methods (Pathak et al., 2014; Gill et al., 2019). Furthermore, irrigation and nitrogen interact synergistically within the soil-plant system, as adequate soil moisture facilitates nitrogen dissolution, transport and uptake, while balanced nitrogen nutrition enhances root proliferation and water extraction, thereby improving overall crop performance (Pradhan et al., 2014; Chouhan et al., 2023).

Recent field studies further indicate that wheat growth and resource-use responses depend on the coordinated timing of irrigation and nitrogen supply. Under drip or micro-sprinkling systems, irrigation scheduling combined with staged nitrogen application influenced plant height, biomass, yield, and water- and nitrogen-use efficiency (Zain et al., 2023; Shen et al., 2024). Comparable evidence from semi-arid environments also shows that irrigation schedules and nutrient management jointly affect wheat productivity and nutrient uptake (Ali et al., 2025). Studies published in other agricultural journals have likewise reported significant effects of irrigation-fertigation management on wheat growth and water productivity (Pippal et al., 2025) and of combined organic and inorganic nutrient management on bread-wheat performance (Gosa et al., 2025).

Although numerous studies have independently investigated irrigation scheduling and nitrogen management in wheat, information on their integrated optimization under the semi-arid conditions of Rajasthan remains limited, particularly with respect to crop growth dynamics. Understanding the response of plant stand, plant height and dry matter accumulation to different irrigation regimes and nitrogen scheduling strategies is essential for developing efficient agronomic practices that establish a strong vegetative foundation for subsequent crop productivity. Therefore, the present study was undertaken to evaluate the effects of different irrigation regimes and nitrogen scheduling practices on the growth attributes of wheat under semi-arid conditions.

2. Materials and Methods

2.1 Experimental Site and Climatic Conditions

A field experiment was conducted during the *Rabi* season of 2024-25 at the Research Farm of Vivekananda Global University, Jaipur, Rajasthan, India. The experimental site is located at 26°05′ N latitude and 75°28′ E longitude, at an altitude of 427 m above mean sea level, and falls under the Agro-climatic Zone IIIA (Semi-Arid Eastern Plains) of Rajasthan. The climate of the region is semi-arid, characterised by hot summers and cool winters. During the crop-growing period, the maximum and minimum temperatures ranged from 17.3 to 37.9°C and 0.3 to 21.5°C, respectively. A total rainfall of 94.5 mm was received during the cropping season. Relative humidity varied between 34 and 69%, while average sunshine duration ranged from 4.1 to 9.7 h day^{-1}, providing favourable environmental conditions for wheat cultivation.

2.2 Soil Characteristics

Prior to sowing, composite soil samples were collected from the 0–15 cm soil layer at different locations within the experimental field, air-dried, ground, and passed through a 2-mm sieve for physicochemical analysis. The experimental soil had a loamy-sand texture with a pH of 9.20, electrical conductivity (EC) of 1.35 dS m^{-1}, organic carbon content of 0.21%, and available nitrogen, phosphorus (P_2O_5), and potassium (K_2O) contents of 120.7, 15.12, and 152.24 kg ha^{-1}, respectively. Soil texture was determined by the International Pipette Method (Piper, 1950), while pH and EC were measured following Jackson (1973). Organic carbon was estimated by the Walkley and Black (1934) method, whereas available nitrogen, phosphorus, and potassium were determined using the alkaline potassium permanganate method (Subbiah & Asija, 1956), Olsen's method (Olsen et al., 1954), and the neutral normal ammonium acetate extraction method followed by flame photometry (Jackson, 1967), respectively.

2.3 Experimental Design and Treatments

The experiment was conducted in a split-plot design with three replications. Irrigation regimes were assigned to the main plots, while nitrogen scheduling treatments were allocated to the subplots using the randomisation procedure of Fisher and Yates (1963). The study consisted of nine treatment combinations comprising three irrigation regimes and three nitrogen scheduling treatments.

Main-plot treatments (Irrigation regimes):

- **I_1:** Three irrigations
- **I_2:** Four irrigations
- **I_3:** Five irrigations

Sub-plot treatments (Nitrogen scheduling):

- **N_1:** 50% nitrogen at basal + 50% at crown root initiation (CRI)
- **N_2:** 50% nitrogen at basal + 25% at CRI + 25% at jointing stage
- **N_3:** 33.33% nitrogen at each of the basal, CRI, and jointing stages

2.4 Crop Establishment and Management

The experimental field was prepared by one deep ploughing followed by cross cultivation and planking to obtain a fine seedbed. Individual plots were demarcated according to the experimental layout. Wheat was sown at a seed rate of 100 kg ha^{-1} in rows spaced 22.5 cm apart with a sowing depth of approximately 5 cm. Recommended crop management practices were followed uniformly in all experimental plots throughout the growing season. Manual hoeing and weeding were carried out at 25 days after sowing (DAS) to maintain weed-free conditions. Irrigations were applied according to the respective treatment schedules using the check basin method. Plant protection measures were adopted as and when required following standard agronomic recommendations.

2.5 Fertiliser Application

Nitrogen was applied at a total rate of 120 kg N ha^{-1} through urea and diammonium phosphate (DAP), while phosphorus and potassium were applied at 60 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1} through DAP and muriate of potash (MOP), respectively. The nitrogen contributed through DAP was included in calculating the total nitrogen dose. The full doses of phosphorus and potassium and the basal nitrogen were applied at sowing, whereas the remaining nitrogen was top-dressed according to the respective nitrogen scheduling treatments: N_1 (50% basal + 50% at crown root initiation, CRI), N_2 (50% basal + 25% at CRI + 25% at jointing), and N_3 (33.33% at each of the basal, CRI, and jointing stages).

2.6 Growth Observations

Plant stand was recorded at 20 DAS and at harvest from five randomly selected 1-m row lengths in each net plot, and the results were expressed as plants m^{-1} row length. Plant height was measured at 30, 60, and 90 DAS and at harvest from five randomly selected plants in each plot by measuring the distance from the soil surface to the tip of the main shoot, and the results were expressed in centimetres (cm). Dry matter accumulation was recorded at the same growth stages by harvesting all plants from a 1-m row length in each net plot. The plant samples were oven-dried at 65 ± 2°C to a constant weight, and the results were expressed as g m^{-1} row length.

2.7 Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design as described by Panse and Sukhatme (1985). Prior to analysis, the assumptions of residual normality and homogeneity of variance were examined and found to be satisfactory. Statistical analyses were performed using OPSTAT statistical software (CCS Haryana Agricultural University, Hisar, India). Treatment means were compared using the least significant difference (LSD) test at the 5% level of significance whenever the F-test was significant. Standard error of mean (SEm±), critical difference (CD) at P = 0.05, and coefficients of variation (CV) were computed for the comparison of treatment means.

3. Results

3.1 Analysis of Variance

The analysis of variance (ANOVA) revealed significant differences among irrigation regimes and nitrogen scheduling treatments for most of the growth parameters evaluated during the crop growth period (Table 1).

Plant stand recorded at 20 DAS and at harvest was not significantly influenced by irrigation regimes, nitrogen scheduling or their interaction (I × N), indicating uniform crop establishment under all treatments. In contrast, plant height and dry matter accumulation exhibited significant responses to irrigation regimes and nitrogen scheduling from 60 DAS onwards. The effects of irrigation and nitrogen scheduling on plant height at 60 DAS, 90 DAS and at harvest were significant ($P \leq 0.05$), whereas no significant differences were observed at 30 DAS. Similarly, dry matter accumulation was not significantly affected at 30 DAS but differed significantly among irrigation and nitrogen treatments at 60 DAS, 90 DAS and at harvest. The interaction effect (I × N) remained non-significant for all growth parameters throughout the study, indicating that the responses to irrigation and nitrogen scheduling were independent of each other (Table 1).

3.2 Effect of Irrigation Regimes and Nitrogen Scheduling on Plant Stand

3.2.1 Irrigation Regimes

The data presented in Table 2 and Fig. 1 revealed that irrigation regimes did not significantly influence plant stand either at 20 DAS or at harvest. However, slight numerical variations were observed among the treatments. The highest plant stand was recorded under five irrigations (I_3), with 32.43 and 30.90 plants m^{-1} row length at 20 DAS and harvest, respectively, followed by four irrigations (I_2), whereas the lowest values (31.76 and 30.15 plants m^{-1} row length) were recorded under three irrigations (I_1). The absence of significant differences indicated that irrigation regimes had no appreciable effect on crop establishment and plant survival.

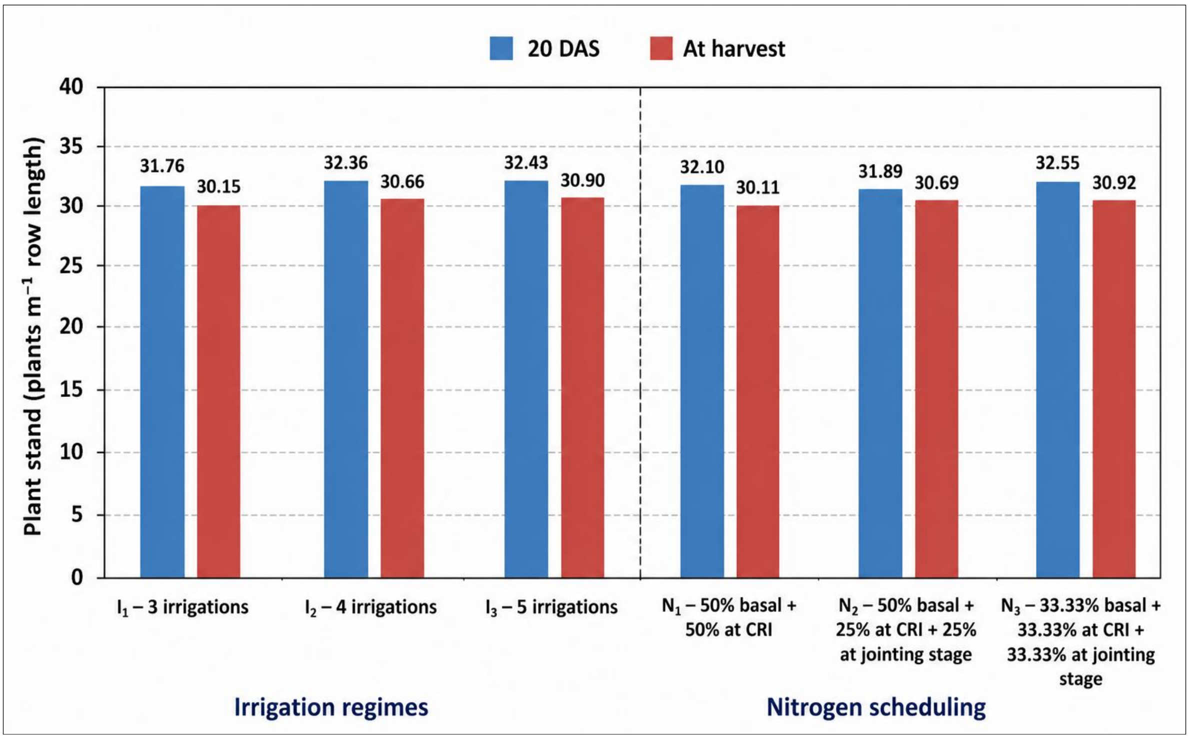

Fig. 1. Effect of irrigation regimes and nitrogen scheduling on plant stand of wheat at different growth stages

3.2.2 Nitrogen Scheduling

Nitrogen scheduling also failed to exert a significant effect on plant stand at both observation stages (Table 2 and Fig. 1). Numerically, treatment N_3 (33.33% basal + 33.33% at CRI + 33.33% at jointing stage) recorded the highest plant stand of 32.55 plants m^{-1} row length at 20 DAS and 30.92 plants m^{-1} row length at harvest, followed by N_1 and N_2. The results indicated that different nitrogen application schedules did not significantly affect crop establishment under the prevailing experimental conditions.

Table 1. Analysis of variance (Mean Sum of Squares) for growth parameters of wheat as influenced by irrigation regimes and nitrogen levels

Source of variation	d.f.	Plant stand		Plant height (cm)				Dry matter accumulation (g row^{-1})			
		20 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest
Replication (R)	2	18.5044	13.9422	3.6989	17.3255	13.8744	16.2389	2.6489	53.6304	104.7082	138.0430
Irrigation (I)	2	1.2084	1.3215	0.4637	369.7764**	288.3792**	223.3731**	2.3546	242.3014**	811.4411**	5252.7816**
Error (a)	4	9.1667	10.9444	2.7778	23.7778	20.6667	18.4444	2.7778	53.3933	78.1711	191.9055
Nitrogen (N)	2	1.0233	1.5681	0.5529	238.7217**	210.7713**	227.1171**	1.9083	241.0992**	734.8032**	5276.6913**
I × N	4	0.00004	0.00008	0.00002	0.85705	0.37972	0.27736	0.00047	0.10995	0.68860	19.82825
Error (b)	**12**	**9.8889**	**9.0000**	**2.7778**	**21.0000**	**17.8889**	**17.2222**	**2.7778**	**53.2267**	**53.3378**	**173.4382**

Note: DAS = Days after sowing. Significant at P ≤ 0.05

Table 2. Effect of irrigation regimes and nitrogen scheduling on plant stand of wheat (plants m⁻¹ row length)

Treatments	20 DAS	At harvest
Irrigation regimes		
I_1 – 3 irrigations	31.76	30.15
I_2 – 4 irrigations	32.36	30.66
I_3 – 5 irrigations	32.43	30.90
SEm±	1.01	1.10
CD (P = 0.05)	NS	NS
Nitrogen scheduling		
N_1 – 50% basal + 50% at CRI	32.10	30.11
N_2 – 50% basal + 25% at CRI + 25% at jointing stage	31.89	30.69
N_3 – 33.33% basal + 33.33% at CRI + 33.33% at jointing stage	32.55	30.92
SEm±	1.05	1.00
CD (P = 0.05)	NS	NS
CV (%)*	9.41	10.82

Note: DAS = Days after sowing; CRI = Crown Root Initiation; NS = Non-significant

3.3 Effect of Irrigation Regimes and Nitrogen Scheduling on Plant Height

3.3.1 Irrigation Regimes

The data presented in Table 3 and Fig. 2 showed that irrigation regimes did not exert a significant effect on plant height at 30 DAS. However, significant differences were observed at 60 DAS, 90 DAS and at harvest. Among the irrigation regimes, five irrigations (I_3) recorded the highest plant height of 68.14, 83.06 and 87.58 cm at 60 DAS, 90 DAS and harvest, respectively, and remained statistically at par with four irrigations (I_2), while both treatments were significantly superior to three irrigations (I_1). The lowest plant height was recorded under I_1 with values of 55.32, 71.86 and 77.68 cm at 60 DAS, 90 DAS and harvest, respectively. Compared with I_1, treatment I_3 increased plant height by 23.17%, 15.59% and 12.74% at 60 DAS, 90 DAS and harvest, respectively.

Table 3. Effect of irrigation regimes and nitrogen scheduling on plant height at different growth stages of wheat (cm)

Treatments	30 DAS	60 DAS	90 DAS	At harvest
Irrigation regimes				
I_1 – 3 irrigations	20.94	55.32	71.86	77.68
I_2 – 4 irrigations	21.25	61.83	76.07	81.65
I_3 – 5 irrigations	21.38	68.14	83.06	87.58
SEm±	0.56	1.63	1.52	1.43
CD (P = 0.05)	NS	6.38	5.95	5.62
Nitrogen scheduling				
N_1 – 50% basal + 50% at CRI	20.92	57.15	72.34	77.62
N_2 – 50% basal + 25% at CRI + 25% at jointing stage	21.23	60.82	76.65	81.69
N_3 – 33.33% basal + 33.33% at CRI + 33.33% at jointing stage	21.41	67.32	82.00	87.61
SEm±	0.56	1.53	1.41	1.38
CD (P = 0.05)	NS	4.71	4.34	4.26
CV (%)*	**7.87**	**7.90**	**5.90**	**5.22**

Note: DAS = Days after sowing; CRI = Crown Root Initiation; NS = Non-significant

3.3.2 Nitrogen Scheduling

Nitrogen scheduling had no significant influence on plant height at 30 DAS; however, significant differences were observed from 60 DAS onwards (Table 3 and Fig. 2). The application of nitrogen in three equal splits [N_3 (33.33% basal + 33.33% at CRI + 33.33% at jointing stage)] produced the tallest plants with heights of 67.32, 82.00 and 87.61 cm at 60 DAS, 90 DAS and harvest, respectively, and proved significantly superior to the remaining treatments. Compared with N_1, plant height under N_3 increased by 17.80%, 13.35% and 12.87% at 60 DAS, 90 DAS and harvest, respectively, while the corresponding increases over N_2 were 10.69%, 6.98% and 7.25%, respectively.

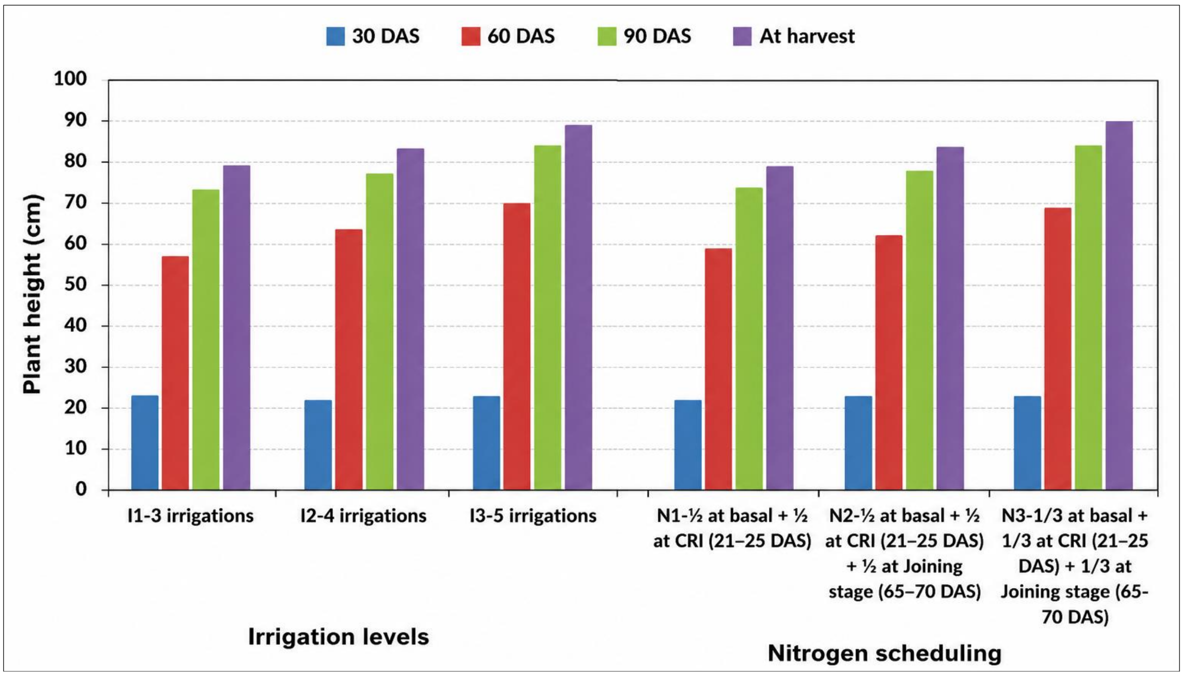

Fig. 2. Effect of irrigation regimes and nitrogen scheduling on plant height of wheat at different growth stages

Table 4. Effect of irrigation regimes and nitrogen scheduling on dry matter accumulation at different growth stages of wheat (g m⁻¹ row length)

Treatments	30 DAS	60 DAS	90 DAS	At harvest
Irrigation regimes				
I_1 – 3 irrigations	18.20	135.52	171.28	202.50
I_2 – 4 irrigations	18.93	139.51	176.30	229.39
I_3 – 5 irrigations	19.19	145.81	189.65	250.71
SEm±	0.56	2.44	2.95	4.62
CD (P = 0.05)	NS	9.56	11.57	18.13
Nitrogen scheduling				
N_1 – 50% basal + 50% at CRI	18.26	135.92	171.32	202.34
N_2 – 50% basal + 25% at CRI + 25% at jointing stage	18.91	138.92	176.92	229.64
N_3 – 33.33% basal + 33.33% at CRI + 33.33% at jointing stage	19.15	146.00	189.00	250.63
SEm±	0.56	2.43	2.43	4.39
CD (P = 0.05)	NS	7.49	7.50	13.53
CV (%)*	**8.88**	**5.21**	**4.94**	**6.09**

Note: DAS = Days after sowing; CRI = Crown Root Initiation; NS = Non-significant

3.4 Effect of Irrigation Regimes and Nitrogen Scheduling on Dry Matter Accumulation

3.4.1 Irrigation Regimes

Dry matter accumulation increased progressively with crop growth irrespective of treatments (Table 4 and Fig. 3). Irrigation regimes did not significantly influence dry matter accumulation at 30 DAS; however, significant differences were observed at 60 DAS, 90 DAS and harvest. Among the irrigation treatments, five irrigations (I_3) recorded the highest dry matter accumulation of 145.81, 189.65 and 250.71 g m^{-1} row length at 60 DAS, 90 DAS and harvest, respectively. The lowest dry matter accumulation was observed under three irrigations (I_1), with 135.52, 171.28 and 202.50 g m^{-1} row length at the corresponding stages. Compared with I_1, treatment I_3 enhanced dry matter accumulation by 7.59%, 10.73% and 23.81% at 60 DAS, 90 DAS and harvest, respectively, whereas the corresponding increases over I_2 were 4.52%, 7.57% and 9.29%, respectively.

3.4.2 Nitrogen Scheduling

Nitrogen scheduling did not significantly affect dry matter accumulation at 30 DAS, whereas significant differences were observed at 60 DAS, 90 DAS and harvest (Table 4 and Fig. 3). The highest dry matter accumulation was recorded under N_3 (33.33% basal + 33.33% at CRI + 33.33% at jointing stage), registering 146.00, 189.00 and 250.63 g m^{-1} row length at 60 DAS, 90 DAS and harvest, respectively. The lowest dry matter accumulation was recorded under N_1, with corresponding values of 135.92, 171.32 and 202.34 g m^{-1} row length. Compared with N_1, treatment N_3 increased dry matter accumulation by 7.42%, 10.32% and 23.87% at 60 DAS, 90 DAS and harvest, respectively, while the corresponding increases over N_2 were 5.10%, 6.83% and 9.14%, respectively.

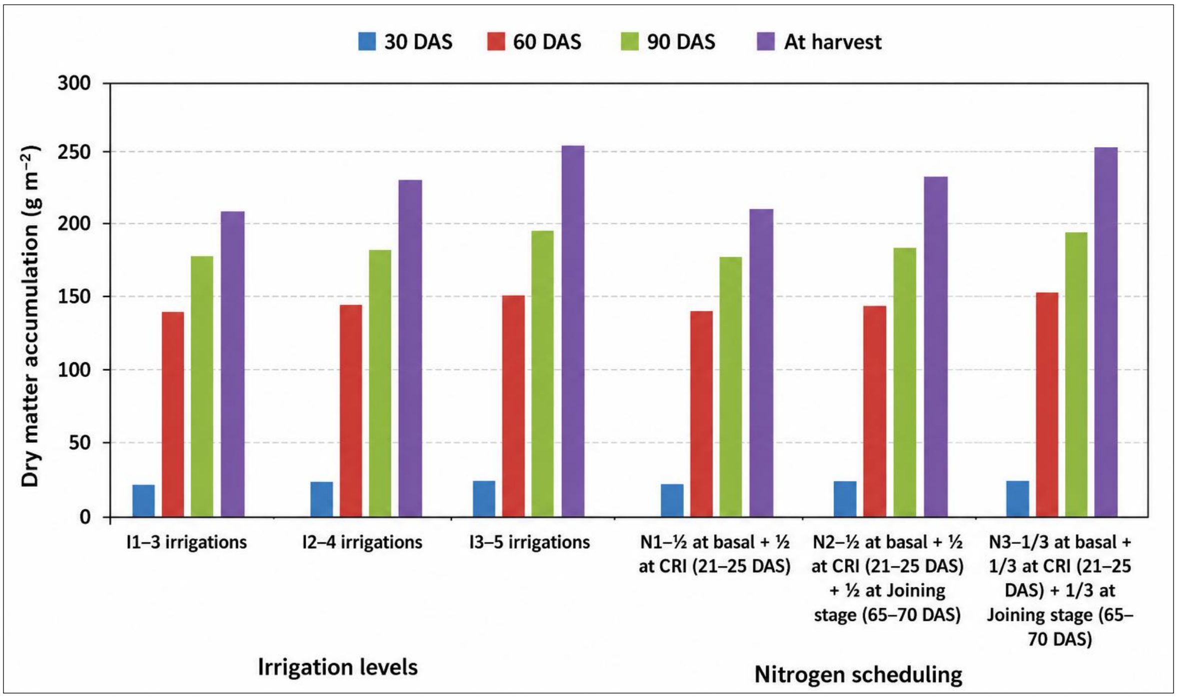

Fig. 3. Effect of irrigation regimes and nitrogen scheduling on dry matter accumulation of wheat at different growth

4. Discussion

4.1 Effect of Irrigation Regimes on Growth Attributes

The present investigation demonstrated that irrigation regimes exerted a pronounced influence on wheat growth, particularly during the active vegetative and reproductive phases of crop development. Although plant stand remained unaffected by irrigation treatments, significant improvements in plant height and dry matter accumulation were observed from 60 DAS onwards under higher irrigation levels. The non-significant differences in plant stand suggests that crop establishment was primarily governed by seed viability and favourable germination conditions, whereas subsequent vegetative growth depended largely on soil moisture availability. The significantly greater plant height recorded under five irrigations (I_3) may be attributed to the maintenance of favourable soil moisture throughout the crop growth period. Adequate soil moisture enhances cell division, cell elongation and meristematic activity, thereby promoting internodal elongation and vigorous vegetative growth. Similar observations were reported by Brahma et al. (2007), who observed increased plant height under frequent irrigation schedules due to improved moisture availability. Bikrmaditya et al. (2011) also reported that optimum soil moisture significantly enhanced wheat growth by improving physiological and metabolic activities.

Adequate irrigation improves nutrient diffusion towards the root zone, enhances nutrient uptake and sustains higher metabolic activity, ultimately resulting in vigorous plant growth and greater canopy development. Kumar et al. (2015) similarly reported that optimum irrigation promoted better root growth and nutrient absorption, resulting in significantly taller plants. Likewise, Chaudhary et al. (2022) observed that increasing irrigation levels significantly improved vegetative growth owing to enhanced water availability during the critical growth stages. In contrast, the lower plant height observed under three irrigations (I_1) was probably due to intermittent moisture stress, which restricted cell expansion, reduced stomatal conductance and photosynthetic activity, and consequently limited biomass production (Dey et al., 2025). Similar reductions in plant growth under moisture-deficit conditions have been reported by El-Shafei and Mattar (2022), who demonstrated that restricted irrigation adversely affected plant growth through reduced photosynthetic efficiency and water availability. Ankit et al. (2024) further emphasised that inadequate irrigation during critical phenological stages considerably reduced vegetative growth and water productivity in wheat. Comparable findings were also reported by Kaur et al. (2024) and Shen et al. (2024), who documented improvements in wheat growth and water-related performance under appropriately scheduled irrigation.

Dry matter accumulation followed a trend similar to plant height, with significantly greater biomass production under I_3 than under I_1. The improvement in dry matter accumulation may be attributed to sustained soil moisture during critical growth stages, which promoted greater leaf expansion, prolonged leaf area duration and enhanced photosynthetic efficiency. Saren et al. (2004) reported that optimum irrigation significantly increased dry matter accumulation by maintaining favourable soil moisture throughout the crop growth period. Similarly, Kumar and Pannu (2012) observed that adequate irrigation improved nutrient uptake and photosynthetic activity, resulting in higher biomass production. Adequate soil moisture also facilitates efficient absorption and translocation of nutrients through the transpiration stream, thereby increasing carbohydrate synthesis and accumulation in plant tissues. Kumar et al. (2015) reported that improved irrigation scheduling enhanced biomass production through better root growth and nutrient utilisation. Similar observations were made by Narolia et al. (2016), who reported significantly higher dry matter accumulation under optimum irrigation due to improved crop water relations and nutrient uptake. Choudhary et al. (2023) further demonstrated that appropriate irrigation scheduling substantially enhanced biomass accumulation by maintaining favourable soil moisture during the active growth period.

Conversely, moisture deficit under limited irrigation reduced leaf expansion, accelerated leaf senescence and decreased assimilate production, resulting in lower dry matter accumulation. Similar findings were reported by El-Shafei and Mattar (2022), while Ankit et al. (2024) concluded that inadequate irrigation significantly reduced biomass production because of impaired photosynthesis and reduced nutrient absorption. The absence of a significant interaction between irrigation regimes and nitrogen scheduling for all growth parameters indicates that the beneficial effects of irrigation were expressed independently of nitrogen application schedules. These findings suggest that maintaining adequate soil moisture throughout the critical growth stages is fundamental for sustaining vegetative growth, irrespective of nitrogen-splitting pattern, thereby highlighting the pivotal role of efficient irrigation management in maximising wheat growth under semi-arid conditions.

4.2 Effect of Nitrogen Scheduling on Growth Attributes

Nitrogen scheduling significantly influenced plant height and dry matter accumulation during the later stages of crop growth, whereas plant stand remained unaffected. The highest plant height and dry matter accumulation were consistently recorded under N_3, where nitrogen was applied in three equal splits at basal, crown root initiation (CRI), and jointing stages. The non-significant response of plant stand indicates that nitrogen scheduling had little influence on crop establishment, as seedling emergence is largely governed by seed vigour and favourable soil moisture conditions during the initial stages of growth.

The superior growth observed under N_3 may be attributed to the continuous availability of nitrogen throughout the crop growth cycle. The split application synchronised nitrogen supply with crop demand during the critical phenological stages, thereby reducing nitrogen losses and improving nitrogen use efficiency, as also reported by Pathak et al. (2003). Similar observations were made by Pathak et al. (2014), who emphasised that synchronising nitrogen application with crop demand enhances fertiliser use efficiency and supports sustained vegetative growth. Continuous nitrogen availability under N_3 promoted chlorophyll synthesis, protein formation, and photosynthetic activity, which collectively enhanced cell division, stem elongation and biomass production. Improved nitrogen nutrition also encouraged greater root development, resulting in enhanced water and nutrient uptake throughout the growing season. Kumar and Dhar (2010) similarly reported that adequate nitrogen availability throughout the crop growth period improved vegetative growth and overall crop vigour. Likewise, Pandey et al. (2013) observed that appropriately timed nitrogen applications significantly enhanced plant height by ensuring sufficient nitrogen availability during rapid vegetative growth.

The comparatively lower plant height and dry matter accumulation recorded under N_1 may be associated with the rapid depletion of available nitrogen following its early application, resulting in insufficient nitrogen supply during the later growth stages when crop demand is highest. Although N_2 improved growth over N_1, its performance remained inferior to N_3 because nitrogen availability during the reproductive phase was comparatively limited. Similar findings were reported by Jat et al. (2014a), who observed that improved nitrogen scheduling significantly enhanced wheat growth through better nutrient availability during critical developmental stages. Comparable results were also documented by Jat et al. (2014b), where split nitrogen application improved crop growth by maintaining an adequate nitrogen supply throughout the season. The significant increase in dry matter accumulation under N_3 can be explained by sustained photosynthetic activity resulting from prolonged chlorophyll retention and delayed leaf senescence. Continuous nitrogen availability maintained a larger photosynthetically active canopy, thereby increasing carbohydrate synthesis and biomass production. Enhanced assimilate production and efficient translocation from source to sink also contributed to greater dry matter accumulation. These findings are consistent with those of Pradhan et al. (2014), who reported higher biomass production and improved radiation use efficiency under optimum nitrogen management. Similarly, Gill et al. (2019) attributed increased biomass accumulation to improved nitrogen uptake and utilisation under split nitrogen application.

The beneficial effect of three equal nitrogen splits on wheat growth may further be associated with improved nitrogen recovery and reduced fertiliser losses through leaching, volatilisation, and denitrification. Sustained nitrogen availability throughout the crop growth period ensures continuous metabolic activity, resulting in greater vegetative development and biomass accumulation. Similar conclusions were drawn by Amani and Behzad (2020), who reported higher nitrogen use efficiency and better crop growth under split nitrogen application. Dubey et al. (2018) also observed significant improvements in plant growth parameters with timely nitrogen application due to enhanced nutrient availability during active growth stages. The present findings are further supported by Choudhary et al. (2023), who reported that appropriate nitrogen scheduling substantially improved plant height, dry matter accumulation and overall crop growth by maintaining a continuous nitrogen supply during critical growth stages. Therefore, the present study indicates that splitting nitrogen into three equal applications at basal, CRI and jointing stages is an effective nitrogen-management strategy for sustaining vegetative growth and supporting biomass production in wheat under semi-arid conditions.

5. Conclusion

The study showed that irrigation frequency and nitrogen-application timing significantly influenced wheat plant height and dry matter accumulation from 60 days after sowing, whereas plant establishment remained unaffected. Among the irrigation regimes evaluated, five irrigations produced the greatest plant height and dry matter accumulation at the later growth stages. Among the nitrogen schedules, application in three equal splits at the basal, crown root initiation, and jointing stages consistently resulted in superior growth. The non-significant irrigation × nitrogen interaction indicates that the responses to these factors were independent under the experimental conditions; therefore, the results do not establish a uniquely optimal irrigation–nitrogen combination. Adequate irrigation and appropriately timed split nitrogen application may be considered as separate agronomic practices for supporting sustained vegetative development under semi-arid conditions. Broader recommendations require confirmation through multi-season and multi-location studies that also assess grain yield, irrigation quantity, soil-water dynamics, water-use efficiency, nitrogen-use efficiency, nutrient losses, and economic returns.

6. Limitations

The experiment was conducted for one growing season at a single location and included only three irrigation frequencies and three nitrogen schedules. Irrigation quantity, soil-water dynamics, nitrogen losses, grain yield, water-use efficiency, nitrogen-use efficiency, and economic returns were not measured.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Ali, M., Bari, A., Ibrahim, M., Ahmed, I., Ahmed, U., Zafar, R., Ahmad, W., Saeed, M., & Khalid, M. (2025). Impact of irrigation schedule and integrated nutrient management on wheat yield and nutrients uptake under semi-arid regions. *Irrigation Science, 43*, 519–532. https://doi.org/10.1007/s00271-024-00986-8

Amani, A., & Behzad, M. A. (2020). Effect of split application of nitrogen on growth and yield of wheat (*Triticum aestivum* L.). *Journal of Experimental Agriculture International, 42*(6), 44–48. https://doi.org/10.9734/jeai/2020/v42i630536

Ankit, Khanna, M., Dass, A., Sudhishri, S., Babu, S., Kaur, R., Shekhawat, K., Prajapati, V. K., Sahoo, R. N., Singh, T., Meena, M. C., Upadhyay, P. K., & Jain, N. (2024). Wheat (*Triticum aestivum*) response under soil moisture and crop water stress based irrigation scheduling at variable nitrogen regimes. *The Indian Journal of Agricultural Sciences, 94*(11), 1171–1176. https://doi.org/10.56093/ijas.v94i11.152091

Bikrmaditya, Verma, R., Ram, S., & Sharma, B. (2011). Effect of soil moisture regimes and fertility levels on growth, yield and water-use efficiency of wheat (*Triticum aestivum* L.). *Progressive Agriculture, 11*(1), 73–78. https://agris.fao.org/search/en/providers/122535/records/65deae807c7033e84beb6fec

Brahma, R., Janawade, A. D., & Palled, Y. B. (2007). Effect of irrigation schedules, mulch and antitranspirant on growth, yield and economics of wheat. *Karnataka Journal of Agricultural Sciences, 20*(1), 6–9. http://14.139.155.167/test5/index.php/kjas/article/view/829

Chaudhary, A. N., Patel, A. M., Mor, V. B., & Chaudhary, H. N. (2022). Effect of irrigation level and weed management practices on wheat growth, yield and economics. *Indian Journal of Weed Science, 54*(1), 46–50. https://doi.org/10.5958/0974-8164.2022.00008.9

Choudhary, K. M., Sharma, S., Jajoria, D. K., & Bamboriya, S. D. (2023). Effect of irrigation scheduling and nitrogen management on yield and yield attributes of wheat. *The Pharma Innovation Journal, 12*(11), 462–465. https://www.thepharmajournal.com/archives/?ArticleId=23900&issue=11&vol=12&year=2023

Chouhan, S., Kumari, S., Kumar, R., & Chaudhary, P. L. (2023). Climate-resilient water management for sustainable agriculture. *International Journal of Environment and Climate Change, 13*(7), 411–426. https://doi.org/10.9734/ijecc/2023/v13i71894

Dey, P., Pattanaik, D., Dash, D., Singhal, R. K., Gaikwad, D. J., Baig, M. J., Kumar, R., Lone, A. A., & Rahimi, M. (2025). Mechanisms of low-light stress in rice: Current insights and future directions. *Plant Growth Regulation, 105*, 1949–1968. https://doi.org/10.1007/s10725-025-01396-2

Directorate of Economics and Statistics. (2024). *Agricultural statistics at a glance 2024*. Ministry of Agriculture and Farmers Welfare, Government of India. https://desagri.gov.in/document-report/agricultural-statistics-at-a-glance-2024/

Dubey, S. N., Tiwari, A., Pandey, V. K., Singh, V., & Singh, G. (2018). Effect of nitrogen levels and its time of application on growth parameters of barley (*Hordeum vulgare* L.). *Journal of Pharmacognosy and Phytochemistry, 7*(1), 333–338. https://www.phytojournal.com/archives/2018.v7.i1.2517/effect-of-nitrogen-levels-and-its-time-of-application-on-growth-parameters-of-barley-hordeum-vulgare-l

El-Shafei, M., & Mattar, M. A. (2022). Irrigation scheduling and production of wheat with different water quantities in surface and drip irrigation: Field experiments and modelling using CROPWAT and SALTMED. *Agronomy, 12*(7), 1488. https://doi.org/10.3390/agronomy12071488

Fageria, N. K., & Baligar, V. C. (2005). Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy, 88*, 97–185. https://doi.org/10.1016/S0065-2113(05)88004-6

Fisher, R. A., & Yates, F. (1963). *Statistical tables for biological, agricultural and medical research* (6th ed.). Oliver & Boyd. https://digital.library.adelaide.edu.au/items/8d93d3ef-a4d1-4c27-b976-5bcdf3cce5eb

Food and Agriculture Organization of the United Nations. (2024). *FAOSTAT* [Data set]. https://www.fao.org/faostat/en/#data

Gill, S. C., Sharma, R. K., Tripathi, S. C., Chhokar, R. S., Meena, R. P., & Jha, A. (2019). Nitrogen top dressing just before irrigation improves wheat growth, productivity, nitrogen-use efficiency and profitability. *Journal of Cereal Research, 11*(1), 74–83. https://doi.org/10.25174/2249-4065/2019/83006

Gosa, R., Ketema, T., Eshetu, M., & Getachew, G. (2025). Effects of vermicompost and inorganic fertilizers on soil properties, yield components, and bread wheat yield in Sinana District, Bale Highlands, Ethiopia. *Asian Journal of Agriculture and Allied Sciences, 8*(1), 270–278. https://doi.org/10.56557/ajaas/2025/v8i171

Jackson, M. L. (1967). *Soil chemical analysis*. Prentice-Hall of India.

Jackson, M. L. (1973). *Soil chemical analysis* (2nd ed.). Prentice-Hall of India. https://krishikosh.egranth.ac.in/items/c7da3b48-c39d-4cfd-a599-428deb7ae0b0

Jat, S. L., Nepalia, V., Choudhary, J., & Singh, D. (2014a). Effect of nitrogen and weed management on productivity and quality of durum wheat (*Triticum durum*). *Indian Journal of Agronomy, 59*(2), 281–285. https://doi.org/10.59797/ija.v59i2.4551

Jat, S. L., Nepalia, V., Singh, D., Choudhary, J., & Upadhyay, B. (2014b). Influence of herbicides and nitrogen levels on weed dynamics and durum wheat (*Triticum durum* Desf.) yield. *Annals of Agricultural Research, 35*(3), 330–336. https://epubs.icar.org.in/index.php/AAR/article/view/44076

Kaur, G., Subhash, S., Sharma, V., & Chhabra, V. (2024). Plant stress index (PSI)-based irrigation scheduling of wheat in Punjab, India. *Journal of Agrometeorology, 26*(3), 290–294. https://doi.org/10.54386/jam.v26i3.2608

Kumar, A., & Dhar, S. (2010). Evaluation of organic and inorganic sources of nutrients in maize (*Zea mays*) and their residual effect on wheat (*Triticum aestivum*) under different fertility levels. *The Indian Journal of Agricultural Sciences, 80*(5), 364–371. https://doi.org/10.56093/ijas.v80i5.199

Kumar, B., Dhar, S., Vyas, A. K., & Paramesh, V. (2015). Impact of irrigation schedules and nutrient management on growth, yield and root traits of wheat (*Triticum aestivum*) varieties. *Indian Journal of Agronomy, 60*(1), 87–91. https://doi.org/10.59797/ija.v60i1.4419

Kumar, P., & Pannu, R. K. (2012). Effect of different sources of nutrition and irrigation levels on yield, nutrient uptake and nutrient-use efficiency of wheat. *International Journal of Life Science and Pharma Research, 1*(4), 187–192. https://independent.academia.edu/ParvinderKumar39

Kumari, S., Kumar, R., Chouhan, S., & Chaudhary, P. L. (2023). Influence of various organic amendments on growth and yield attributes of mung bean (*Vigna radiata* L.). *International Journal of Plant & Soil Science, 35*(12), 124–130. https://doi.org/10.9734/ijpss/2023/v35i122975

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy, 87*, 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8

Marcussen, T., Sandve, S. R., Heier, L., Spannagl, M., Pfeifer, M., International Wheat Genome Sequencing Consortium, Jakobsen, K. S., Wulff, B. B. H., Steuernagel, B., Mayer, K. F. X., & Olsen, O.-A. (2014). Ancient hybridizations among the ancestral genomes of bread wheat. *Science, 345*(6194), 1250092. https://doi.org/10.1126/science.1250092

Narolia, R. S., Meena, H., Singh, P., Meena, B. S., & Ram, B. (2016). Effect of irrigation scheduling and nutrient management on productivity, profitability and nutrient uptake of wheat (*Triticum aestivum*) grown under zero-tilled conditions in south-eastern Rajasthan. *Indian Journal of Agronomy, 61*(1), 53–58. https://doi.org/10.59797/ija.v61i1.4345

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (USDA Circular No. 939). U.S. Department of Agriculture. https://agris.fao.org/search/en/providers/122535/records/65dded244c5aef494fd7641c

Pandey, A. K., Kureel, R. S., Singh, B., Tripathi, H. P., Singh, G., Kumar, S., & Kumar, A. (2013). Effect of nitrogen scheduling on growth, yield and quality of late-sown wheat. *International Journal of Agricultural Science and Technology, 2*(1), 22–27. https://www.researchgate.net/publication/300097663_Effect_of_Nitrogen_Scheduling_on_Growth_Yield_and_Quality_Of_Late_Sown_Wheat

Panse, V. G., & Sukhatme, P. V. (1985). *Statistical methods for agricultural workers* (4th enlarged ed.). Indian Council of Agricultural Research.

Pathak, H., Aggarwal, P. K., Roetter, R. P., Kalra, N., Bandyopadhyay, S. K., Prasad, S., & van Keulen, H. (2003). Modelling the quantitative evaluation of soil nutrient supply, nutrient-use efficiency and fertilizer requirements of wheat in India. *Nutrient Cycling in Agroecosystems, 65*, 105–113. https://doi.org/10.1023/A:1022177231332

Pathak, H., Ladha, J. K., & Aggarwal, P. K. (2014). Nitrogen-use efficiency: Challenges and opportunities for sustainable agriculture. *Indian Journal of Fertilisers, 10*(12), 94–112.

Paudel, P., Pandey, M. K., Subedi, M., Paudel, P., & Kumar, R. (2024). Genomic approaches for improving drought tolerance in wheat (*Triticum aestivum* L.): A comprehensive review. *Plant Archives, 24*(1), 1289–1300. https://doi.org/10.51470/PLANTARCHIVES.2024.v24.no.1.180

Piper, C. S. (1950). *Soil and plant analysis*. Interscience Publishers.

Pippal, R., Singh, S. K., Kumar, H., Singh, N. K., Sahu, A., & Srivastava, M. (2025). Impact of irrigation water requirements and fertigation levels on wheat growth, yield and water productivity. *Journal of Experimental Agriculture International, 47*(8), 600–610. https://doi.org/10.9734/jeai/2025/v47i83701

Pradhan, S., Sehgal, V. K., Sahoo, R. N., Bandyopadhyay, K. K., & Singh, R. (2014). Yield, water, radiation and nitrogen-use efficiencies of wheat (*Triticum aestivum* L.) as influenced by nitrogen levels in a semi-arid environment. *Indian Journal of Agronomy, 59*(2), 267–275. https://doi.org/10.59797/ija.v59i2.4549

Reddy, B. R. K., Kumar, B., Kumar, R., & Thota, H. (2023). Analysis of heterotic potential for yield and its contributing traits in wheat (*Triticum aestivum* L.). *International Journal of Environment and Climate Change, 13*(9), 388–400. https://doi.org/10.9734/ijecc/2023/v13i92246

Santhoshini, A., Dubey, N., Avinashe, H. A., Thonta, R., & Kumar, R. (2023). Inheritance studies in a segregating population of bread wheat (*Triticum aestivum* L.). *International Journal of Environment and Climate Change, 13*(9), 277–287. https://doi.org/10.9734/ijecc/2023/v13i92230

Saren, B. K., Dey, S., & Mandal, D. (2004). Effect of irrigation and sulphur on yield attributes, productivity, consumptive use and consumptive-use efficiency of wheat (*Triticum aestivum*). *The Indian Journal of Agricultural Sciences, 74*(5), 257–261.

Shen, X., Liu, J., Liu, L., Zeleke, K., Yi, R., Zhang, X., Gao, Y., & Liang, Y. (2024). Effects of irrigation and nitrogen topdressing on water- and nitrogen-use efficiency for winter wheat with micro-sprinkling hose irrigation in North China. *Agricultural Water Management, 302*, 109005. https://doi.org/10.1016/j.agwat.2024.109005

Shewry, P. R. (2009). Wheat. *Journal of Experimental Botany, 60*(6), 1537–1553. https://doi.org/10.1093/jxb/erp058

Shiferaw, B., Smale, M., Braun, H. J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10: Past successes and future challenges to the role played by wheat in global food security. *Food Security, 5*, 291–317. https://doi.org/10.1007/s12571-013-0263-y

Subbiah, B. V., & Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Current Science, 25*(8), 259–260.

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic-acid titration method. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003

Zain, M., Si, Z., Ma, H., Cheng, M., Khan, A., Mehmood, F., Duan, A., & Sun, C. (2023). Developing a tactical irrigation and nitrogen-fertilizer management strategy for winter wheat through drip irrigation. *Frontiers in Plant Science, 14*, 1231294. https://doi.org/10.3389/fpls.2023.1231294

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/162851