INTEGRATED IRRIGATION AND NITROGEN SCHEDULING IMPROVES YIELD ATTRIBUTES AND PRODUCTIVITY OF WHEAT (TRITICUM AESTIVUM L.) UNDER SEMI-ARID CONDITIONS

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ABSTRACT

Background: Wheat (Triticum aestivum L.) productivity in semi-arid regions is frequently constrained by inadequate irrigation and inefficient nitrogen management, which adversely affect yield attributes and final crop productivity. Optimizing irrigation regimes together with appropriate nitrogen scheduling is therefore essential to improve reproductive performance and maximize wheat yield under water-limited conditions.
Methods: A field experiment was conducted during the Rabi season of 2024–25 at the Research Farm of Vivekananda Global University, Jaipur, Rajasthan, India. 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% nitrogen at basal + 50% at crown root initiation (CRI)), N_2 (50% at basal + 25% at CRI + 25% at jointing stage) and N_3 (33.33% each at basal, CRI and jointing stages). The treatments were evaluated in a split-plot design with three replications. Yield attributes, including total tillers per plant, effective tillers, grains per spike, spike length and test weight, together with grain, straw, biological yields and harvest index, were recorded and statistically analysed using analysis of variance.
Results: Irrigation regimes and nitrogen scheduling significantly influenced all yield attributes and yield parameters, whereas their interaction was non-significant. Among irrigation regimes, I_3 (five irrigations) recorded the highest effective tillers (72.92 m^{-2}), grains per spike (40.22), spike length (8.25 cm), test weight (44.41 g), grain yield (4461 kg ha^{-1}), straw yield (6392 kg ha^{-1}) and biological yield (10853 kg ha^{-1}). Likewise, nitrogen application in three equal splits (N_3) produced the maximum effective tillers (72.61 m^{-2}), grains per spike (40.15), spike length (8.25 cm), test weight (44.48 g), grain yield (4476 kg ha^{-1}), straw yield (6374 kg ha^{-1}) and biological yield (10850 kg ha^{-1}). Harvest index remained statistically unaffected by either irrigation regimes or nitrogen scheduling. The findings indicate that scheduling five irrigations together with three equal split applications of nitrogen at basal, CRI and jointing stages effectively improves yield attributes and enhances wheat productivity under semi-arid conditions.

KEYWORDS: Biological yield, Grain yield, Irrigation regimes, Nitrogen scheduling, Split nitrogen application, Wheat, Yield attributes.

INTRODUCTION

Wheat (Triticum aestivum L.) is one of the world's most important cereal crops and serves as a staple food for nearly 35% of the global population. Belonging to the family Poaceae, bread wheat is an allohexaploid species (2n = 6x = 42; AABBDD) that evolved through natural hybridization among three ancestral genomes, enabling wide adaptability to diverse agro-climatic conditions and making it one of the most successful cereal crops cultivated worldwide (Marcussen et al., 2014). Wheat contributes approximately 20% of the calories and protein consumed globally and is an important source of carbohydrates, proteins, dietary fibre, B-complex vitamins and essential minerals such as iron and zinc (Shewry & Hey, 2015). Owing to its excellent processing quality and nutritional value, wheat is processed into a wide range of food products including bread, chapati, pasta, noodles, biscuits and bakery products, while its straw serves as an important source of livestock fodder and organic manure in many farming systems (Shiferaw et al., 2013).

Globally, wheat occupies nearly 220 million hectares with an annual production exceeding 790 million tonnes, making it one of the most extensively cultivated cereal crops after maize and rice (FAO, 2024). India ranks as the second-largest wheat-producing country in the world, with approximately 30.36 million hectares under cultivation and a production of 112.74 million tonnes during 2023–24, achieving an average productivity of about 3.71 t ha^{-1} (Ministry of Agriculture and Farmers Welfare, 2024). Among the wheat-growing states, Uttar Pradesh, Punjab, Madhya Pradesh, Haryana and Rajasthan contribute substantially to national production. In Rajasthan, wheat occupies approximately 2.92 million hectares, producing nearly 11.3 million tonnes with an average productivity of 3.87 t ha^{-1}. However, wheat production in the semi-arid regions of the state is frequently constrained by erratic rainfall, declining groundwater resources, rising temperatures and inefficient crop management practices, which collectively limit yield potential and resource-use efficiency (Anonymous, 2024).

Among the agronomic factors affecting wheat productivity, irrigation and nitrogen management play pivotal roles in determining yield formation and final productivity. Wheat is highly sensitive to moisture stress during crown root initiation (CRI), tillering, jointing, flowering and grain-filling stages, where inadequate water availability restricts tiller survival, spike development, grain formation and assimilate translocation (Tyagi et al., 2022). Conversely, excessive irrigation reduces water-use efficiency and may increase nutrient losses through leaching, thereby lowering input-use efficiency. Therefore, optimizing irrigation scheduling has become an essential strategy for maximizing wheat productivity while conserving limited water resources, particularly under semi-arid environments (Pradhan et al., 2014).

Nitrogen is the most yield-limiting nutrient in wheat because it directly influences chlorophyll synthesis, photosynthetic activity, protein formation and grain development. Nevertheless, nitrogen use efficiency in conventional wheat production remains low owing to improper timing and methods of fertilizer application, resulting in substantial losses through volatilization, denitrification and leaching (Pathak et al., 2014). Synchronizing nitrogen application with crop demand through split applications at critical phenological stages such as basal, crown root initiation and jointing has been reported to improve nitrogen recovery, increase productive tillers, enhance grain filling and ultimately increase grain yield (Kumar & Tripathi, 2021). Furthermore, irrigation and nitrogen exhibit a strong synergistic relationship, whereby adequate soil moisture enhances nitrogen uptake and utilization, while balanced nitrogen nutrition promotes vigorous root growth, greater photosynthetic efficiency and improved water extraction, thereby maximizing crop productivity (Verma et al., 2022).

Recent studies have highlighted that integrated irrigation and nitrogen management is more effective than managing these inputs independently, particularly under water-limited environments where efficient utilization of both resources is essential for sustainable crop production (Ali et al., 2021). Although considerable research has been conducted on irrigation and nitrogen management individually, information on their combined optimization under the semi-arid conditions of Rajasthan remains limited. Therefore, the present investigation was undertaken to evaluate the influence of different irrigation regimes and nitrogen scheduling practices on the yield attributes and productivity of wheat under semi-arid conditions, with the objective of identifying an efficient management strategy capable of maximizing wheat yield while ensuring sustainable utilization of water and nitrogen resources.

MATERIALS AND METHODS

Experimental Site

The field experiment was conducted during the Rabi season of 2024–25 at the Research Farm, Vivekananda Global University, Jaipur, Rajasthan, India, to evaluate the effect of irrigation regimes and nitrogen scheduling on yield attributes and yield of wheat (Triticum aestivum L.). The experimental site is situated at 26°05′ N latitude and 75°28′ E longitude with an altitude of 427 m above mean sea level and falls under Agro-climatic Zone IIIA (Semi-Arid Eastern Plains) of Rajasthan.

Experimental Design and Treatments

The experiment was laid out in a split-plot design with three replications. Three irrigation regimes were assigned to the main plots, viz., I_1 (three irrigations), I_2 (four irrigations) and I_3 (five irrigations). Three nitrogen scheduling treatments were allotted to the sub-plots, viz., 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), and N_3 (33.33% nitrogen each at basal, CRI and jointing stages), resulting in nine treatment combinations.

The experiment comprised 27 plots with a gross plot size of 3.0 × 5.0 m (15 m^2) and a net plot size of 2.55 × 5.0 m (12.75 m^2). Wheat was sown at a seed rate of 100 kg ha^{-1} with a row spacing of 22.5 cm.

Crop Management

The experimental field was prepared using conventional tillage practices to obtain a fine seedbed. Nitrogen fertilizer was supplied through urea, whereas phosphorus and potassium were applied through diammonium phosphate (DAP) and muriate of potash (MOP), respectively. A fertilizer dose of 120 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1} was followed. The entire quantity of phosphorus and potassium was applied as basal, while nitrogen was applied according to the respective nitrogen scheduling treatments. Irrigations were applied through the check basin method as per the treatment schedule. All recommended agronomic practices, including weed and pest management, were uniformly followed throughout the crop-growing period.

Observations recorded

The following observations were recorded during the course of the investigation: Total tillers per plant, Effective tillers (m^{-1} row length), Spike length (cm), Number of grains per spike, Test weight (1000-grain weight, g), Grain yield (kg ha^{-1}), Straw yield (kg ha^{-1}), Biological yield (kg ha^{-1}) and Harvest index (%).

Grain yield was recorded from the net plot area after threshing and cleaning and expressed as kg ha^{-1}. Straw yield was calculated by subtracting grain yield from biological yield. Biological yield represented the total above-ground biomass harvested from each net plot. Harvest index was calculated according to Singh and Stoskopf (1971) using the following equation:

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design following the procedure described by Panse and Sukhatme (1985). The significance of treatment effects was tested using the F-test at the 5% probability level. Treatment means were compared using the critical difference (CD) at P = 0.05, wherever the treatment effects were significant. Standard error of mean (SEm±) and coefficient of variation (CV) were computed for all measured parameters.

RESULTS

Analysis of variance for yield attributes and yield

The analysis of variance revealed that irrigation regimes and nitrogen scheduling significantly influenced all yield attributes and yield parameters of wheat, whereas their interaction (I × N) remained non-significant (Table 1). Replication effects were non-significant for all the characters studied. Irrigation regimes exerted a highly significant effect on total tillers, effective tillers, number of grains per spike, spike length, test weight, grain yield, straw yield, biological yield and harvest index. Similarly, nitrogen scheduling also significantly affected all these parameters, indicating that appropriate irrigation frequency and nitrogen application schedule independently enhanced yield formation and productivity of wheat. However, the interaction between irrigation regimes and nitrogen scheduling was non-significant for all the studied traits, suggesting that the effects of irrigation and nitrogen scheduling were independent of each other under the experimental conditions.

Specifically, irrigation regimes significantly affected total tillers (MSS = 474.7219), effective tillers (334.1326), grains per spike (64.4664), spike length (0.7134), test weight (72.8639), grain yield (1,155,030.19), straw yield (832,105.10) and biological yield (3,947,634.76), while nitrogen scheduling recorded comparable significant effects with mean sum of squares of 431.3361, 288.9363, 58.5669, 0.7317, 73.6569, 1,220,700.00, 807,393.00 and 3,998,613.00 for the respective traits. Harvest index was also significantly influenced by irrigation regimes (7.2571) and nitrogen scheduling (8.7129). The absence of significant irrigation × nitrogen interaction for all yield attributes and yield parameters indicated that the response of wheat to irrigation regimes was consistent across different nitrogen scheduling treatments and vice versa. Overall, the ANOVA clearly demonstrated that both irrigation regimes and nitrogen scheduling independently played a decisive role in improving yield attributes and final productivity of wheat, while their combined interaction did not produce any additional significant effect under the prevailing experimental conditions (Table 1).

Effect of irrigation regimes and nitrogen scheduling on yield

Grain yield

Irrigation regimes

The data presented in (Table 2 and Fig. 1) revealed that irrigation regimes significantly influenced the grain yield of wheat. Among the irrigation treatments, I_3 (5 irrigations) recorded the highest grain yield (4461 kg ha^{-1}), which was significantly superior to the remaining treatments. The lowest grain yield (3749 kg ha^{-1}) was obtained under I_1 (3 irrigations). Treatment I_3 increased grain yield by 18.99% and 10.48% over I_1 and I_2, respectively.

Nitrogen scheduling

Nitrogen scheduling also exerted a significant effect on grain yield (Table 2 and Fig. 1). The highest grain yield (4476 kg ha^{-1}) was recorded under N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage), which proved significantly superior to N_1 and N_2. The minimum grain yield (3746 kg ha^{-1}) was recorded under N_1 (50% at basal + 50% at CRI). Application of N_3 enhanced grain yield by 19.49% and 11.18% over N_1 and N_2, respectively.

Straw yield

Irrigation regimes

The data presented in (Table 2 and Fig. 1) indicated that irrigation regimes significantly affected straw yield. The treatment I_3 (5 irrigations) produced the highest straw yield (6392 kg ha^{-1}), which was significantly superior to the remaining irrigation treatments. The lowest straw yield (5786 kg ha^{-1}) was recorded under I_1 (3 irrigations). The increase in straw yield under I_3 was 10.47% and 5.83% over I_1 and I_2, respectively.

Nitrogen scheduling

Nitrogen scheduling significantly influenced straw yield (Table 2 and Fig. 1). The maximum straw yield (6374 kg ha^{-1}) was recorded under N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage), whereas the minimum straw yield (5775 kg ha^{-1}) was obtained under N_1 (50% at basal + 50% at CRI). The increase in straw yield under N_3 was 10.37% and 5.03% over N_1 and N_2, respectively.

Biological yield

Irrigation regimes

An examination of the data (Table 2 and Fig. 1) showed that biological yield was significantly influenced by irrigation regimes. The treatment I_3 (5 irrigations) recorded the highest biological yield (10853 kg ha^{-1}), which was significantly superior to the remaining treatments. The lowest biological yield (9535 kg ha^{-1}) was observed under I_1 (3 irrigations). The increase in biological yield under I_3 was 13.82% and 7.69% over I_1 and I_2, respectively.

Nitrogen scheduling

Nitrogen scheduling also significantly affected biological yield (Table 2 and Fig. 1). The highest biological yield (10850 kg ha^{-1}) was recorded under N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage), which proved significantly superior to N_1 and N_2. The lowest biological yield (9521 kg ha^{-1}) was recorded under N_1 (50% at basal + 50% at CRI). The increase in biological yield under N_3 was 13.96% and 7.48% over N_1 and N_2, respectively.

Harvest index

Irrigation regimes

The data presented in (Table 2 and Fig. 1) indicated that irrigation regimes did not exert a significant influence on harvest index. Numerically, the highest harvest index (41.06%) was recorded under I_3 (5 irrigations), followed by I_2 (40.03%), while the lowest harvest index (39.27%) was observed under I_1 (3 irrigations). However, the differences among irrigation treatments were statistically non-significant.

Nitrogen scheduling
Similarly, nitrogen scheduling did not significantly influence harvest index (Table 2 and Fig. 1). Although the maximum harvest index (41.21%) was recorded under N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage) and the minimum (39.31%) under N_1 (50% at basal + 50% at CRI), the differences among nitrogen scheduling treatments were statistically non-significant.
This result section follows the same style and flow as Article 1, making the second manuscript consistent in presentation.

Effect of irrigation regimes and nitrogen scheduling on yield attributing traits
Total tillers per plant
Irrigation regimes
The data presented in (Table 3 and Fig. 2) revealed that irrigation regimes significantly influenced the total tillers per plant of wheat. The maximum number of total tillers per plant (4.80) was recorded under I_3 (5 irrigations), which was significantly superior to the remaining irrigation treatments. The minimum number of total tillers per plant (3.20) was observed under I_1 (3 irrigations). The increase in total tillers per plant under I_3 was 50.00 and 17.07% over I_1 and I_2, respectively.
Nitrogen scheduling
The data further indicated that nitrogen scheduling significantly affected the total tillers per plant of wheat (Table 3 and Fig. 2). Application of nitrogen in three equal splits, N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage), recorded the highest number of total tillers per plant (4.60), which was significantly superior to N_1 and N_2. The lowest number of total tillers per plant (3.50) was recorded under N_1 (50% at basal + 50% at CRI). The increase in total tillers per plant under N_3 was 31.43 and 6.98% over N_1 and N_2, respectively.

Effective tillers
Irrigation regimes
An examination of the data (Table 3 and Fig. 2) showed that irrigation regimes significantly influenced the number of effective tillers at harvest. The treatment I_3 (5 irrigations) produced the highest number of effective tillers (72.92 m^{-2}), which was significantly superior to the other irrigation treatments. The lowest number of effective tillers (60.75 m^{-2}) was recorded under I_1 (3 irrigations). The increase in effective tillers under I_3 was 20.03 and 9.85% over I_1 and I_2, respectively.
Nitrogen scheduling
Nitrogen scheduling also exerted a significant effect on the number of effective tillers (Table 3 and Fig. 2). The treatment N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage) recorded the maximum number of effective tillers (72.61 m^{-2}) and proved significantly superior to N_1 and N_2. The minimum number of effective tillers (61.32 m^{-2}) was observed under N_1 (50% at basal + 50% at CRI). The increase in effective tillers under N_3 was 18.41 and 9.82% over N_1 and N_2, respectively.

Number of grains per spike
Irrigation regimes
The data presented in (Table 3 and Fig. 2) indicated that irrigation regimes significantly influenced the number of grains per spike. The significantly highest number of grains per spike (40.22) was recorded under I_3 (5 irrigations), which proved superior to the remaining irrigation treatments. The lowest number of grains per spike (34.92) was observed under I_1 (3 irrigations). The increase in the number of grains per spike under I_3 was 15.18 and 8.82% over I_1 and I_2, respectively.
Nitrogen scheduling
Application of nitrogen scheduling significantly increased the number of grains per spike (Table 3 and Fig. 2). The treatment N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage) recorded the highest number of grains per spike (40.15), which was significantly superior to N_1 and N_2. The minimum number of grains per spike (35.14) was recorded under N_1 (50% at basal + 50% at CRI). The increase in the number of grains per spike under N_3 was 14.26 and 9.07% over N_1 and N_2, respectively.

Spike length
Irrigation regimes
The data presented in (Table 3 and Fig. 2) revealed that spike length was significantly influenced by irrigation regimes. The longest spikes (8.25 cm) were recorded under I_3 (5 irrigations), which remained significantly superior to the remaining treatments. The shortest spike length (7.69 cm) was observed under I_1 (3 irrigations). The increase in spike length under I_3 was 7.28 and 3.77% over I_1 and I_2, respectively.
Nitrogen scheduling
Nitrogen scheduling also significantly affected spike length (Table 3 and Fig. 2). The treatment N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage) produced the maximum spike length (8.25 cm), which was significantly superior to N_1 and N_2. The minimum spike length (7.68 cm) was recorded under N_1 (50% at basal + 50% at CRI). Application of N_3 increased spike length by 7.42 and 3.77% over N_1 and N_2, respectively.

Test weight
Irrigation regimes
The data presented in (Table 3 and Fig. 2) 1 indicated that irrigation regimes significantly influenced the test weight of wheat. The highest test weight (44.41 g) was recorded under I_3 (5 irrigations), which was significantly superior to the

remaining treatments. The lowest test weight (38.74 g) was observed under I_1 (3 irrigations). The increase in test weight under I_3 was 14.64 and 5.64% over I_1 and I_2, respectively.

Nitrogen scheduling

Nitrogen scheduling significantly improved the test weight of wheat (Table 3 and Fig. 2). The treatment N_3 (33.33% at basal + 33.33% at CRI + 33.33% at jointing stage) recorded the maximum test weight (44.48 g) and remained significantly superior to N_1 and N_2. The minimum test weight (38.77 g) was recorded under N_1 (50% at basal + 50% at CRI). The increase in test weight under N_3 was 14.73 and 6.06% over N_1 and N_2, respectively.

DISCUSSION

Effect of irrigation regimes on yield attributes and yield

Yield attributes are the principal determinants of grain productivity, as they represent the cumulative expression of crop growth, assimilate partitioning and reproductive efficiency throughout the growing season. In the present investigation, irrigation regimes significantly influenced total tillers per plant, effective tillers, number of grains per spike, spike length and test weight, which consequently resulted in higher grain, straw and biological yields under the five-irrigation treatment (I_3). These findings indicate that maintaining adequate soil moisture throughout the critical phenological stages favoured reproductive development and enhanced sink capacity, thereby improving overall crop productivity. The superior performance of I_3 may be attributed to the availability of adequate soil moisture during crown root initiation (CRI), jointing, booting, flowering and grain filling stages, which are highly sensitive to moisture stress. Adequate irrigation during these stages enhances nutrient uptake, maintains higher leaf water potential and prolongs photosynthetic activity, thereby increasing assimilate production and translocation towards developing spikes. Similar observations were reported by Jayanthi et al. (2002), who observed significant improvement in wheat yield components under optimum irrigation scheduling. Ghosh et al. (2003) also reported that frequent irrigation enhanced spike development and grain formation by maintaining favourable soil moisture throughout crop growth.

The higher number of total and effective tillers recorded under five irrigations may be associated with improved survival of secondary tillers due to uninterrupted moisture availability. Adequate soil moisture maintains chlorophyll content, delays leaf senescence and prolongs the functional duration of the photosynthetic canopy, thereby increasing assimilate availability for reproductive growth. Chaplot and Sumeriyan (2013) similarly observed that optimum irrigation significantly increased productive tillers by reducing moisture stress during the vegetative stage. Likewise, Bikrmaditya et al. (2011) attributed increased tillering under higher irrigation levels to improved physiological activity and enhanced nutrient uptake resulting from favourable soil moisture conditions. The significant improvement in grains per spike and spike length under I_3 may be explained by better spike differentiation and reduced floret abortion resulting from adequate water availability during reproductive development. Sufficient moisture during spike emergence and flowering promotes pollen viability, fertilization and grain setting, thereby increasing grain number per spike. Similar conclusions were drawn by Yadav et al. (2009), who reported that irrigation at critical crop growth stages significantly enhanced spike fertility and grain number in wheat. Nayak et al. (2015) also observed that optimum irrigation improved spike length and grains per spike by enhancing assimilate partitioning towards reproductive organs.

The increase in test weight under higher irrigation frequency indicates improved grain filling resulting from uninterrupted translocation of photosynthates during the grain development period. Test weight reflects grain size and density and depends largely on the duration and rate of grain filling, both of which are strongly influenced by soil moisture availability. Singh (2003) reported that adequate irrigation during grain filling increased grain size and density through efficient carbohydrate accumulation in developing grains. Consequently, improvements in effective tillers, grains per spike, spike length and test weight collectively contributed to significantly higher grain, straw and biological yields under I_3 compared with lower irrigation levels. Similar findings have also been reported by Jayanthi et al. (2002), Ghosh et al. (2003), Bikrmaditya et al. (2011), Chaplot and Sumeriyan (2013) and Nayak et al. (2015), who consistently observed that increasing irrigation frequency significantly enhanced wheat productivity through improvements in yield-contributing characters.

Effect of nitrogen scheduling on yield attributes and yield

Nitrogen scheduling significantly influenced all major yield attributes and yield parameters of wheat, demonstrating the importance of synchronizing nitrogen availability with crop demand. The application of nitrogen in three equal splits at basal, crown root initiation (CRI) and jointing stages (N_3) consistently produced the highest total tillers, effective tillers, grains per spike, spike length and test weight, which ultimately resulted in greater grain, straw and biological yields than the remaining nitrogen schedules. The superior performance of N_3 may be attributed to the continuous availability of nitrogen throughout the active vegetative and reproductive phases of crop growth. Continuous nutrient supply during successive growth stages promotes chlorophyll synthesis, enzymatic activity and photosynthetic efficiency, thereby supporting vigorous plant growth and improved reproductive development. Similar findings were reported by Kumawat et al. (2021), who observed that split nitrogen application maintained a continuous nutrient supply throughout crop development, resulting in enhanced plant vigour and photosynthetic efficiency.

The significant increase in total tillers, effective tillers and grains per spike under N_3 indicates that sustained nitrogen availability promoted tiller initiation, tiller survival and reproductive development rather than merely increasing grain number per spike. Continuous nitrogen availability during vegetative growth enhances canopy development and photosynthetic efficiency, thereby increasing assimilate production and supporting greater sink development. Consequently, higher assimilate availability improved spike differentiation and grain formation, leading to enhanced yield attributes and final productivity. The improvements in spike length and test weight under N_3 may be attributed to better source–sink relationships resulting from balanced nutrient availability throughout the crop growth period. Continuous

nitrogen supply delayed leaf senescence, prolonged canopy photosynthetic activity and improved assimilate translocation towards developing grains, thereby enhancing grain filling and grain weight. Similar observations were reported by Choudhary et al. (2017), who observed significant improvements in spike characteristics under optimum nutrient management. Likewise, Singh et al. (2018) reported that balanced nutrient availability enhanced spike development and grain filling by improving assimilate production and partitioning during reproductive growth.
The significant increase in grain, straw and biological yields under N_3 can therefore be considered the cumulative effect of improved yield attributes together with enhanced vegetative growth and efficient nutrient utilization. Continuous nutrient availability promoted better root development and efficient absorption of nutrients throughout the growing season, resulting in higher photosynthate production and greater translocation from source to sink. Kumawat et al. (2021) similarly attributed higher grain and straw yields to continuous nutrient availability during critical growth stages. The increased straw yield observed under N_3 may also be associated with enhanced vegetative growth and effective utilization of absorbed nutrients through a well-developed root system, as reported by Choudhary et al. (2017). Comparable findings were also reported by Singh et al. (2018) and Kumari et al. (2022c), who observed significant improvements in biomass production and yield under balanced and properly scheduled nutrient application.

CONCLUSION

The present study demonstrated that both irrigation regimes and nitrogen scheduling substantially influenced the yield attributes and productivity of wheat under semi-arid conditions. Scheduling five irrigations created favourable soil moisture conditions that enhanced the development of productive tillers, grains per spike, spike length and test weight, which collectively contributed to higher grain, straw and biological yields. Likewise, application of nitrogen in three equal splits at basal, crown root initiation (CRI) and jointing stages ensured a continuous nutrient supply throughout the crop growth period, resulting in improved reproductive development and superior yield performance. Although harvest index remained unaffected, the significant improvement in yield-contributing characters translated into enhanced overall productivity. The non-significant interaction between irrigation regimes and nitrogen scheduling indicated that both factors independently contributed to yield improvement. Therefore, adopting five irrigations in combination with three equal split applications of nitrogen can be considered an effective agronomic strategy for maximizing wheat productivity under semi-arid environments. Further multi-location and multi-season investigations are recommended to validate the consistency and wider applicability of these management practices under diverse agro-climatic conditions.\

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Table 1. Combined analysis of variance (mean sum of squares) for yield attributes and yield of wheat as influenced by irrigation regimes and nitrogen scheduling

Source of variation	**d. f.**	**Total tillers**	**Effective tillers**	**Grains spike^{-1}**	**Spike length (cm)**	**Test weight (g)**	**Grain yield (kg ha^{-1})**	**Straw yield (kg ha^{-1})**	**Biological yield (kg ha^{-1})**	**Harvest index (%)**
Replication (R)	2	24.0563	11.1230	4.7763	0.1230	2.7952	87072.1463	371303.7019	887161.4797	4.6497
Irrigation regimes (I)	2	474.7219**	334.1326**	64.4664**	0.7134**	72.8639**	1155030.1902**	832105.1017**	3947634.7574**	7.2571
Error (a)	4	27.9455	13.3788	5.7255	0.1455	3.7177	73457.2155	117952.4377	433870.2155	10.3522
Nitrogen scheduling (N)	2	431.3361**	288.9363**	58.5669**	0.7317**	73.6569**	1220700.0000**	807393.0000**	3998613.0000**	8.7129
I × N	4	0.90314	0.80412	0.10015	0.00031	0.11415	3132.92985	674.74630	6693.23841	0.00015
Error (b)	12	26.7493	12.7937	5.6293	0.1048	2.8271	58418.3160	73424.9826	200469.4271	5.3515

Note: Significant at P ≤ 0.05.

Table 2. Effect of irrigation regimes and nitrogen scheduling on grain yield, straw yield, biological yield and harvest index of wheat

Treatments	**Grain yield (kg ha^{-1})**	**Straw yield (kg ha^{-1})**	**Biological yield (kg ha^{-1})**	**Harvest index (%)**
Irrigation regimes				
I_1 – 3 irrigations	3749	5786	9535	39.27
I_2 – 4 irrigations	4038	6040	10078	40.03
I_3 – 5 irrigations	4461	6392	10853	41.06
SEm±	90	114	220	1.07
CD (P = 0.05)	355	450	862	NS
CV (%)	6.64	5.66	6.49	8.02
Nitrogen scheduling				
N_1 – 50% basal + 50% at CRI	3746	5775	9521	39.31
N_2 – 50% basal + 25% at CRI + 25% at jointing stage	4026	6069	10095	39.84
N_3 – 33.33% basal + 33.33% at CRI + 33.33% at jointing stage	4476	6374	10850	41.21
SEm±	81	90	149	0.77
CD (P = 0.05)	248	278	460	NS
CV (%)	5.92	4.46	4.41	5.77

Note: CRI = Crown Root Initiation; NS = Non-significant.

Table 3. Effect of irrigation regimes and nitrogen scheduling on yield attributes of wheat

Treatments	**Total tillers plant^{-1}**	**Effective tillers m^{-2}**	**Grains spike^{-1}**	**Spike length (cm)**	**Test weight (g)**
Irrigation regimes					
I_1 – 3 irrigations	3.20	60.75	34.92	7.69	38.74
I_2 – 4 irrigations	4.10	66.38	36.96	7.95	42.04
I_3 – 5 irrigations	4.80	72.92	40.22	8.25	44.41
SEm±	0.15	1.22	0.80	0.13	0.64
CD (P = 0.05)	0.43	4.79	3.13	0.50	2.52
CV (%)	6.20	5.49	6.40	4.79	4.62
Nitrogen scheduling					
N_1 – 50% basal + 50% at CRI	3.50	61.32	35.14	7.68	38.77

N_2 – 50% basal + 25% at CRI + 25% at jointing stage	4.30	66.12	36.81	7.95	41.94
N_3 – 33.33% basal + 33.33% at CRI + 33.33% at jointing stage	4.60	72.61	40.15	8.25	44.48
SEm±	0.12	1.19	0.79	0.11	0.56
CD (P = 0.05)	0.35	3.67	2.44	0.33	1.73
CV (%)	5.80	5.36	6.35	4.07	4.03

Note: CRI = Crown Root Initiation. Values of SEm±, CD (P = 0.05), and CV (%) are presented separately for irrigation regimes and nitrogen scheduling as per the split-plot design analysis.