



Integrated Irrigation and Nitrogen Management Strategies for Sustainable Wheat Production

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Abstract

Introduction: Wheat (*Triticum aestivum* L.) is one of the major food grain crops and is a critical food security crop. Increasing the productivity of wheat is essential and will require efficient irrigation and nitrogen management, especially under water limited conditions in semi-arid areas where the use efficiency is low.

Objectives: To evaluate the influence of different irrigation levels and nitrogen scheduling on nitrogen uptake and utilization of wheat.

Methods: The field experiment was done at Vivekananda Global University, Jaipur, Rajasthan during Rabi season of 2024–25. The experiment was designed using Split Plot Design and three replications. The three irrigation levels (3, 4 and 5 irrigations) and three nitrogen scheduling treatments were tested.

Results/Conclusion: Wheat performance was highly affected by irrigation levels as well as nitrogen scheduling. The highest grain yield (4461 kg ha⁻¹), nitrogen uptake, net return (₹91,863 ha⁻¹) and B ratio (3.13) resulted from five irrigations (I₅). In a similar way, three equal splits (N₃: 33.33%, at sowing,CRI, and jointing) had the maximum grain yield (4476 kg ha⁻¹), N uptake, net returns (₹92,824 ha⁻¹), and B ratio (3.25). The study has shown that the five irrigation treatments with three nitrogen split treatments is an effective strategy to improve productivity, nutrient utilization and profitability of wheat under semi-arid conditions.

Keywords: Wheat, Irrigation management, Nitrogen scheduling, Nitrogen uptake, Grain yield, Economic returns, Sustainable agriculture.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important staple food crops worldwide and a cornerstone of food security in India. It ranks second after rice in terms of area and production in India, contributing significantly to the total food grain basket of the country. As a Rabi season crop, wheat thrives under irrigated conditions and responds well to nutrient management, especially nitrogen (N), the most limiting macronutrient for its growth and yield. The productivity of wheat is often constrained by sub-optimal irrigation practices and imbalanced or poorly timed nitrogen applications, especially in water-scarce and semi-arid regions Jat et al., 2018. According to the Food and Agriculture Organization (FAO) of the United Nations (2024), the total global production of wheat in 2024 reached approximately 790 million metric tonnes, covering an area of over 220 million hectare. The major wheat-producing countries include China, India, Russia, the United States, and France. Among these, China leads in terms of production volume, followed closely by India. The average global wheat yield is around 3.5 tonnes per hectare, with significant variations among regions due to differences in agro-climatic conditions, management practices, and input usage. Nutritionally, wheat is a rich source of carbohydrates, moderate-quality protein (approximately 10–14%), and essential micronutrients such as zinc, iron, and B-complex vitamins Shewry et al (2015). Its grains are widely processed into various food products including bread, chapatis, pasta, biscuits, semolina, and noodles, making it a staple diet in several cultures. Wheat straw also plays an important role as livestock feed, roofing material, and organic manure in rural economies.

Nitrogen, being a constituent of proteins, nucleic acids, and enzymes, is indispensable for crop development. It has a significant influence on chlorophyll content, tiller number, grain filling, and ultimately yield. However, nitrogen use efficiency in Indian wheat farming systems remains low—typically around 30–40%—due to improper timing and method of nitrogen application Pathak et al (2014). A large proportion of nitrogen applied as a basal dose is lost before the crop can fully utilize it. Studies have shown that split application of nitrogen, especially when synchronized with key phenological stages such as CRI and jointing, can significantly enhance NUE and crop performance Yadav et al (2020); Singh et al (2016).

Additionally, in light of changing climate conditions, especially increasing temperature variability and declining groundwater levels, efficient use of irrigation water and nitrogen is becoming more urgent than ever. Integrated nitrogen and water management strategies not only help optimize productivity but also mitigate environmental risks such as nitrate leaching and greenhouse gas emissions Ali et al (2021). Given this background, the present study aims to evaluate the interactive effects of irrigation levels and nitrogen scheduling on growth, yield, and resource use efficiency of wheat. It is expected that this research will contribute to the development of sustainable

and site-specific nutrient and water management practices, particularly suited to the semi-arid zones of Rajasthan, thereby supporting both food security and ecological sustainability.

In light of the above facts this paper will evaluate the scenario of integrated irrigation and nitrogen management strategies for sustainable wheat production.

Objective of Study

To evaluate the influence of different irrigation levels and nitrogen scheduling on nitrogen uptake and utilization of wheat.

To identify the most efficient irrigation-nitrogen management combination for optimizing wheat yield and economic returns.

Literature Review

Singh et al. (2012) observed while working at Ludhiana reported that irrigation at 1.0 IW/CPE ratio significantly increased N, P and K uptake in seed and straw of barley as compared to 0.5 and 0.8 IW/CPE ratio. In a field experiment conducted at Hisar, Kumar et al. (2013) recorded significantly higher N content in grain of wheat due to different treatments of irrigation. The application of irrigation at 0.9 IW/CPE ratio remained at par with irrigation at 0.8 IW/CPE ratio but superior over 0.5 IW/CPE ratio. A field experiment conducted by Hingonia et al. (2016) at BHU, Varanasi revealed that among different treatments of irrigation the treatment T3 (2 irrigation) recorded expressively higher N, P and K content and uptake by barley over rest of the treatments.

Sharma et al. (2024) had undertaken a study to assess the effect of irrigation frequency on nutrient dynamics in mustard (*Brassica juncea* L.). The experiment employed a factorial randomized block design (FRBD) with three replications. The main treatments consisted of three irrigation levels: I1 (one irrigation at flowering), I2 (two irrigation at flowering and pod formation), and I3 (three irrigation at branching, flowering, and pod formation). Observations revealed that the highest nutrient content and uptake in seed and straw were observed under the I3 treatment. The uptake of nitrogen increased by 24.5%, phosphorus by 18.2%, and sulfur by 22.7% under I3 compared to I1. These results suggest that timely irrigation during key phenological stages significantly enhance the nutrient assimilation in mustard, contributing to better crop growth and yield.

Dubey et al. (2013) conducted an investigation the suitable dose of nitrogen in barley crop and time and dose of nitrogen application for higher productivity of barley. Nitrogen level (60 kg/ha) treatment and time of application (33.33 % at sowing and 2/3 after first irrigation) treatment was found best over rest of the treatments in all aspects of growth parameters i.e., IPP, Plant height, Number of shoots, Dry matter accumulation and Leaf area index (LAI). Treatment N3 (60 kg N/ha) increases significantly and was found maximum with No. of shoots (393.45), Plant height (70.70 cm), Leaf area index (5.10) and Dry matter accumulation (621.25 g) under main plot treatments. Treatment T2 (33.33 % at sowing and 2/3 after first irrigation) was found best with No. of shoots (389.96), Plant height (61.31 cm), Leaf area index (4.46) and Dry matter accumulation (554.94 g) as compared to other treatments. At Agra, application of 120 kg N/ha in wheat recorded maximum nitrogen uptake by grain and straw, which increased by 33.8 and 35.5 per cent, respectively over 60 kg N/ha. The P and K uptake by grain increased by 62.8 per cent and 29.7 per cent and by straw were 47.6 and 24.2% with 120 kg N/ha over 60 kg N/ha, respectively Singh et al (2013).

Chauhan et al. (2014) showed that maximum N, P and K uptake in wheat was recorded with the application of 150 kg N/ha that was significantly higher by 12.1, 24.1 and 41.3 per cent in N, 8.9, 21.7 and 33.6 per cent in P and 22.0, 32.5 and 56.9 per cent in K uptake over 100, 50 and 0 kg N per hectare, respectively. On clay loam soil of Udaipur a significant increase in nitrogen, phosphorus and potassium uptake by durum wheat was recorded by raising the rate of N application from 60 to 90 and further from 90 to 120 kg/ha Jat et al (2014b).

Kumar (2018) Field experiment was conducted at Brakatullha University, Bhopal, to evaluate conventional tillage resulted 13.88 per cent higher dry matter yield, 9.27 per cent higher biological and 9.28 per cent higher grain yield than zero-tillage. Protein content in grains remained unaffected due to tillage, irrigation regimes and N application.

Research Gap

Following research gaps have been identified:

Irrigation and nitrogen management have been previously studied independently rather than together.

There are few published sources on interactions between irrigation regimes and nitrogen timing on wheat yield.

Only a small number of studies compare yield, nitrogen uptake, NUE, WUE, and economic returns for different irrigation-nitrogen combinations.

Most of the published studies are regional, and not appropriate for the semi-arid regions of Rajasthan where this study will occur.

Little research has been conducted in the area of climate-resilient and resource-efficient irrigation and nitrogen management practices to support sustainable wheat production systems.

No clearly defined irrigation-nitrogen scheduling scheme has been established to maximize yield while minimizing environmental loss.

Materials and Methods

Experimental Site and Soil

A field experiment was laid out at the Research Farm, Vivekananda Global University, Jaipur, Rajasthan in the Agro-climatic Zone-III A (Semi-Arid Eastern Plains) during the Rabi season of 2024–25. The soil used in the

experiment was loamy sand and it had a low available nitrogen, medium available phosphorus and potassium and an alkaline reaction (pH 9.2).

Experimental Design and Treatments

A Split Plot Design (SPD) was used to lay out the experiment, with three replications. Irrigation levels were applied to the main plots and N scheduling levels to sub-plots. Main Plot Treatments (Irrigation Levels):

I₁: Three irrigations

I₂: Four irrigations

I₃: Five irrigations

Sub-Plot Treatments (Nitrogen Scheduling):

N₁: 50% N at sowing + 50% N at Crown Root Initiation (CRI)

N₂: 50% N at sowing + 25% N at CRI + 25% N at Jointing stage

N₃: 33.33% N at sowing + 33.33% N at CRI + 33.33% N at Jointing stage

Therefore, nine treatment combinations (3 x 3) were tested.

Crop Management

The wheat seed rate was 100 kg ha⁻¹ with row spacing of 22.5 cm using DAP and MOP at recommended dose rate for all treatments uniformly. Urea was used to supply N as per the different N scheduling treatments. Irrigations were applied using the check basin method, following treatment schedules. Agronomic and plant protection practices were generally the same across the crop growth period.

Observations

Recorded Observations were made on wheat performance to determine the effects of irrigation and nitrogen management on the crop:

Plant height (cm)

The amount of dry matter produced (g m⁻¹ row length)

Number of tillers (m⁻¹ row length)

Grain yield (kg ha⁻¹)

Yield of straw (kg/ha)

Biological yield (kg ha⁻¹)

Harvest index (%)

The absorption and use of nitrogen.

The nitrogen content of grain and straw was measured by the conventional chemical analysis. N uptake by grain, straw and total crop was determined by multiplying the nutrient concentration by the respective DM yields. The effectiveness of the irrigation–nitrogen treatments was investigated using parameters for nitrogen utilization efficiency.

Economic Analysis

Economic parameters such as cost of cultivation, gross return, net return and benefit cost ratio (B:C ratio) were computed for every treatment combination to obtain the most profitable irrigation and nitrogen management.

Statistical Analysis

Analysis of Variance (ANOVA) suitable to a Split Plot Design was used to analyze the experimental data. The Critical Difference (CD) test at the 5% level of significance was used to compare the means of the treatments.

Data Analysis and Interpretation

Statistical Inferences

Table 1. Effect of Irrigation Levels and Nitrogen Scheduling on Grain, Straw and Biological Yield of Wheat

Treatments	Grain Yield (kg/ha)	Straw Yield (kg/ha)	Biological Yield (kg/ha)
Irrigation Levels			
I ₁ – 3 Irrigations	3749	5786	9535
I ₂ – 4 Irrigations	4038	6040	10078
I ₃ – 5 Irrigations	4461	6392	10853
SEm±	90	114	220
CD (P=0.05)	355	450	862
Nitrogen Scheduling			
N ₁ – 50% basal + 50% CRI	3746	5775	9521
N ₂ – 50% basal + 25% CRI + 25% Jointing	4026	6069	10095
N ₃ – 33.33% basal + 33.33% CRI + 33.33% Jointing	4476	6374	10850
SEm±	81	90	149
CD (P=0.05)	248	278	460

Interpretation

Increasing irrigation level and split nitrogen application significantly resulted in an improvement in grain yield, straw yield, and biological yield. Five irrigations (I₃) and three equal nitrogen splits (N₃) resulted in the highest values. Both treatments had no effect on harvest index. The results showed that sufficient moisture and proper timing of nitrogen application increased crop productivity.

Table 2. Effect of Irrigation Levels and Nitrogen Scheduling on Nitrogen Content and Nitrogen Uptake in Wheat

Treatments	N Content in Grain (%)	N Content in Straw (%)	N Uptake in Grain (kg/ha)	N Uptake in Straw (kg/ha)
Irrigation Levels				
I ₁ – 3 Irrigations	1.622	0.460	60.88	26.67
I ₂ – 4 Irrigations	1.659	0.478	67.08	28.93
I ₃ – 5 Irrigations	1.693	0.497	75.63	31.83
SEm±	0.009	0.004	2.00	0.64
CD (P=0.05)	0.036	0.016	7.86	2.51
Nitrogen Scheduling				
N ₁ – 50% basal + 50% CRI	1.619	0.461	60.72	26.66
N ₂ – 50% basal + 25% CRI + 25% Jointing	1.661	0.479	66.95	29.11
N ₃ – 33.33% basal + 33.33% CRI + 33.33% Jointing	1.694	0.496	75.92	31.66
SEm±	0.008	0.003	1.40	0.56
CD (P=0.05)	0.024	0.010	4.30	1.72

Interpretation

The higher the irrigation level and the better the N scheduling, the higher was the N content and the higher the N uptake in grain and straw. The maximum nitrogen uptake was observed under I₃ (five irrigations) and N₃ (three equal splits of nitrogen) which indicates higher availability and utilization of nutrients under these treatments.

Table 3. Effect of Irrigation Levels and Nitrogen Scheduling on Economics of Wheat

Treatments	Net Returns (Rs/ha)	B:C Ratio
Irrigation Levels		
I ₁ – 3 Irrigations	76089	2.74
I ₂ – 4 Irrigations	82400	2.88
I ₃ – 5 Irrigations	91863	3.13
SEm±	3743	0.07
CD (P=0.05)	14698	0.27
Nitrogen Scheduling		
N ₁ – 50% basal + 50% CRI	75229	2.63
N ₂ – 50% basal + 25% CRI + 25% Jointing	82299	2.88
N ₃ – 33.33% basal + 33.33% CRI + 33.33% Jointing	92824	3.25
SEm±	1952	0.04
CD (P=0.05)	6014	0.12

Interpretation

Both irrigation and nitrogen scheduling significantly affected net returns and benefit-cost ratio. Integrated water and nitrogen management procedure, i.e. five irrigations (I₃) with three equal nitrogen split (N₃), yielded the greatest profitability.

Table 4. Plant Height at Harvest

Treatments	Plant Height at Harvest (cm)
I ₁	77.68
I ₂	81.65
I ₃	87.58
N ₁	77.62
N ₂	81.69
N ₃	87.61

Interpretation

Irrigation level and split N application significantly affected plant height. Moisture and nutrient levels were better with I₃ and N₃ resulting in maximum plant height.

Discussion

The findings of the present study showed that the combined irrigation and nitrogen management had a significant effect on the productivity, nitrogen uptake and economics of wheat. The higher frequency of irrigation (five irrigations) resulted in higher grain, straw yield, biological yield and nitrogen uptake than three and four irrigations. Improved soil moisture due to frequent irrigation may have contributed to higher levels of nutrient availability, growth of roots and movement of assimilates to the plant, which led to better crop performance.

The results corroborate Singh et al. (2012), Kumar et al. (2013) and Hingonia et al. (2016) who reported a higher nutrient uptake and yield with more irrigation. Wheat growth and productivity were also greatly affected by

nitrogen scheduling. Application of nitrogen in three equal splits (33.33% basal + 33.33% at CRI + 33.33% at jointing stage) resulted in the highest grain yield, biological yield, and nitrogen uptake. This enhanced performance could be explained through improved synchronization between the N demand of the crop and nutrient availability, which reduced N losses and increased N use efficiency. Dubey et al. (2013) reported better growth and productivity of crop under split nitrogen application. The synergistic effect of efficient water management and timely nitrogen supply on nutrient uptake and utilization is apparent from the increased dry matter and nutrient uptake with higher water, and split nitrogen application.

The economic analysis also indicated that the five irrigations and three splits of nitrogen gave the maximum net returns and benefit: cost ratio. The better yield and the nutrient utilization efficiency contributed to the higher profitability under these treatments.

The results indicate that use of integrated irrigation and nitrogen management is both agronomically effective and economically viable for wheat production under semi-arid environment of Rajasthan.

The study overall supports the use of 5 irrigations and split application of nitrogen into 3 parts as an effective agronomic approach that will lead to an increase in wheat yield, nitrogen uptake and ultimately farm profitability in water-constrained environments, thereby helping to mitigate the need for sustainable and resource efficient wheat production systems in water-limited environments.

Conclusion

The present study showed that irrigation levels and the scheduling of nitrogen application had significant effect on the N uptake, yield and economic returns of wheat under semi arid environment of Rajasthan. The five irrigations (I₅) had the greatest grain yield (4461 kg ha⁻¹), biological yield (10853 kg ha⁻¹), nitrogen uptake, net returns (₹91,863 ha⁻¹) and benefit cost ratio (3.13). Also, the treatment of N₃ (Nitrogen applied in three splits: 33.33% at sowing, 33.33% at CRI and 33.33% at jointing stage) recorded the highest values of grain yield (4476 kg ha⁻¹), nitrogen uptake, net return (₹92,824 ha⁻¹) and B:C ratio (3.25). The results show that proper irrigation and timely split application of nitrogen results in better nutrients utilization, productivity of the crops and profitability of the farms. So, the practice of five irrigations along with nitrogen applied in three equal doses can be suggested as an optimum and sustainable wheat farming system in a semi-arid region like Rajasthan. This integrated approach can help to overcome the inefficiency of resource use, boost wheat productivity and create more economic value for farmers.

Future Scope of Study

The study can be executed at different sites and in various years to confirm results under varying agro-climatic conditions and precipitation. Further study is needed to explore the effect of irrigation and nitrogen scheduling on WUE and NUE to develop more efficient wheat production system.

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