



RESEARCH ARTICLE

Optimising irrigation and zinc management improves wheat yield, quality and resource use-efficiency in the Indo-Gangetic Plains

Pramod Ulhas Lawate^{1,2}, Saroj Kumar Prasad², Manoj Kumar Singh², Achin Kumar^{3*}, Dinesh Jinger⁴,
Prerna Dogra⁵, Kavitha P Jadhav¹, K Rajan¹ & Anusha N M⁶

¹Department of Agronomy, ICAR-Indian Institute of Soil and Water Conservation Regional Centre, Ballari 583 104, Karnataka, India

²Departments of Agronomy, Banaras Hindu University, Varanasi 221 005, Uttar Pradesh, India

³Department of Soil Science, Bihar Agricultural University, Sabour, Bhagalpur 813 210, Bihar, India

⁴Department of Agronomy, ICAR-Indian Institute of Soil and Water Conservation, Regional Centre, Chandigarh 134 114, Haryana, India

⁵Department of Soil Science and Agricultural Chemistry, Sri Karan Narendra Agriculture University, Jobner 303 328, Rajasthan, India

⁶Department of Horticulture, Indian Institute of Soil and Water Conservation Regional Centre, Ballari 583 104, Karnataka, India

*Correspondence email - achinrana1@gmail.com

Received: 25 February 2026; Accepted: 06 July 2026; Available online: Version 1.0: 07 September 2026

Cite this article: Lawate PU, Prasad SK, Singh MK, Kumar A, Jinger D, Dogra P, Jadhav KP, K Rajan, Anusha NM. Optimising irrigation and zinc management improves wheat yield, quality and resource use-efficiency in the Indo-Gangetic Plains. *Plant Science Today*. 2026;13(sp5):01–11. <https://doi.org/10.14719/pst.14238>

Abstract

The Indo-Gangetic plains in India have low wheat productivity and quality due to inadequate irrigation and nutrient management in predominantly zinc (Zn)-deficient soils. To address these challenges, a two-year field experiment was conducted to evaluate the individual and combined effects of irrigation scheduling and Zn application on wheat yield, quality and efficiency indices. The study followed a randomised block design with 3 replications, comprising 4 irrigation schedules based on critical Zadoks growth stages and five Zn application strategies involving basal and foliar treatments. Results showed that in general, among irrigation schedules treatment I₂ (crown root initiation (CRI) + late jointing + milking) enhanced the wheat grain yield (11–12 %), protein content (18.4–18.7 %) and partial factor productivity (15.9–18.2 kg kg⁻¹) during both the years. Among Zn treatment, Zn₄ (10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar sprays at Z45 and Z71) improved the 15–18 % grain yield whereas Zn₂ enhanced 18.7–19.10 % protein content than control (Zn₁). However, the combined effect of I₂ × Zn₄ numerically increased the grain yield by 22–25 %, protein yield (35 %) and various efficiency indices over the control (I₁ × Zn₁) during both years of experimentation. Overall, the synchronised I₂ × Zn₄ treatment emerged as the best agronomic strategy for improving yield, nutritional quality and sustainability of wheat under water-limited conditions. This approach enhanced the productivity, profitability and nutritional security of wheat in the Indo-Gangetic plains. Future research should validate this framework across diverse agro-ecological regions and socio-economic context.

Keywords: irrigation scheduling; wheat productivity; Zadoks scale; zinc management; zinc-use efficiency

Introduction

Wheat (*Triticum aestivum* L.) is a major global staple food crop and plays a critical role in India's food security which holds the largest cultivated area and second highest production worldwide (1). It is a main source of carbohydrates, protein and essential minerals and is regularly consumed by 60–65 % of the population in the Indo-Gangetic Plains of northern India (2, 3). However, since the Green Revolution, yield growth in major wheat systems has stagnated, or declined, largely due to unsustainable agronomic practices, inefficient irrigation and imbalance nutrient management (4). Among the major production constraints, inefficient irrigation scheduling and poor nutrient management are the major constraints for considerable yield losses approximately 30 % and 40 % respectively. Such losses pose a direct threat to sustaining future wheat productivity if not properly addressed (5). Conversely, the precise management of these inputs can improve yields, highlighting the critical need for optimised resource management (6).

Water scarcity driven by over-extraction of groundwater and erratic rainfall pattern is becoming a serious constraint on wheat productivity, even in irrigated regions. Although irrigation coverage in Indian wheat system has expanded considerably, but precise scheduling of water application remains a critical challenge, particularly in semi-arid regions. Previous research showed that irrigation applied at critical growth stages such as tillering, booting and grain filling, is essential for achieving optimum yield and improving water use efficiency (WUE), whereas excessive irrigation may negatively affect grain yield and reduce input use efficiency (7–9). Parallel to irrigation, nutrient management play an important role in determining wheat productivity. Hidden hunger caused by micronutrient deficiencies, especially zinc (Zn), imposes a severe limitation to crop performance and overall nutritional quality.

About 49 % soils of the world and about 48 % in India are Zn deficient, especially calcareous soils under cereal-based cropping system (10–12). Zn is an important micronutrient for plants, animals

and humans and plays a crucial role in enzyme activation, nitrogen metabolism and chlorophyll formation (13, 14). In human, Zn deficiency is widely prevalent among populations reliant on wheat and is associated with weakened immune system and impaired growth (15). Previous studies have reported that foliar application of Zn on post-flowering stage can enhance Zn uptake in crops (16, 17). However, foliar application alone may not provide sufficient or continuous supply throughout the crop growth period, while basal soil application can improve soil Zn reserve and sustained more availability. Recent research between 2020–24 further indicates that the combined use of soil and foliar Zn application can significantly improve both crop yield and Zn uptake (18, 19). Moreover, Zn plays a central role in enhancing drought tolerance by improving antioxidant defense mechanisms and regulating plant water relations (12, 20, 21). Therefore, both Zn nutrition and irrigation management are critical determinants of wheat productivity and grain nutritional quality. Their interaction can substantially influence crop performance, nutrient acquisition and use efficiency under irrigated conditions (22–25)

Although substantial progress has been achieved in irrigation and Zn management strategy individually, information on their combined effects remains limited. In particular, the combined effect of basal and foliar Zn application under phenology-based precise irrigation scheduling (Zadoks scale) on wheat yield, grain nutritional quality, Zn use efficiency indices and economic returns has not been adequately explored (17). Therefore, to address this knowledge gap, the present study was conducted. We hypothesised that the integrated management of irrigation and Zn nutrition would enhance wheat productivity, improve grain quality and increase Zn-use efficiency in resource limiting regions. These findings of this study are expected to develop and validate the sustainable agronomic strategies for future research across different agro-climatic zones.

Materials and Methods

Experimental site and initial soil properties

A two-year field experiment was conducted at the Agricultural Research Farm of Banaras Hindu University, Varanasi, India (25°18' N, 83°03' E; 128 m above mean sea level). The experimental site falls under a semi-arid to sub-humid climatic region. The weather data recorded during the study period are presented in Table 1. The soil of the experimental area was sandy clay loam, neutral in pH (7.40), low in organic carbon (0.33 %) and moderate in fertility. The available nutrients concentration was 213.50 kg N ha⁻¹, 18.50 kg P₂O₅ ha⁻¹, 218.27 kg K₂O ha⁻¹ and 0.48 mg Zn kg⁻¹. The experimental soil was taxonomically classified as Typic Ustochrepts, which is suitable for wheat cultivation.

Experimental details

The experiment was conducted using a randomised block design (RBD) with 3 replications to evaluate the effects of irrigation schedules and Zn fertilisation on wheat. A total of 20 treatment combinations of irrigation and Zn application was tested (Table 2). Irrigation was scheduled at critical growth stages of wheat under 4 treatments. The first irrigation was uniformly applied at the crown root initiation (CRI) stage in all treatments. Thereafter, irrigations were imposed at different phenological stages. Treatment I₁ received irrigations at the late tillering and flowering stages, treatment I₂ at the late jointing and milking stages, treatment I₃ at the flowering and dough stages and treatment I₄ at the milking and dough stages. Thus, 3 irrigations were applied in each treatment during the crop growth period. Five Zn treatments were applied at different Zadoks growth stages. Treatment Zn₁ was the control with no Zn application. Treatment Zn₂ received 5 kg Zn ha⁻¹ as basal along with two foliar sprays of 0.25 % ZnSO₄·7H₂O at Zadoks growth stages Z45 and Z71. Treatment Zn₃ received 5 kg Zn ha⁻¹ as basal along with two foliar sprays of 0.25 % ZnSO₄·7H₂O at Z60 and Z83. Treatment

Table 1. Weather data of experimental site for the wheat growing seasons

Months	Rainfall		Evaporation		Temperature (°C)				Relative Humidity (%)				Sunshine (h)	
	(mm)		(mm)		Monthly minimum		Monthly maximum		Monthly minimum		Monthly maximum			
	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16	2014–15	2015–16
November	0.0	0.0	1.9	2.1	11.9	17.2	27.8	28.4	49.0	53.0	84.0	86.0	7.3	4.3
December	2.8	0.8	1.2	1.4	8.8	10.6	20.7	23.0	55.5	49.5	90.2	89.5	3.8	3.8
January	47.2	7.7	0.8	1.5	10.3	10.1	18.2	22.9	71.4	50.8	91.4	87.4	2.8	4.1
February	0.0	2.4	2.3	2.6	14.1	13.5	25.7	27.5	54.5	51.0	87.0	82.5	5.9	6.9
March	19.8	35.4	3.7	4.0	16.9	17.5	30.6	32.2	41.2	39.2	75.5	67.2	8.3	8.1
April	61.3	0.0	5.2	7.6	22.2	22.9	35.2	40.1	40.7	20.6	65.0	43.3	7.6	8.5

Source: Meteorological cell, Department of Agronomy, Banaras Hindu University. All values of rainfall, evaporation, mean temperature, relative humidity and sunshine duration represent monthly averages

Table 2. Treatments details of experiment

Symbol	Treatment details
Irrigation scheduling	
I ₁	CRI + Late Tillering + Flowering
I ₂	CRI + Late Jointing + Milking
I ₃	CRI + Flowering + Dough
I ₄	CRI + Milking + Dough
Zinc fertilisation	
Zn ₁	0 kg Zn ha ⁻¹ (control)
Zn ₂	5 kg Zn ha ⁻¹ as basal + 0.25% ZnSO ₄ ·7H ₂ O foliar spray at Z 45+ 0.25% at Z71
Zn ₃	5 kg Zn ha ⁻¹ as basal + 0.25% ZnSO ₄ ·7H ₂ O foliar spray at Z 60+ 0.25% at Z83
Zn ₄	10 kg Zn ha ⁻¹ as basal +0.25% ZnSO ₄ ·7H ₂ O foliar spray at Z 45+ 0.25% spray at Z71.
Zn ₅	10 kg Zn ha ⁻¹ as basal +0.25% ZnSO ₄ ·7H ₂ O foliar spray at Z 60+ 0.25% spray at Z83.

Z: Zadoks scale; Z45: Boot swollen; Z 60: Pollination (Anthesis); Z 71: Dough stage; Z83: Early dough.

Zn₄ received 10 kg Zn ha⁻¹ as basal along with two foliar sprays of 0.25 % ZnSO₄·7H₂O at Z45 and Z71, whereas treatment Zn₅ received 10 kg Zn ha⁻¹ as basal along with two foliar sprays of 0.25 % ZnSO₄·7H₂O at Z60 and Z83.

Wheat variety HUW-234 was sown at 120 kg ha⁻¹. Standard agronomic practices, including pre- and post-sowing tillage, were followed. Nitrogen (N), phosphorus (P) and potassium (K) were applied at recommended doses of 150, 60 and 60 kg ha⁻¹ respectively, using urea, diammonium phosphate (DAP) and muriate of potash (MOP). DAP and MOP were applied entirely as basal doses, while urea was applied in split, ½ at sowing and ½ at 30 days after sowing. Irrigation water was applied using a Parshall flume, ensuring a uniform depth of 6 ± 1 cm per event. Although each treatment received 3 irrigations in addition to the common CRI, the timing of application varied according to the treatment. The total applied irrigation water across treatments was approximately 18 ± 3 cm, excluding effective rainfall during both crop growth periods. Zinc was applied both as a basal dose through zinc sulfate monohydrate and as foliar sprays at precise wheat growth stages (Z45-boot swollen; Z60-anthesis; Z71-dough stage and Z83-early dough). Foliar sprays were prepared at 0.25 % ZnSO₄·7H₂O with 0.1 % Tween-20 as a surfactant to ensure uniform leaf coverage and absorption.

Observations recorded

Yield data (kg ha⁻¹)

Biological yield was determined by weighing the sundried and tied bundles of harvested wheat crops after 7 days of harvesting. Each plot was threshed separately with the help of mini thresher. Grains were separated from chaffs and straw and then grain yield was recorded for each plot. Harvest index was computed as a ratio of grain yield to biological yield and calculated in percentage (26).

$$\text{Harvest index (\%)} = \frac{\text{Economic yield (kg ha}^{-1}\text{)}}{\text{Biological yield (kg ha}^{-1}\text{)}} \times 100 \quad (1)$$

Protein content (%) in grain and protein yield (kg ha⁻¹)

Protein content was calculated by multiplying nitrogen content by a factor of 6.25 and protein yield (kg ha⁻¹) was calculated as (27):

$$\text{Protein yield (kg ha}^{-1}\text{)} = \frac{\text{Protein content (\%)} \times \text{Grain yield (kg ha}^{-1}\text{)}}{100} \quad (2)$$

Water productivity (WP)

This was calculated from calculated kg of grain yield produced per hectare to amount of water applied to crop expressed in kg m⁻³.

$$\text{WP} = \frac{\text{Economic (grain/seed) yield (kg ha}^{-1}\text{)}}{\text{Irrigation water applied (cm)}} \quad \text{kg m}^{-3} \quad (3)$$

Zinc content in grain and straw

Zinc content was determined by standard procedure using atomic absorption spectrophotometry and expressed in mg kg⁻¹ (28).

Estimation of Zn use efficiency indices

The Zn use efficiency indices were calculated using the standard

procedures described by (29–31). The following indices were used to assess the efficiency of applied Zn in improving crop productivity and nutrient use efficiency.

Agronomic efficiency (AE): AE represents the increase in grain yield obtained per unit of Zn applied. AE is the effectiveness of fertiliser application in enhancing crop production and is expressed as kg of grain yield produced per kg of Zn applied (kg kg⁻¹) and was calculated using the following equation:

$$\text{Agronomic efficiency (AE) (kg kg}^{-1}\text{)} = \frac{\text{GY}_{\text{Zn}} - \text{GY}_{\text{C}}}{\text{Zn}_{\text{a}}} \quad (4)$$

Physiological efficiency (PE): PE indicates the ability of a plant to convert the absorbed nutrient into economic yield. It is expressed as kg of grain produced per kg of nutrient uptake (kg kg⁻¹) and was calculated using the following equation:

$$\text{Physiological Efficiency (PE) (kg kg}^{-1}\text{)} = \frac{\text{Y}_{\text{Zn}} - \text{Y}_{\text{C}}}{\text{U}_{\text{Zn}} - \text{U}_{\text{C}}} \quad (5)$$

Partial factor productivity (PFP): PFP is an indicator of overall nutrient-use efficiency and represents the amount of grain yield produced per unit of nutrient applied. It is expressed as kg of grain yield produced per kg of nutrient applied (kg kg⁻¹) and was calculated using the following equation:

$$\text{Partial factor productivity (PFP) (kg kg}^{-1}\text{)} = \frac{\text{GY}_{\text{Zn}}}{\text{Zn}_{\text{a}}} \quad (6)$$

Apparent recovery efficiency (ARE): ARE represents the proportion of the applied nutrient that is taken by the crops. It is expressed as percentage (%) and was calculated using the following equation:

$$\text{Apparent recovery efficiency (ARE) (\%)} = \frac{\text{U}_{\text{Zn}} - \text{U}_{\text{C}}}{\text{Zn}_{\text{a}}} \quad (7)$$

where GY_{Zn} is the grain yield of Zn treated plots, GY_C is the yield of untreated plots, Zn_a is the total amount of Zn applied, Y_{Zn} is the grain and straw yield of Zn treated plots, Y_C is the grain and straw yield of untreated plots, U_{Zn} is the Zn uptake in grain and straw of Zn treated plots and U_C is the Zn uptake in grain and straw of untreated plots.

Zinc harvest index (%)

Zinc HI represents the proportion of total zinc accumulated in the above ground plant biomass that is translocated and stored in the grain. It is expressed as percentage (%) and was calculated using the following equation:

$$\text{Zinc harvest index (\%)} = \frac{\text{Zinc uptake in grain (kg ha}^{-1}\text{)}}{\text{Total Zinc uptake in above ground biomass kg ha}^{-1}} \times 100 \quad (8)$$

Economic analysis

The economic viability of different irrigation scheduling and Zn applications, economic analyses were evaluated following the standard procedure (32). Actual grain and straw yield of wheat crops were normalised for more precise evaluation. Seed, fertiliser, plant protection measures, harvesting, threshing and labor costs were considered as fixed costs and remained the same for all treatments. The cost incurred for irrigation and Zn application was included as a variable cost. Net benefit was calculated by deducting gross income from the total cost. The benefit-cost ratio (B : C) was computed by

dividing the gross income by the total cost of cultivation.

Statistical analysis

The data obtained from the experiment were analysed statistically using analysis of variance (ANOVA) technique following the standard procedure (33). Significance of differences among treatments was tested using the standard F-test and mean compared using Duncan's multiple range test (DMRT) to separate treatment means and identify significant differences among them at 5 % significance level ($P \leq 0.05$).

Results

Effect of irrigation scheduling and zinc fertilisation on wheat productivity

The results indicated that both irrigation scheduling and Zn fertilisation had a significant effect ($P \leq 0.05$) on wheat grain yield, straw yield and biological yield, whereas their interaction was significant only for harvest index (Fig. 1). Among the irrigation treatment, I_2 producing the maximum grain yield (2881 and 2962 kg ha^{-1}) and biological yield (7069 and 7176 kg ha^{-1}) during the 1st and 2nd years respectively. It produced about 11 % and 10 % higher grain

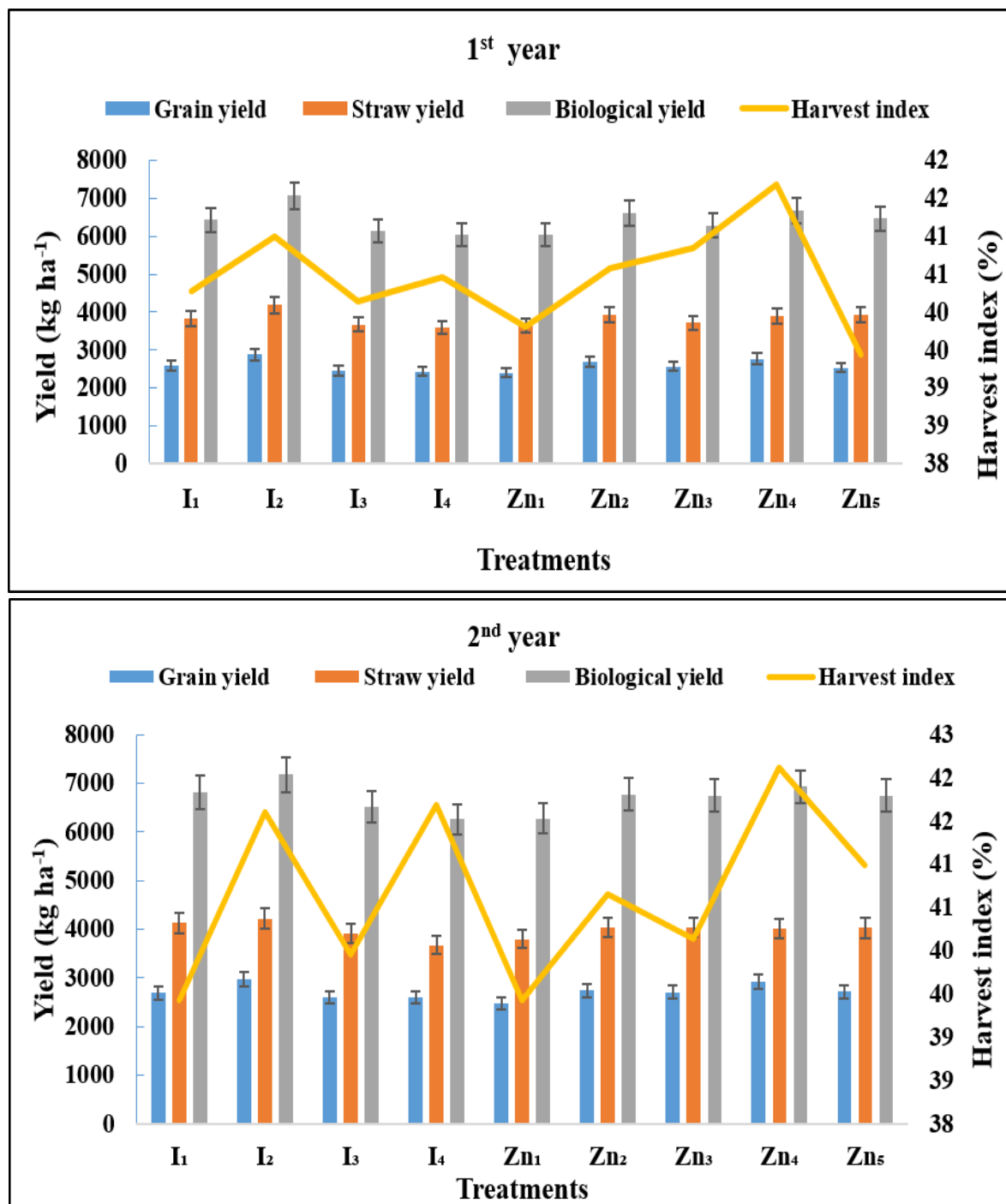


Fig 1. Effect of irrigation scheduling and zinc fertilisation on grain yield, straw yield, biological yield and harvest index of wheat during the 2014–15 and 2015–16 seasons. Error bars indicate LSD at $p \leq 0.05$.

I_1 : CRI + late tillering + flowering, I_2 : CRI + late jointing + milking, I_3 : CRI + flowering + dough, I_4 : CRI + milking + dough, Zn_1 : 0 kg Zn ha^{-1} , Zn_2 : 5 kg Zn ha^{-1} as basal + 0.25 % $ZnSO_4$ foliar spray at Z45 + 0.25 % at Z 71, Zn_3 : 5 kg Zn ha^{-1} as basal + 0.25 % $ZnSO_4$ foliar spray at Z60 + 0.25 % spray at Z83, Zn_4 : 10 kg Zn ha^{-1} as basal + 0.25 % $ZnSO_4$ foliar spray at Z45 + 0.25 % spray at Z71, Zn_5 : 10 kg Zn ha^{-1} as basal + 0.25 % $ZnSO_4$ foliar spray at Z60 + 0.25 % spray at Z83.

yield than I_1 during the 1st and 2nd year respectively. The highest straw yield 4188 kg ha⁻¹ was observed under I_2 in the 1st year, while in the 2nd year differences among treatments were non-significant. Overall, I_2 was significantly superior to I_1 , I_3 and I_4 in most yields' attributes, whereas harvest index (%) showed non-significant across irrigation treatments during both the years. Similarly, Zn application significantly influenced wheat productivity. The Zn_4 treatment produced the maximum grain yield about 2775 and 2913 kg ha⁻¹ in 1st and 2nd years respectively. The grain yield increase in Zn_4 treatment was 15 % and 18 % higher than control (Zn_1) during the 1st and 2nd years, respectively. Straw yield, biological yields and harvest index (%) followed a similar trend but differences among treatments were not statistically significant. However, the combination of $I_2 \times Zn_4$ was gave the highest harvest index (43.68 %) in the 1st year, while no significant interaction effect was observed in 2nd year. Overall, the integration of precise irrigation scheduling at critical growth stages combined with balanced Zn application enhanced wheat productivity.

Effect of irrigation scheduling and Zn fertilisation on protein content and protein yield

The results showed that both irrigation scheduling and zinc fertilisation significantly ($P \leq 0.05$) influenced the protein content, while protein yield was significantly ($P \leq 0.05$) affected only by zinc application, as presented in Table 3. Among irrigation treatment, I_3 produced the highest protein content (11.19 % and 11.40 % during the 1st and 2nd year, respectively). This was, significantly higher than I_1 and I_2 treatments. Protein content under I_3 was about 18 % and 7 % higher than I_1 and I_2 respectively. However, protein yield did not differ significantly among irrigation schedules across both the years. In contrast, Zn fertilisation has a significant effect on both protein content and protein yield compared with control (Zn_1) across both the years. The lowest protein content and protein yield were recorded under Zn_1 , whereas highest protein content was recorded with Zn_2 (10.66 and 10.86 % during the 1st and 2nd year respectively). Although, all zinc treatments (Zn_2 , Zn_3 , Zn_4 and Zn_5) were statistically

at par for protein content across both years. Similarly, the maximum protein yield was recorded under Zn_4 (288.2 and 306.5 kg ha⁻¹ during the 1st and 2nd year, respectively), which was about 35 % higher than Zn_1 across both the years. However, Zn_4 was statistically at par with Zn_2 , Zn_3 and Zn_5 . Overall, these findings suggest that zinc applications improve grain quality and protein production in wheat. However, the interaction effect between $I \times Zn$ was non-significant for both parameters across both the years.

Effect of irrigation scheduling and Zn fertilisation on water productivity

The results indicated that irrigation scheduling and Zn fertilisation had a significant ($P \leq 0.05$) effect on water productivity across both the years, as presented in Table 3. Among the irrigation schedules, treatment I_2 gave the highest water productivity, with value 0.78 and 1.03 kg m⁻³ in 1st and 2nd years respectively. This treatment was significantly superior to the other irrigation schedules. In contrast, I_1 , I_3 and I_4 showed statistically similar responses, showed comparatively lower and almost equal water productivity. Regarding Zn fertilisation, Zn_4 produced the highest water productivity (0.75 and 1.02 kg m⁻³ during 1st and 2nd years respectively), showed a clear advantage over Zn_1 and a moderate superiority over the other zinc levels. The treatment Zn_2 , Zn_3 and Zn_5 were statistically at par showed the moderate Zn application improved water productivity, although the responses were at par. Overall, water productivity was higher in 2nd years than 1st year across all treatments. However, the interaction effect between irrigation scheduling and Zn fertilisation ($I \times Zn$) was non-significant across both the years.

Effect of irrigation scheduling and Zn fertilisation on B:C ratio

The B : C ratio was significantly ($p \leq 0.05$) influenced by irrigation scheduling, while Zn fertilisation did not show any significant effect across both the years, as presented in Table 3. Among the irrigation treatments, I_2 gave the highest B:C ratio (1.89 and 1.91 in the 1st and 2nd years respectively), showed the best economic returns compared with other irrigation schedules. The B : C ratio under I_2 was significantly higher than under I_1 , I_3 and I_4 . In contrast, whereas the

Table 3. Effect of irrigation scheduling and zinc fertilisation on protein content, protein yield and benefit cost ratio

Treatment	Protein content (%)		Protein yield (kg ha ⁻¹)		Water productivity (Kg m ⁻³)		B : C Ratio	
	1 st year	2 nd year	1 st year	2 nd year	1 st year	2 nd year	1 st year	2 nd year
Irrigation scheduling (I)								
I_1	9.43 ^b	9.63 ^b	244.9	259.5	0.70 ^b	0.94 ^b	1.71 ^b	1.78 ^{ab}
I_2	9.88 ^b	10.01 ^b	286.0	298.6	0.78 ^a	1.03 ^a	1.89 ^a	1.91 ^a
I_3	11.19 ^a	11.40 ^a	275.8	296.9	0.66 ^b	0.91 ^b	1.63 ^b	1.71 ^b
I_4	10.45 ^{ab}	10.61 ^{ab}	255.2	277.4	0.66 ^b	0.91 ^b	1.61 ^b	1.67 ^b
SEm±	0.35	0.35	11.5	13.5	0.02	0.03	0.04	0.05
CD (0.05)	1.01	1.00	NS	NS	0.05	0.08	0.12	0.14
Zinc fertilisation (Zn)								
Zn_1	8.95 ^b	9.15 ^b	214.1 ^b	226.6 ^b	0.65 ^c	0.88 ^b	1.67 ^a	1.73 ^a
Zn_2	10.66 ^a	10.86 ^a	286.5 ^a	299.8 ^a	0.72 ^{ab}	0.96 ^{ab}	1.76 ^a	1.79 ^a
Zn_3	10.61 ^a	10.78 ^a	272.6 ^a	291.5 ^a	0.69 ^{bc}	0.95 ^{ab}	1.69 ^a	1.78 ^a
Zn_4	10.40 ^a	10.54 ^a	288.2 ^a	306.5 ^a	0.75 ^a	1.02 ^a	1.76 ^a	1.82 ^a
Zn_5	10.56 ^a	10.73 ^a	266.1 ^a	291.2 ^a	0.68 ^{bc}	0.94 ^{ab}	1.66 ^a	1.72 ^a
SEm±	0.39	0.39	12.9	15.1	0.02	0.03	0.05	0.06
CD (0.05)	1.13	1.11	36.9	43.1	0.06	0.09	NS	NS
$I \times Zn$	NS	NS	NS	NS	NS	NS	NS	NS

I_1 : CRI + late tillering + flowering; I_2 : CRI + late jointing + milking; I_3 : CRI + flowering + dough; I_4 : CRI + milking + dough, Zn_1 : 0 kg Zn ha⁻¹, Zn_2 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % at Z 71, Zn_3 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83, Zn_4 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % spray at Z71, Zn_5 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83. NS: Non-significant. Means followed by different letters within a column differ significantly at $p \leq 0.05$

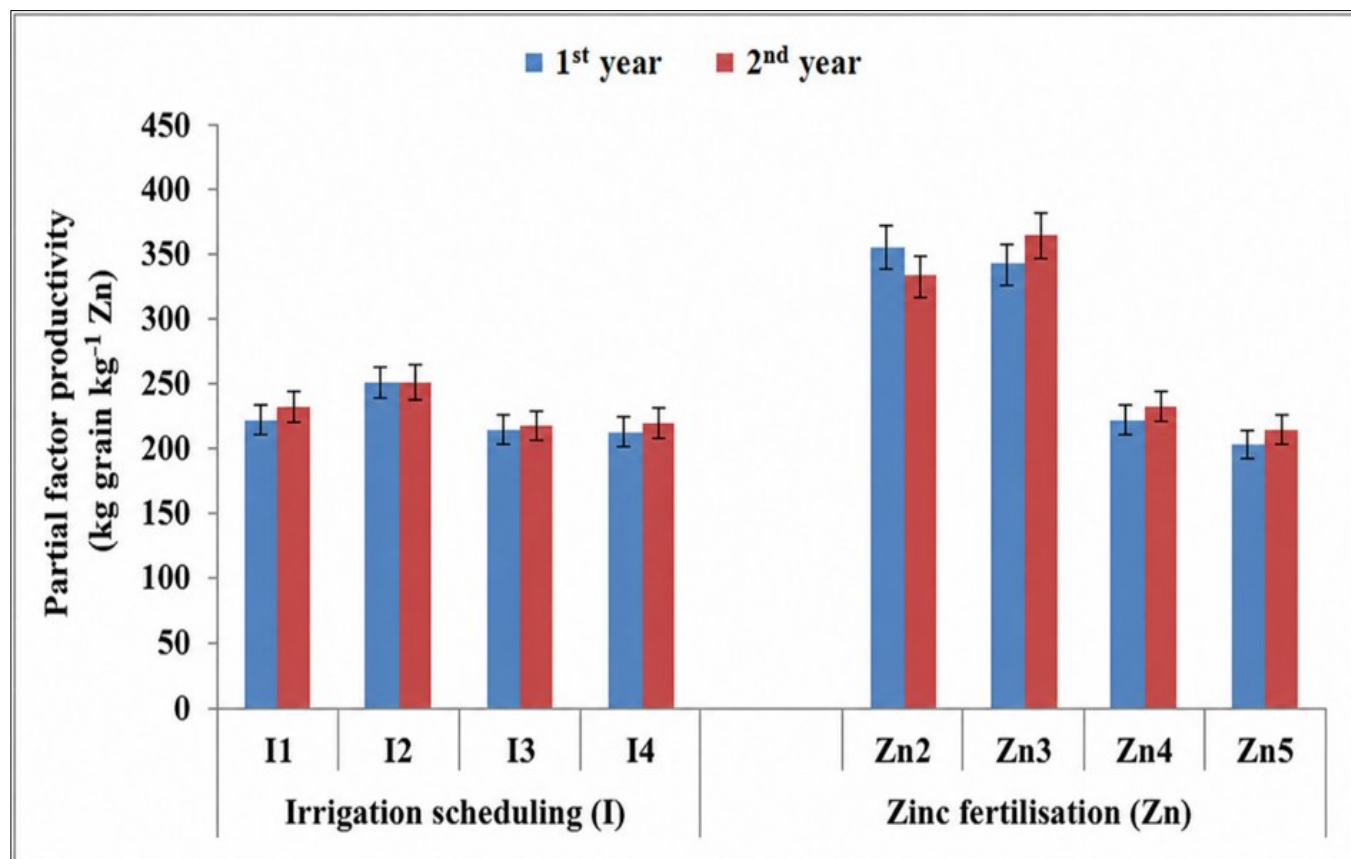


Fig. 2. Effect of irrigation scheduling and zinc fertilisation on partial factor productivity of wheat. Error bars indicate LSD ($p < 0.05$).

I1 : CRI + late tillering + flowering; I2 : CRI + late jointing + milking; I3 : CRI + flowering + dough; I4 : CRI + milking + dough; Zn1 : 0 kg Zn ha⁻¹, Zn2 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % at Z 71, Zn3 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83, Zn4 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % spray at Z71, Zn5 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83.

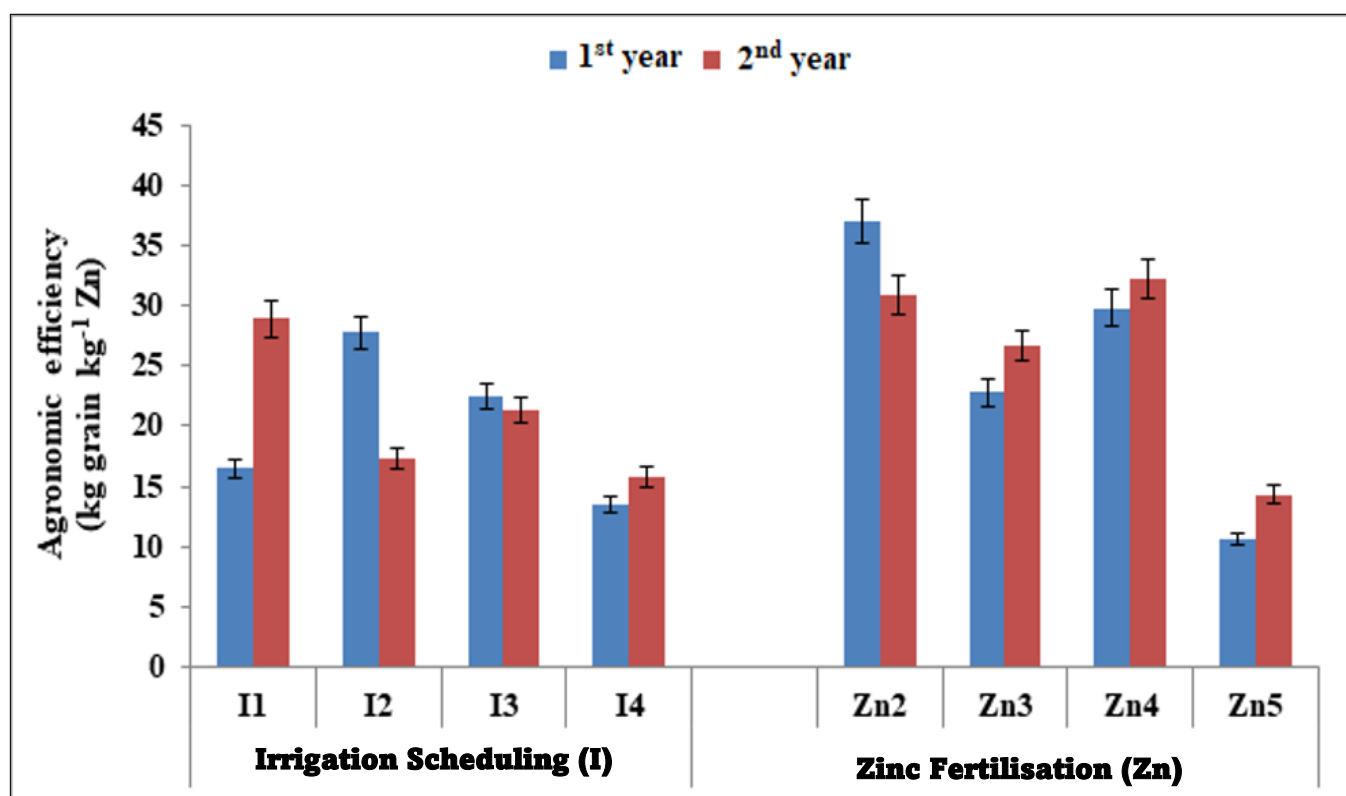


Fig. 3. Effect of irrigation scheduling and zinc fertilisation on agronomic efficiency of wheat.

I1 : CRI + late tillering + flowering, I2 : CRI + late jointing + milking, I3 : CRI + flowering + dough, I4 : CRI + milking + dough, Zn1 : 0 kg Zn ha⁻¹, Zn2 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % at Z 71, Zn3 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83, Zn4 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % spray at Z71, Zn5 : 10 kg Zn ha⁻¹ as basal + 0.25 %

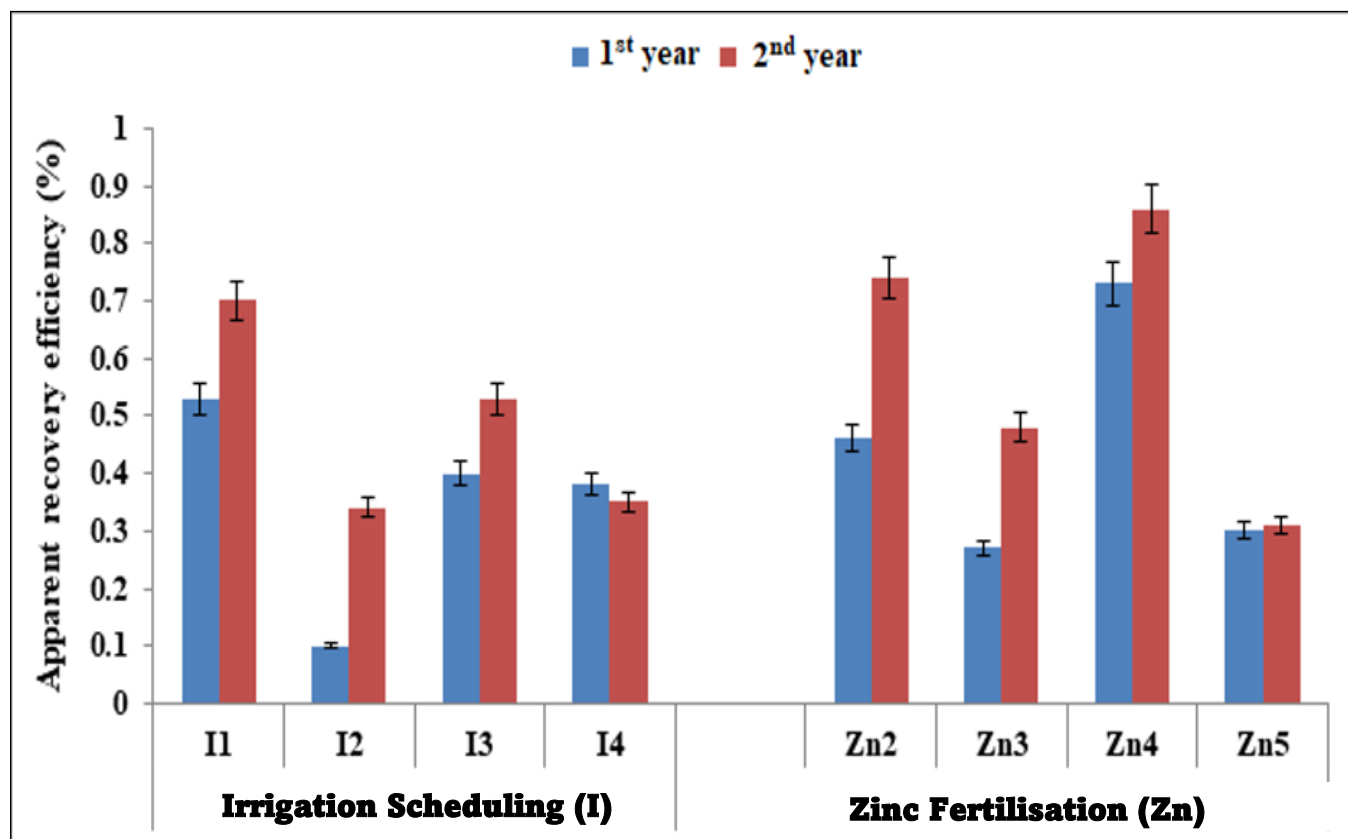


Fig. 4. Effect of irrigation scheduling and zinc fertilisation on apparent recovery efficiency of wheat.

I1 : CRI + late tillering + flowering; I2 : CRI + late jointing + milking; I3 : CRI + flowering + dough; I4 : CRI + milking + dough, Zn1 : 0 kg Zn ha⁻¹, Zn2 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % at Z71, Zn3 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83, Zn4 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % spray at Z71, Zn5 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83.

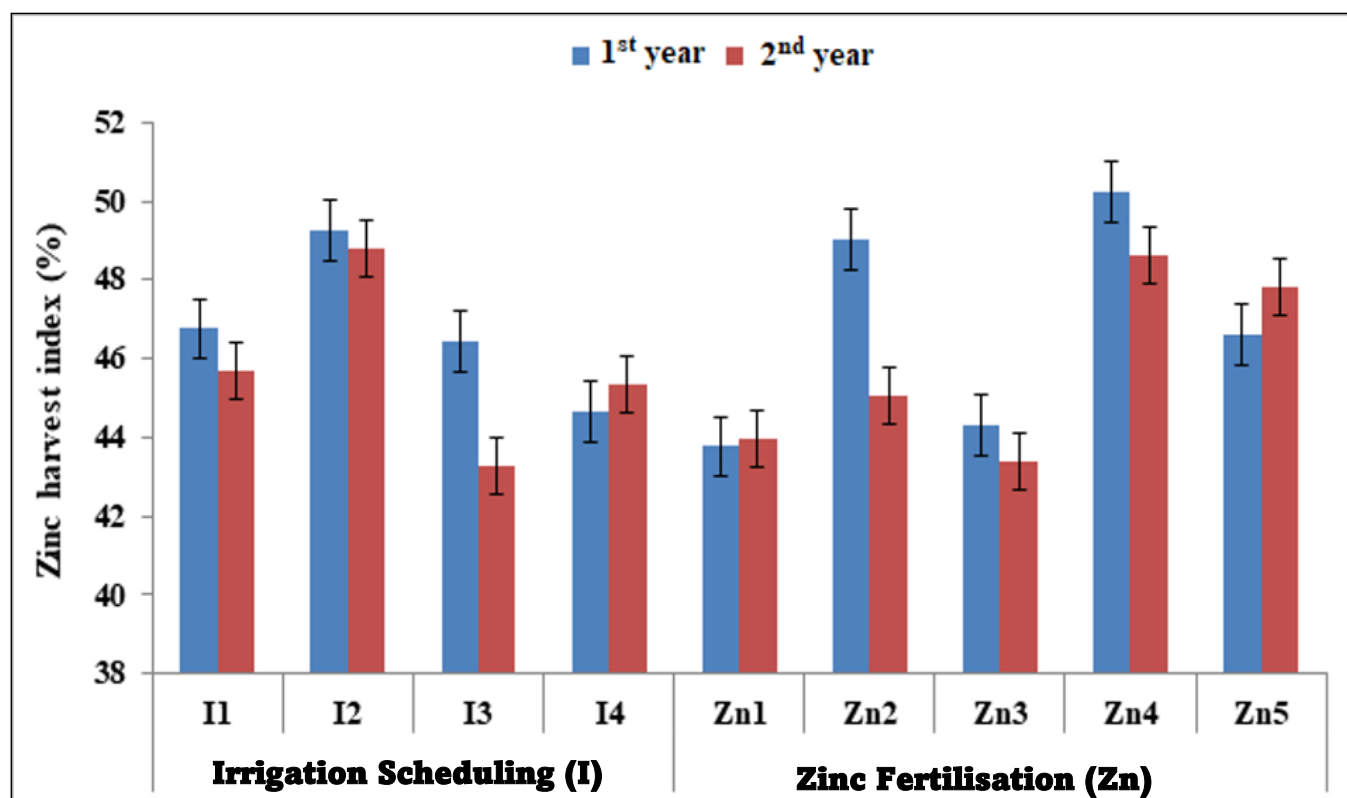


Fig. 5. Effect of irrigation scheduling and zinc fertilisation on apparent zinc harvest index of wheat.

I1 : CRI + late tillering + flowering, I2 : CRI + late jointing + milking, I3 : CRI + flowering + dough, I4 : CRI + milking + dough, Zn1 : 0 kg Zn ha⁻¹, Zn2 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % at Z71, Zn3 : 5 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83, Zn4 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z45 + 0.25 % spray at Z71, Zn5 : 10 kg Zn ha⁻¹ as basal + 0.25 % ZnSO₄ foliar spray at Z60 + 0.25 % spray at Z83.

lowest B : C ratio was observed in I_4 and I_3 , with a similar trend recorded in both the years. In contrast, Zn fertilisation treatments showed the B : C ratio range from 1.66 to 1.76 and 1.72 to 1.82 during 1st and 2nd year respectively. However, these differences were not statistically significant across both the years. However, the interaction effect between irrigation scheduling and Zn fertilisation ($I \times Zn$) was found to be non-significant across both the years.

Effect of irrigation scheduling and Zn fertilisation on Zn efficiency indices

Irrigation scheduling and Zn fertilisation significantly ($P \leq 0.05$) influenced Zn-use efficiency indices, although the magnitude of response was varied across both the years (Fig. 2–5). Among irrigation schedules, I_2 treatment generally showed the highest PFP, with value 251.5 and 251.4 kg grain kg⁻¹ Zn during 1st and 2nd years, respectively. The PFP in I_2 increased by 18.2 and 15.9 % over the least efficient schedule (I_4) during 1st and 2nd years respectively. The Apparent recovery efficiency (ARE) was highest under I_1 treatment followed by I_3 , I_4 and I_2 during the 1st year, whereas in the 2nd year difference among irrigation scheduling was non-significant. Zinc application had a significant ($P \leq 0.05$) effect on PFP (kg kg⁻¹), AE (kg kg⁻¹) and ARE (%). The highest PFP was observed under Zn_2 (357.3 kg grain kg⁻¹ Zn) during the 1st year and under Zn_3 (365.4 kg grain kg⁻¹ Zn) during the 2nd year. PFP under Zn_2 was statistically at par with Zn_3 during the 1st year. The AE followed a similar trend, treatment Zn_2 gave the highest AE (37.0 kg kg⁻¹), followed by Zn_4 (29.8 kg kg⁻¹) in the 1st year, while in 2nd year it was statistically non-significant. The lowest AE was recorded under Zn_5 (10.60 kg grain kg⁻¹ Zn), indicated diminished yield response at higher Zn application rates. The ARE ranged from 0.27 to 0.86 %. The highest ARE was recorded under Zn_4 treatment were 0.73 % and 0.86 % during the 1st and 2nd years respectively. Overall, ARE generally higher in 2nd year than 1st year across all Zn treatments. However, the interaction effect between irrigation scheduling and Zn fertilisation ($I \times Zn$) was not significant across both the years.

Discussion

Effect of irrigation scheduling and Zn fertilisation on wheat productivity

The experiment supported the hypothesis that precise irrigation scheduling and Zn application would enhance wheat productivity and profitability. Irrigation scheduling and Zn fertilisation play a critical role at growth stages that govern sink establishment and grain filling. The maximum grain and biological yield recorded under the I_2 irrigation schedule (CRI+ late jointing + milking) demonstrates that synchronising water supply with critical physiological window is paramount for wheat productivity. Irrigation at CRI stage promotes root and tiller development, while water availability during jointing and milking stage directly supports spikelet formation, grain filling and nutrient assimilation, thereby enhancing biomass accumulation and overall yield (34, 35). Omission of irrigation during these stages constrains photosynthetic activity and accelerates senescence, limiting yield potential (36, 37). Similar findings have been reported previously (38). The superior performance of Zn_4 treatment, highlights the central role of Zn as a cofactor for enzymes involved in auxin synthesis, carbohydrate metabolism and protein synthesis, which are critical for crop production (12, 39). Basal application supports early growth, while foliar sprays at booting (Z45) and anthesis (Z71) address peak demand, effectively mitigating hidden

hunger and improving both yield and harvest index, as supported by meta-analyses (40). The significant interaction effect on harvest index, particularly the peak performance of the $I_2 \times Zn_4$ combination, reveals a synergistic physiological link. Optimal irrigation improves soil Zn mobility and root uptake, while also creating a favorable plant water status that enhances the efficiency of applied (41). This synergy ensures that optimised irrigation maximises sink strength, while adequate zinc nutrition provides the biochemical capacity to fill those sinks efficiently, culminating in the highest productivity and partitioning efficiency. Therefore, integrating phenology-based irrigation with a combined soil-foliar Zn strategy is essential for maximising wheat productivity and nutritional output, especially under conditions where either water or Zn may be limiting (39, 41, 42).

Effect of irrigation scheduling and Zn fertilisation on protein content and yield

The distinct effect of irrigation scheduling and Zn on grain protein content primarily influences N assimilation and total protein accumulation. The higher protein content recorded under I_3 (CRI + flowering + dough) suggests that adequate moisture during these stages enhances nitrogen remobilisation from vegetative tissues and enzymatic activity like glutamine synthetase, crucial for amino acid assimilation and protein deposition in the endosperm, thereby elevating grain protein concentration (43, 44). The slightly lower protein content under I_2 compared with I_3 may reflect carbohydrate dilution of protein. In contrast, Zn fertilisation significantly enhanced both protein content and yield highlighted the central role of Zn in N metabolism and protein synthesis. Zinc acts as a cofactor for enzymes involved in N metabolism, protein synthesis and nucleic acid transcription, directly improving N assimilation efficiency and the conversion of absorbed N into grain protein (12, 15, 45). The superior performance of the combined soil and foliar strategy (Zn_4) ensured Zn availability during peak demand, boosting both the concentration of protein in each grain and the total grain mass, resulting in the observed approximately 35 % increase in protein yield (21, 46). The absence of a significant irrigation effect on protein yield indicates that total protein productivity is governed more strongly by Zn availability and associated yield gains than by water-mediated concentration changes alone. Therefore, maximising wheat protein output requires integrated management: irrigation scheduling fine-tunes protein concentration, while targeted Zn nutrition, particularly through combined application, is critical for elevating both protein content and total yield.

Effect of irrigation scheduling and Zn fertilisation on efficiency indices

The significant effects of irrigation scheduling and Zn fertilisation on Zn use efficiency indices demonstrate the critical importance of synchronising water and nutrient management. The consistently higher PFP under the I_2 irrigation schedule demonstrates that adequate soil moisture during CRI, late jointing and milking stages enhances Zn diffusion and root activity, maximising the grain yield produced per unit of applied Zn (47). Conversely, the higher ARE under the I_1 schedule may indicate differences in root foraging efficiency, though the underlying rhizosphere dynamics warrant further study. Zinc application rate exerted a primary influence, with moderate rates (Zn_2 and Zn_3) optimising AE and PFP by overcoming the yield-limiting deficiency without luxury consumption or antagonism, adhering to the law of diminishing returns (46, 48). The peak ARE under the combined soil and foliar treatment (Zn_4) highlights the efficacy of this strategy; basal application builds a soil

reservoir, while foliar sprays bypass soil constraints and directly supply Zn during peak reproductive demand, thereby maximising uptake and translocation (12, 39, 45). The synergy between I_2 irrigation and moderate Zn rates (Zn_2 - Zn_3) for overall PFP reveals a dual mechanism: optimal irrigation ensures efficient Zn uptake and transport, while the correct Zn dose ensures its maximal metabolic conversion into grain yield. This integrated approach is fundamental for sustainable intensification, maximising output per unit of both water and nutrient inputs (49).

Effect of irrigation scheduling and Zn fertilisation on water productivity

Water productivity (WP) was significantly influenced by irrigation scheduling across both the years, indicating that the irrigation timing was more critical than quantity of water applied. The highest WP was recorded under I_2 (CRI + late jointing + milking), produced 0.78 and 1.03 kg m⁻³ during the 1st and 2nd years respectively. This might be due to adequate moisture availability at critical growth stages that enhanced root activity, nutrient uptake, photosynthesis and grain filling (50, 51). In contrast, I_1 , I_3 and I_4 produced the lower and statistically similar WP, possibly due to the omission of irrigation at the late jointing stage, which is essential for spike development and biomass accumulation (52).

Among Zn treatments, Zn_4 (10 kg Zn ha⁻¹ as basal + 0.25 % $ZnSO_4$ foliar spray at Z45 and Z71), produced the highest WP (0.75 and 1.02 kg m⁻³ during the 1st and 2nd years respectively). This improvement might be due to continuous Zn supply (soil and foliar application) throughout the crop growth period, enhancing enzyme activity, chlorophyll synthesis, photosynthetic efficiency and assimilate translocation to develop higher grain yield and WP (53, 54). Similar WP observed under Zn_2 , Zn_3 and Zn_5 indicate that moderate zinc application was sufficient to improve water productivity over the control treatment, increasing Zn levels beyond the optimum requirement may not proportionally enhance water productivity due to diminishing returns (53, 54). The non-significant interaction between irrigation scheduling and Zn fertilisation ($I \times Zn$) indicates that irrigation scheduling and Zn fertilisation affected WP independently (50).

The effect of irrigation scheduling and Zn application on economic analysis

The most significant factor for farming community is profiting maximisation and profitability is principally associated with input cost and economic yield. The highest B:C ratio was observed with I_2 in current study. This might be due to optimum moisture availability at critical growth stages which increased water-use efficiency and assimilation of nutrients in grain, consequently enhanced economic returns and B:C ratio in wheat (50, 55). However, the interaction between irrigation scheduling and zinc fertilisation was non-significant (56, 57).

Conclusion

The study clearly shows that synchronising irrigation scheduling and Zn management can improve wheat productivity, grain quality, resource-use efficiency and profitability. Among the irrigation schedules the optimal treatment I_2 (CRI + late jointing + milking) enhanced the wheat grain yield by 11–12 %, protein content by 18.4–18.7 % and PFP by 15.9–18.2 kg kg⁻¹ across both the years. Similarly, treatment Zn_4 (10 kg Zn ha⁻¹ as basal + 0.25 % $ZnSO_4$ foliar sprays at Z45 and Z71) produced the highest grain yield and

increased by 15–18 % compared with Zn_1 (control). The combined application of $I_2 \times Zn_4$ numerically increased the grain yield by 22–25 %, protein yield by 35 % and various efficiency indices over the $I_1 \times Zn_1$ (control) across both the years of experimentation. Overall, the synchronised $I_2 \times Zn_4$ protocol may serve as the best practical and sustainable agronomic strategy for better wheat productivity, nutritional quality and profitability under water-limited environments in the Indo-Gangetic Plain. This strategy directly aligns with the United Nations Sustainable Development Goals by contributing to food security such as Zero Hunger (SDG 2); improving nutritional quality (SDG 3) and promoting climate-resilient and resource efficient agricultural practices (SDG 13). Future research should validate this framework across diverse agro-ecological regions and soil types and incorporate rigorous economic analysis to assess scalability.

Acknowledgements

The authors express sincere gratitude to the Banaras Hindu University, Varanasi and the Indian Institute of Soil and Water Conservation Regional Centre, Ballari Karnataka, India for their constant support for this research works. We gratefully acknowledge all the researchers whose contributions helped us accomplish this research work. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Authors' contributions

PUL handled data collection, analysis and wrote the main manuscript. SKP and MKS contributed to the conceptualisation and methodology. DJ, PD, KPJ, KR and ANM processed the data, performed formal analysis and created the figures. AK contributed to conceptualisation, interpretation of results, writing, editing and review of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process: The authors used ChatGPT (OpenAI) solely for language editing and grammatical improvement during the preparation of this manuscript. The authors take full responsibility for the accuracy, integrity and originality of the manuscript.

References

1. FAOSTAT. Food and agriculture data [Internet]. Rome: Food and Agriculture Organization of the United Nations; 2024. <http://www.fao.org/faostat>
2. Joshi AK, Mishra B, Chatrath R, Ortiz Ferrara G, Singh RP. Wheat improvement in India: present status, emerging challenges and future prospects. *Euphytica*. 2007;157(3):431-46. <https://doi.org/10.1007/s10681-007-9385-7>
3. DAC&FW. Agricultural statistics at a glance [Internet]. New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India; 2022. <https://coilink.org/20.500.12592/vmcvkm4>

4. Singh SK, Kumar S, Kashyap PL, Sendhil R, Gupta OP. Trajectory of 75 years of Indian agriculture after independence. In: Wheat. Singapore: Springer; 2023. p. 137-62. https://doi.org/10.1007/978-981-19-7997-2_7
5. Hochman Z, Gobbett DL, Horan H. Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Res.* 2018;228:20-30. <https://doi.org/10.1016/j.fcr.2018.08.023>
6. Pratap V, Dass A, Krishnan P, Sudhishri S, Choudhary AK, Bhatia A, et al. Precision nitrogen and water management in double zero-till wheat: effects on photosynthetic parameters, productivity, nutrient-use efficiency and N₂O emission. *Front Plant Sci.* 2025;16:1654933. <https://doi.org/10.3389/fpls.2025.1654933>
7. Mubeen M, Ahmad A, Wajid A, Khaliq T, Sultana SR, Hussain S, et al. Effect of growth stage-based irrigation schedules on biomass accumulation and resource use efficiency of wheat cultivars. *Am J Plant Sci.* 2013;4(7A):1435-42. <https://doi.org/10.4236/ajps.2013.47175>
8. Sheng K, Yang LJ, Jiang ZK, Wang YH, Dong Y, Zhao ZW. Effects of irrigation on yield and quality of high gluten wheat Xinmai 19. *Agric Res Arid Areas.* 2013;31(5):42-47. <https://doi.org/10.7606/j.issn.1000-7601.2013.05.007>
9. Zhang X, Zhang J, Xue J, Wang G. Improving wheat yield and water-use efficiency by optimizing irrigation in northern China. *Sustainability.* 2023;15(13):10503. <https://doi.org/10.3390/su151310503>
10. Sillanpää M. Micronutrient assessment at country level: an international study. *Soils Bulletin No. 63.* Rome: FAO; 1990.
11. Shukla AK, Behera SK, Prakash C, Tripathi A, Patra AK, Dwivedi BS, et al. Deficiency of phyto-available sulphur, zinc, boron, iron, copper and manganese in soils of India. *Sci Rep.* 2021;11(1):19760. <https://doi.org/10.1038/s41598-021-99040-2>
12. Kumar A, Singh AP. Direct and residual effect of zinc and boron on growth parameters of rice and wheat grown in sequence in red and alluvial soils of eastern Uttar Pradesh. *Int J Chem Stud.* 2018;6(1):587-92.
13. López-Millán AF, Ellis DR, Grusak MA. Effect of zinc and manganese supply on the activities of superoxide dismutase and carbonic anhydrase in *Medicago truncatula* wild type and raz mutant plants. *Plant Sci.* 2005;168(4):1015-22. <https://doi.org/10.1016/j.plantsci.2004.11.018>
14. Sinclair SA, Krämer U. The zinc homeostasis network of land plants. *Biochim Biophys Acta Mol Cell Res.* 2012;1823(9):1553-67. <https://doi.org/10.1016/j.bbamcr.2012.05.016>
15. Alloway BJ. Zinc in soils and crop nutrition. 2nd ed. Brussels: International Zinc Association; 2008.
16. Xu M, Liu M, Si L, Ma Q, Sun T, Wang J, et al. Spraying high concentrations of chelated zinc enhances zinc biofortification in wheat grain. *J Sci Food Agric.* 2022;102(9):3590-98. <https://doi.org/10.1002/jsfa.11705>
17. Sattar A, Wang X, Ul-Allah S, Sher A, Ijaz M, Irfan M, et al. Foliar application of zinc improves morphophysiological and antioxidant defense mechanisms, and agronomic grain biofortification of wheat under water stress. *Saudi J Biol Sci.* 2022;29(3):1699-706. <https://doi.org/10.1016/j.sjbs.2021.10.061>
18. Nayak S, Shivay YS, Prasanna R, Mandi S, Parveen S, Baral K, et al. Soil and foliar application of Zn enhances its biofortification, bioavailability and productivity in both biofortified and non-biofortified wheat varieties. *J Food Compos Anal.* 2023;124:105691. <https://doi.org/10.1016/j.jfca.2023.105691>
19. Akça H, Taban S. Optimizing grain zinc biofortification in bread wheat. *J Soil Sci Plant Nutr.* 2024;24:4714-26. <https://doi.org/10.1007/s42729-024-01764-0>
20. Shoormij F, Mirolohi A, Saiedi G, Sabzalian MR, Shirvani M. Zinc foliar application may alleviate drought stress in wheat species through physiological changes. *Plant Stress.* 2024;13:100503. <https://doi.org/10.1016/j.stress.2024.100503>
21. Cakmak I, Kutman UB. Agronomic biofortification of cereals with zinc. *Eur J Soil Sci.* 2018;69(1):172-80. <https://doi.org/10.1111/ejss.12437>
22. Makhadmeh MI, Abid M, Noreen S, Almeer R, Raja V, Akhter MS. Fertigation of wheat cultivars with zinc leads to enhanced yield and marginal rate of return in silty loamy soils. *J King Saud Univ Sci.* 2024;36:103389. <https://doi.org/10.1016/j.jksus.2024.103389>
23. Chattha MU, Hassan MU, Khan I, Chattha MB, Mahmood A, Nawaz M, et al. Biofortification of wheat cultivars to combat zinc deficiency. *Front Plant Sci.* 2017;8:281. <https://doi.org/10.3389/fpls.2017.00281>
24. Dhaliwal SS, Ram H, Shukla AK, Mavi GS. Zinc biofortification of bread wheat, triticale, and durum wheat cultivars by foliar zinc fertilization. *J Plant Nutr.* 2019;42(8):813-22. <https://doi.org/10.1080/01904167.2019.1584218>
25. Hassan MU, Chattha MU, Ullah A, Khan I, Qadeer A, Aamer M, et al. Agronomic biofortification to improve productivity and grain Zn concentration of bread wheat. *Int J Agric Biol.* 2019;21(3):615-20. <https://doi.org/10.17957/IJAB/15.0936>
26. Donald CM. In search of yield. *J Aust Inst Agric Sci.* 1962;28:171-78.
27. AOAC. Fibre and protein in animal feed and forage. *J Assoc Off Anal Chem.* 1989;72(1):182-84.
28. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci Soc Am J.* 1978;42(3):421-28. <https://doi.org/10.2136/sssaj1978.03615995004200030009x>
29. Fageria NK. The use of nutrients in crop plants. Boca Raton (FL): CRC Press; 2009.
30. Shivay YS, Prasad R. Zinc-coated urea improves productivity and quality of basmati rice (*Oryza sativa* L.) under zinc stress condition. *J Plant Nutr.* 2012;35(6):928-51. <https://doi.org/10.1080/01904167.2012.663444>
31. Ayamba BE, Abaidoo RC, Opoku A, Ewusi-Mensah N. Mechanisms underlying nutrient interactions in cropping systems: implications for balanced fertilization and yield improvement. *Agronomy.* 2023;13(7):1450. <https://doi.org/10.3390/agronomy13071450>
32. CIMMYT Economics Program. From agronomic data to farmer recommendations: an economics training manual. Completely revised ed. No. 27. Texcoco (Mexico): CIMMYT; 1988. p. 31-33.
33. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley & Sons; 1984.
34. Lollato RP, Ruiz Diaz DA, DeWolf E, Knapp M, Peterson DE, Fritz AK. Agronomic practices for reducing wheat yield gaps: a quantitative appraisal of progressive producers. *Crop Sci.* 2019;59(1):333-50. <https://doi.org/10.2135/cropsci2018.04.0249>
35. Sharma S, Schulthess AW, Bassi FM, Badaeva ED, Neumann K, Graner A, et al. Introducing beneficial alleles from plant genetic resources into the wheat germplasm. *Biology.* 2021;10(10):982. <https://doi.org/10.3390/biology10100982>
36. Luo Y, Li W, Huang C, Yang J, Jin M, Chen J, et al. Exogenous abscisic acid coordinating leaf senescence and transport of assimilates into wheat grains under drought stress by regulating hormone homeostasis. *Crop J.* 2021;9(4):901-14. <https://doi.org/10.1016/j.cj.2020.08.012>
37. FAO. Crop water requirements and irrigation scheduling. FAO Irrigation and Drainage Paper No. 66. Rome: FAO; 2022.
38. Zhang X, Wang Z, Li Y, Guo R, Liu E, Liu X, et al. Wheat genotypes with higher yield sensitivity to drought overproduced proline and lost minor biomass under severer water stress. *Front Plant Sci.* 2022;13:1035038. <https://doi.org/10.3389/fpls.2022.1035038>
39. Cakmak I. Enrichment of cereal grains with zinc: agronomic or genetic biofortification? *Plant Soil.* 2008;302:1-17. <https://doi.org/10.1007/s11104-007-9469-3>
40. Xia H, Wang L, Qiao Y, Kong W, Xue Y, Wang Z, et al. Elucidating the

source-sink relationships of zinc biofortification in wheat grains: a review. *Food Energy Secur.* 2020;9(4):e243. <https://doi.org/10.1002/fes3.243>

41. Saleem MH, Usman K, Rizwan M, Al Jabri H, Alsafran M. Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Front Plant Sci.* 2022;13:1033092. <https://doi.org/10.3389/fpls.2022.1033092>
42. Ghanem HE, Hamza DA, Zain El-Abdeen AA, Elbatrawy WS, El-Habashy HM. Influence of zinc foliar spray on growth, physiological processes, yield and yield attributes of bread wheat under water stress. *Sci Rep.* 2025;15:14943. <https://doi.org/10.1038/s41598-025-94728-1>
43. Zörb C, Ludewig U, Hawkesford MJ. Wheat yield and quality with reduced nitrogen supply. *Trends Plant Sci.* 2018;23(11):1029-37. <https://doi.org/10.1016/j.tplants.2018.08.011>
44. Kumar S, Singh J, Singh S, Singh MP. Regulation of sucrose metabolism and starch synthesis in wheat under drought stress. *Plant Physiol Biochem.* 2019;142:99-110. <https://doi.org/10.1016/j.plaphy.2019.06.037>
45. Zhao Q, Cao W, Chen X, Stomph TJ, Zou C. Global analysis of nitrogen fertilization effects on grain zinc and iron of major cereal crops. *Glob Food Sec.* 2022;33:100631. <https://doi.org/10.1016/j.gfs.2022.100631>
46. Liu Y, Wang C, Zhang F. Soil and foliar application of zinc on yield and quality of winter wheat. *Agronomy.* 2021;11(8):1600. <https://doi.org/10.3390/agronomy11081600>
47. Rengel Z. Availability of micronutrients in the rhizosphere. In: Marschner's mineral nutrition of higher plants. 3rd ed. Oxford (UK): Academic Press; 2015. p. 561-84.
48. Wang M, Kong F, Liu R, Fan Q, Zhang X. Zinc in wheat grain, processing, and food. *Front Nutr.* 2020;7:124. <https://doi.org/10.3389/fnut.2020.00124>
49. Rietra RPJJ, Heinen M, Dimkpa CO, Bindraban PS. Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. *Commun Soil Sci Plant Anal.* 2017;48(16):1895-920. <https://doi.org/10.1080/00103624.2017.1407429>
50. Manasa N, Rana N, Krishna KV. Effect of irrigation scheduling and zinc fertilization on yield and water productivity of irrigated wheat (*Triticum aestivum* L.). *Pharma Innov J.* 2023;12(10):1979-83.
51. Wang S, Niu Y, Shang L, Li Z, Hu X, Wang D. Supplemental irrigation at the jointing stage of late-sown winter wheat for increased production and water use efficiency. *Field Crops Res.* 2023;302:109069. <https://doi.org/10.1016/j.fcr.2023.109069>
52. Kaur K, Kumar S. Enhancing productivity through effective irrigation and nitrogen scheduling in wheat (*Triticum aestivum* L.). *J Cereal Res.* 2024;16(2):177-83. <https://doi.org/10.25174/2582-2675/2024/156226>
53. Zarea MJ, Karimi N. Grain yield and quality of wheat are improved through post-flowering foliar application of zinc and 6-benzylaminopurine under water deficit condition. *Front Plant Sci.* 2023;13:1068649. <https://doi.org/10.3389/fpls.2022.1068649>
54. Singh S, Thejesh C, Darvhankar M, Mathpal B. Exogenous application of zinc, cytokinin and gibberellic acid affects growth and yield of timely and late-sown wheat. *Indian J Agric Res.* 2024;58(5):761-67. <https://doi.org/10.18805/IJARE.A-6158>
55. Lakra K, Husain K, Pyare R, Verma SK, Meena RS, Singh PK, et al. Productivity and profitability of irrigated bread wheat (*Triticum aestivum* L.) are influenced by irrigation scheduling and weed management approaches. *Gesunde Pflanzen.* 2023;75(4):801-14. <https://doi.org/10.1007/s10343-022-00795-8>
56. Sher A, Sarwar B, Sattar A, Ijaz M, Ul-Allah S, Hayat MT, et al. Exogenous application of zinc sulphate at heading stage of wheat improves the yield and grain zinc biofortification. *Agronomy.* 2022;12(3):734. <https://doi.org/10.3390/agronomy12030734>
57. Mandal A, Singh T, Sarkar A, Dass A, Chaudhary M, Padhan SR, et al. Enhancing yield, water productivity, energy efficiency and economic returns of wheat by optimizing irrigation and nitrogen management practices. *J Soil Water Conserv.* 2024;23(3):249-57. <https://doi.org/10.5958/2455-7145.2024.00030.3>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.