



RESEARCH ARTICLE

Optimising wheat yield and water use efficiency through strategic irrigation scheduling and zinc biofortification

Shagufta Naaz¹, Rajan Kumar^{2*}, Dharminder¹, Sunita Kumari¹ & Sumit Sow¹

¹Department of Agronomy, Post Graduate College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa 848 125, Bihar, India

²Pandit Deen Dayal Upadhyay College of Horticulture and Forestry, Dr. Rajendra Prasad Central Agricultural University, Pusa 848 125, Bihar, India

*Correspondence email - rajan.kumar@rpcau.ac.in

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Abstract

Global wheat production faces dual challenges of water scarcity and micronutrient deficiencies, necessitating sustainable intensification strategies. This study investigates the synergistic effects of optimised irrigation scheduling and zinc (Zn) biofortification on wheat growth, productivity and nutritional quality. A field investigation was executed at Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar during the winter season of 2023–24 under 3 levels of irrigation, viz. irrigation at crown root initiation (CRI), CRI + booting stage and CRI + booting + milking stage and 4 levels of Zn management, viz. control, 2.5 kg, 5.0 kg Zn/ha (basal) and two foliar spray of ZnSO₄. Irrigation scheduling at CRI + booting + milking stage significantly increased the yield attributing characteristics and attained highest grain yield of 3812.6 kg/ha and straw yield of 5370.7 kg/ha. Maximum protein content (9.85 %) was observed when irrigated 3 times (CRI + booting + milking stage). However, water use efficiency and water productivity were significantly highest at irrigation scheduling at the CRI stage. Basal application of 5.0 kg Zn/ha enhanced the grain yield by 23.1 % as compared to control (no Zn). Therefore, irrigation scheduling at CRI + booting + milking stage coupled with basal application of 5.0 kg Zn/ha enhanced wheat productivity by improving water use and nutrient uptake.

Keywords: biofortification; crown root initiation; grain yield; nutritional quality; water productivity

Introduction

Wheat (*Triticum aestivum* L.) stands as a cornerstone of global food security, providing approximately 20 % of the total dietary calories and protein for the human population (1). Distinguished by its high gluten content, wheat remains indispensable for bread production and various food applications across diverse agro-ecological zones. However, contemporary wheat production systems confront unprecedented challenges stemming from escalating water scarcity and widespread micronutrient malnutrition, collectively termed the "hidden hunger" crisis affecting over 2 billion people globally. Agricultural water consumption accounts for approximately 70–80 % of total freshwater withdrawals globally, with this proportion reaching 95 % in developing nations (2). Climate change exacerbates this scenario by reducing water availability in regions where irrigation is most critical, simultaneously diminishing crop productivity and amplifying water demand. With a water footprint of 1827 m³ per tonne, wheat ranks among the most water-intensive crops, necessitating innovative water management strategies that reconcile productivity imperatives with resource conservation objectives (3).

Irrigation timing critically influences wheat performance, as soil moisture availability during key phenological stages- sowing, tillering and reproductive phases directly determines yield outcomes (4, 5). Strategic irrigation scheduling, targeting the crop's most water-

sensitive growth stages, substantially enhances water use efficiency compared to conventional practices (6, 7). The implementation of four irrigations until the late flowering stage (crown root initiation (CRI) + late tillering + late jointing + late flowering) appears to provide results comparable to those achieved with five irrigations up to the late milking stage. Nonetheless, 3 irrigations during CRI, late tillering and late flowering, as well as 2 irrigations at late tillering and late flowering and one irrigation at the late tillering stage, resulted in significantly greater wheat yields compared to equivalent irrigation levels at other physiological stages in the vertisols of Central India (8).

Concurrent with water stress challenges, zinc (Zn) deficiency represents a pervasive constraint limiting wheat productivity and nutritional quality across approximately 50 % of global cereal cultivation areas (9). Zinc functions as an essential micronutrient orchestrating critical physiological processes including photosynthesis, protein synthesis, carbohydrate metabolism, membrane integrity, auxin production and disease resistance mechanisms (10). Zinc biofortification through agronomic interventions encompassing both soil and foliar applications has emerged as a cost-effective strategy to simultaneously enhance crop yields and grain nutritional density (11, 12). Studies indicate that combined soil and foliar Zn application achieved the highest grain and straw yields (14 % and 7 % increases respectively), followed by foliar-only and then soil-only application, while also increasing Zn concentration in grain and straw by 47 % and 37 % respectively and grain nitrogen content by 19 % (13). Zinc

deficiency ranks as the 5th most significant nutritional constraint in developing Asian economies, driving intensified efforts toward agronomic biofortification to address both agricultural productivity and public health nutrition challenges (14, 15).

Despite substantial research on irrigation management and Zn nutrition in wheat individually, a critical knowledge gap remains regarding their interactive effects on productivity, water use efficiency and grain nutritional quality, particularly in the Indo-Gangetic Plains where water scarcity and Zn deficiency frequently occur together. The present study hypothesises that the combined application of optimised irrigation scheduling and Zn fertilisation will synergistically enhance wheat growth, yield, water productivity and grain Zn concentration more effectively than either practice applied alone. Therefore, the objectives of this study are to (i) evaluate the effect of different irrigation regimes on wheat growth, yield and water use efficiency, (ii) assess the influence of various Zn application methods on crop productivity and grain nutritional quality and (iii) determine the interactive effects of irrigation management and Zn fertilisation on yield performance, water productivity, economic returns and grain Zn enrichment to develop sustainable and resource-efficient wheat production strategies for the Indo-Gangetic Plains.

Materials and Methods

Site description

The field experiment was conducted at Dr. Rajendra Prasad Central Agricultural University, Pusa (25°58'42" N, 85°40'30" E and 71 m above sea level), Samastipur, Bihar during the winter season of 2023–24. The size of each plot was 4.2 m length and 3.6 m width having an area of 15.12 m². The soil was entisol soil order with a calcareous sandy loam kind of soil texture having pH 8.24 and electrical conductivity 0.32 ds/m. The soil was low in organic carbon (0.43 %), available nitrogen (N) (190.6 kg/ha), available phosphorous (P) (20.1 kg/ha), available potassium (K) (120.0 kg/ha) and available Zn (0.73 mg/ha). The range of maximum temperatures throughout the crop growth period was 15.1–37.9 °C and the range of lowest

temperature was 7.5–21.1 °C. This region received 1309.1 mm of rainfall on average. An average of 5.01 hr of bright sunlight were seen throughout the crop growing period. A total of 54.6 mm of rainfall occurred during the cropping season (Fig. 1).

Experimental details and crop management

The study was carried out using split plot design. There were 12 treatment combination total, with 3 irrigation levels in main plot (irrigation at crown root initiation (CRI), CRI + booting stage and CRI + booting + milking stage) and 4 Zn levels in sub plot (control (no Zn), 2.5 kg, 5.0 kg Zn/ha (basal); and 2 foliar spray of ZnSO₄ of 0.5 % which was prepared by dissolving 5 g of ZnSO₄ in 1 L of water and applied uniformly using a knapsack sprayer at tillering and ear emergence stages, replicated 3 times. Wheat variety HD 2967 was sown on 29th November 2023 and harvested on 17th April 2024. A 100 kg/ha seed rate was taken and sown at the spacing of 20 cm row to row. The crop was raised with recommended dose of fertiliser, i.e. N, P and K of 120, 60 and 40 kg/ha respectively. Irrigation was applied according to the treatment and using 6 cm depth of irrigation water. A common half dose of N and a full dose of P and K were applied as basal, the remaining 1/4th at active tillering and 1/4th at booting stage was applied to all the plots. Zinc was applied according to the treatment.

Crop sampling and analysis

Data from all experimental plots were collected to assess the impact of various treatments on crop yield. To assess dry matter accumulation, plants were severed at ground level utilising a 0.5 × 0.5 m quadrant from the designated region. Subsequently, the plants were washed, sun-dried and heated in a hot air oven at 65 °C until a constant weight was attained. Yield attributing metrics were recorded at physiological maturity. These data were obtained during sun drying at a moisture content below 15 %. The quantity of effective tillers was determined using a 1 m² quadrant. During the physiological maturity phase, the quantity of tillers bearing spikes was enumerated inside the designated quadrant. Five sample spikes from each treatment were taken from designated rows for spike length measurement. The spike length was quantified in centimeters from the base of the peduncle to the apex of the upper

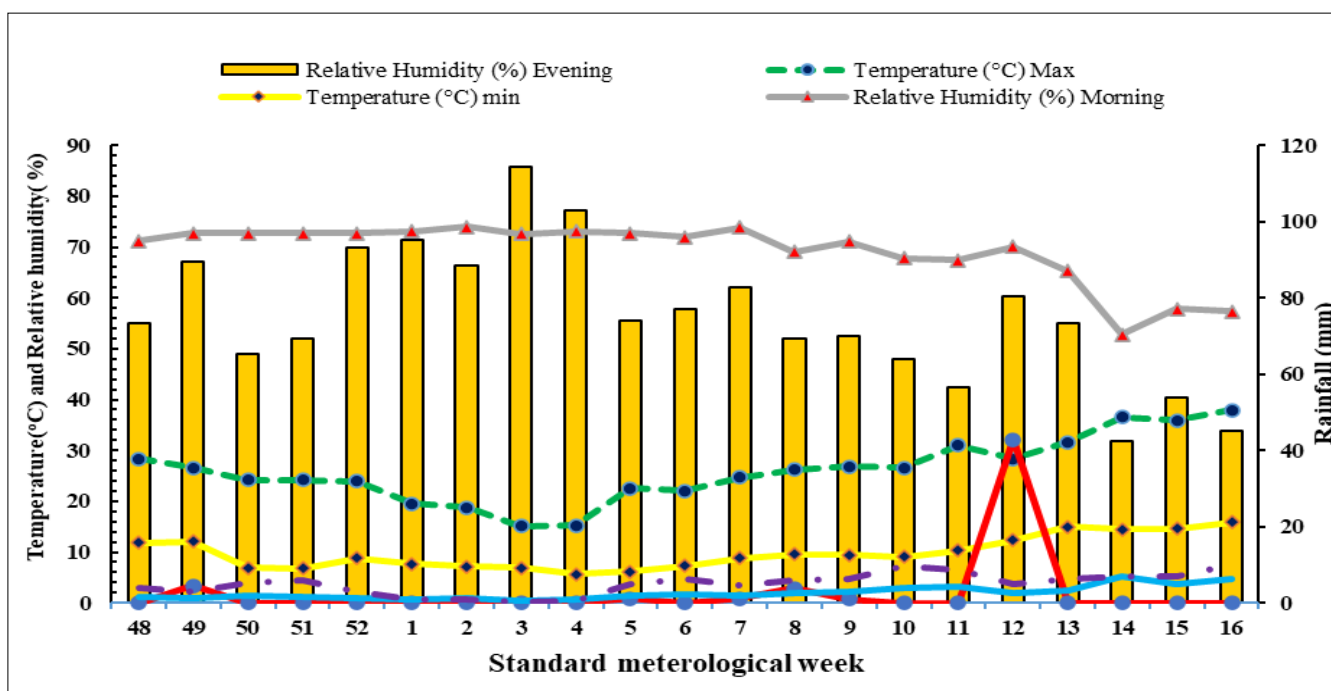


Fig. 1. Weather during wheat cropping season (November 2023 to April 2024).

spikelet. Ten spikes were chosen to measure the number of grains per spike and were threshed individually to count the grains in each spike; the average was then calculated to represent the number of grains per spike. Following the threshing of each net plot, the harvested grain was sun-dried, after which 1000 grains were counted, weighed and recorded as test weight. The grain yield was determined using sun drying, electronic weighing and winnowing of the harvested grain from each net plot. Subsequent to threshing, the grains were separated from the straw, which was subsequently weighed using an electronic balance to ascertain the straw yield in kilogram per hectare. Water use efficiency and water productivity were calculated using standard formula (16):

Water use efficiency (WUE) = Grain yield (kg/ha) / Total water applied (cm)

Where, grain yield is expressed in kilogram per hectare and total water applied includes irrigation water and effective rainfall during the crop growth period.

Water productivity (₹/m^3) = Net returns (₹/ha) / Total water used (m^3/ha)

Where, net returns represent the economic profit obtained from the crop after deducting the cost of cultivation and total water used is expressed in cubic metres per hectare.

The N concentration in the plant sample was ascertained utilising the KEL PLUS automatic N estimation system, which implemented a digestion and distillation process in accordance with the Micro Kjeldahl method (17). The total available P was quantified utilising the vanadomolybdo phosphoric acid yellow color method (18). The total accessible potassium was quantified using a flame photometer following the proper dilution of digested samples (19). The Zn concentration was ascertained utilising the atomic

absorption spectrophotometry technique (20). The uptake of N, P, K and Zn was determined by multiplying the respective nutrient concentration in plant tissues by the corresponding dry matter yield. The protein content (%) in grain was determined by multiplying the N concentration by a factor of 6.25 (21).

Statistical analysis

The experiment used a split plot design, with irrigation scheduling serving as the main plot treatment and Zn application as the sub-plot treatment. The data acquired from the numerous observations was assembled and statistically analysed using Gomez and Gomez's analysis of variance (ANOVA) methods in SAS version 9.4 software (SAS, Inc., North Carolina, USA) (22). Treatment means were compared statistically using *F*-test procedures, with critical difference (CD) at the 5 % probability level used to detect significant differences between treatment mean values.

Results

Dry matter accumulation

The maximum dry matter accumulation (913.9 g/m^2) was observed under irrigation at CRI + booting + milking stage, which was significantly superior to irrigation at CRI stage alone and statistically at par with irrigation at CRI + booting stage (Fig. 2). The CRI + booting + milking stage irrigation treatment resulted in 19.4 % higher dry matter accumulation compared to irrigation at CRI stage only. Among different Zn management practices there is no significant difference in dry matter accumulation at harvest. However, the highest dry matter accumulation was recorded with basal application of 5.0 kg Zn/ha , which exceeded that obtained from foliar application of ZnSO_4 of 0.5 % at tillering and ear emergence stages by 5.7 % (Fig. 2).

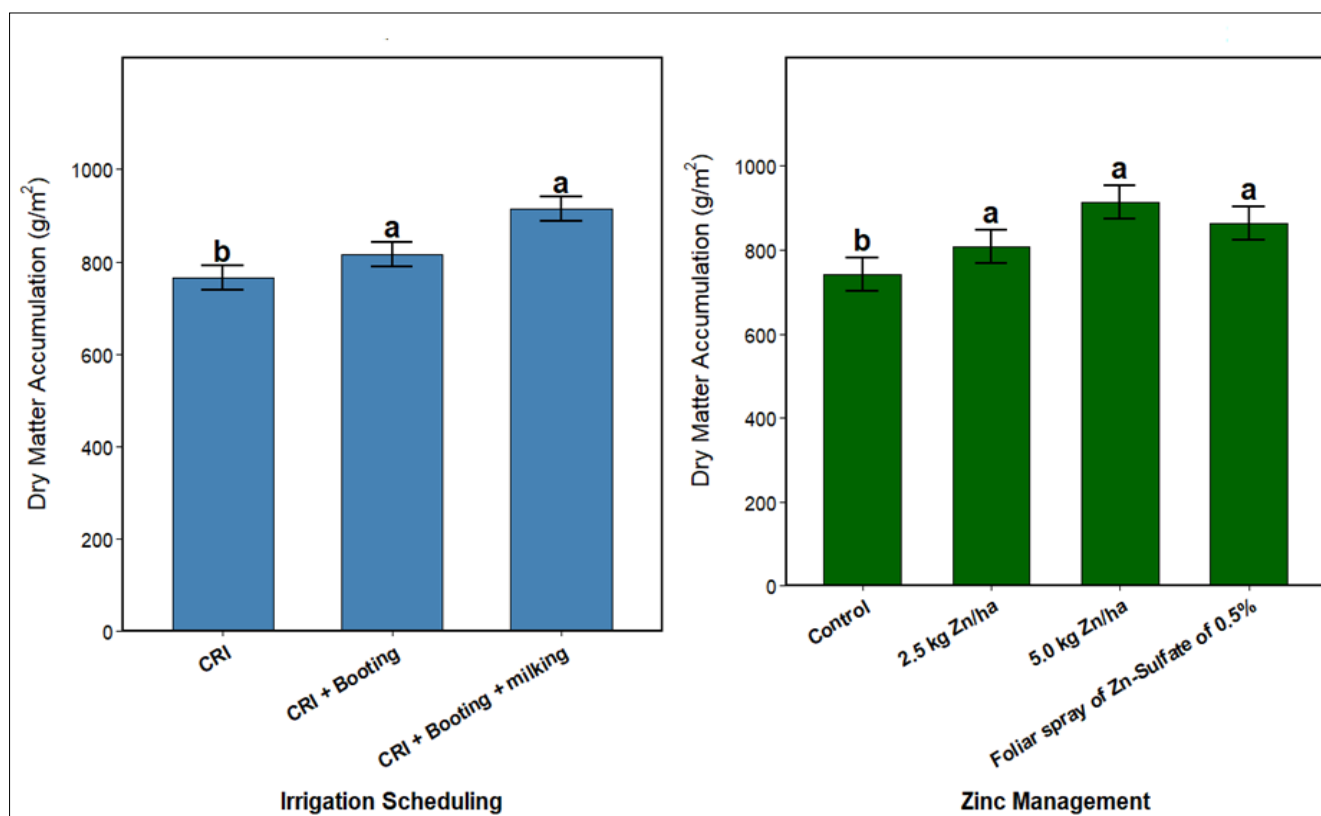


Fig. 2. Dry matter accumulation as affected by different irrigation regimes and zinc application strategies (g/m^2).

CRI: crown root initiation; Treatment means followed by different lowercase letters differ significantly at the $p \leq 0.05$ level according to Duncan's multiple range test.

Yield

Increasing irrigation frequency significantly enhanced yield attributes. Irrigation at CRI + booting + milking stage produced 20.0 % more effective tillers/m² compared to irrigation at CRI stage alone (Table 1). The control plot recorded the lowest number of effective tillers m², which was 18.5 % lower than the basal application of 5.0 kg Zn/ha. The highest number of grains/ear (50.4) was observed under irrigation at CRI + booting + milking stage, representing a 19.4 % increase over irrigation at CRI stage. Among Zn application methods, basal application of 5.0 kg Zn/ha yielded the maximum grains/ear, which was 20.2 % higher than the control treatment. Moreover, test weight was significantly influenced by irrigation scheduling. Irrigation at CRI stage recorded the lowest test weight, which was 12.6 % lower than irrigation at CRI + booting + milking stage (Table 1). Basal application of 5.0 kg Zn/ha produced the highest test weight (40.6 g), exceeding foliar application of ZnSO₄ of 0.5 % at tillering and ear emergence by 1.8 %. Furthermore, spike length showed maximum response to irrigation at CRI + booting + milking stage, recording an 18.2 % increase over irrigation at CRI stage. Zinc application levels significantly affected spike length, with the control plot exhibiting 19.7 % lower spike length than basal application of 5.0 kg Zn/ha (Table 1).

Grain yield was significantly influenced by irrigation regime, with the maximum yield (3812.7 kg/ha) obtained under irrigation at CRI + booting + milking stage. Among Zn management practices,

basal application of 5.0 kg Zn/ha produced the highest grain yield (3811.4 kg/ha), which was 5.7 % higher as compared to the foliar application of ZnSO₄ of 0.5 % at tillering and ear emergence (Table 2). Similarly, the highest straw yield (5370.7 kg/ha) was recorded under irrigation at CRI + booting + milking stage, representing a 1.32 % increase over irrigation at CRI + booting stage. Basal application of 5.0 kg Zn ha⁻¹ yielded maximum straw (5203.7 kg ha⁻¹), which was 1.07 % higher than foliar application of ZnSO₄ of 0.5 % at tillering and ear emergence (Table 2).

Water use efficiency and grain quality

Maximum water use efficiency was achieved under irrigation at CRI stage, recording 71 % higher efficiency compared to irrigation at CRI + booting + milking stage. Among Zn application treatments, basal application of 5.0 kg Zn/ha exhibited the highest water use efficiency, which was 6.5 % greater than foliar application of ZnSO₄ of 0.5 % at tillering and ear emergence. Similarly, irrigation at CRI stage and basal application of 5.0 kg Zn/ha recorded maximum water productivity (Table 3).

Protein content was not significantly affected by both irrigation and Zn management. The highest protein content (9.85 %) was observed under irrigation at CRI + booting + milking stage, representing a 3.7 % increase over irrigation at CRI stage (Table 3). Among Zn management practices, basal application of 5.0 kg Zn/ha produced the maximum protein content (9.91 %), which was 5.2 % higher than no application of Zn (control).

Table 1. Influence of irrigation scheduling and zinc application strategies on yield contributing traits of the wheat

Treatments	Number of effective tillers/m ²	Number of grains/ear	Test weight (g)	Spike or ear length (cm)
Irrigation scheduling (I)				
Irrigation at CRI stage	246.7	42.2	35.3	8.6
Irrigation at CRI + booting stage	263.3	45.0	38.1	9.2
Irrigation at CRI + booting + milking stage	296.0	50.4	40.4	10.2
SEm (±)	9.1	1.5	0.7	0.3
CD (<i>p</i> < 0.05)	35.7	5.8	2.8	1.2
Zn management (Z)				
Control	239.8	41.9	34.4	8.3
2.5 kg/ha (basal)	261.7	44.6	37.7	9.0
5.0 kg/ha (basal)	294.6	50.4	40.6	10.3
Foliar spray of ZnSO ₄ of 0.5 % at tillering and ear emergence stages	278.6	47.6	39.9	9.7
SEm (±)	12.8	2.2	1.8	0.4
CD (<i>p</i> < 0.05)	38.1	6.5	5.4	1.2
Interaction (I × Z)	NS	NS	NS	NS

*SEm: standard error of the mean; CD: critical difference; NS: non-significant; CRI: crown root initiation.

Table 2. Yield (kg/ha) as influenced by different irrigation regime and zinc management strategies in wheat

Treatments	Grain yield	Straw yield
Irrigation scheduling (I)		
Irrigation at CRI stage	3192.0	4655.9
Irrigation at CRI + booting stage	3406.0	4914.0
Irrigation at CRI + booting + milking stage	3812.7	5370.7
SEm (±)	63.2	85.3
CD (<i>p</i> < 0.05)	248.2	334.9
Zn management (Z)		
Control	3095.0	4696.4
2.5 kg/ha (basal)	3370.8	4872.2
5.0 kg/ha (basal)	3811.4	5203.7
Foliar spray of ZnSO ₄ of 0.5 % at tillering and ear emergence stages	3604.3	5148.6
SEm (±)	104.4	134.1
CD (<i>p</i> < 0.05)	310.2	398.3
Interaction (I × Z)	NS	NS

*SEm: standard error of the mean; CD: critical difference; NS: non-significant; CRI: crown root initiation.

Table 3. Impact of irrigation timing and zinc application strategies on water use efficiency, water productivity and grain protein content of wheat

Treatments	Water use efficiency (kg/ha-cm)	Water productivity (₹/m³)	Protein content (%)
Irrigation scheduling (I)			
Irrigation at CRI stage	278.5	0.40	9.49
Irrigation at CRI + booting stage	195.1	0.29	9.73
Irrigation at CRI + booting + milking stage	162.5	0.26	9.85
SEm (±)	3.2	0.01	0.12
CD ($p < 0.05$)	12.5	0.03	NS
Zn management (Z)			
Control	190.0	0.27	9.42
2.5 kg/ha (basal)	207.2	0.29	9.65
5.0 kg/ha (basal)	232.6	0.36	9.91
Foliar spray of ZnSO ₄ of 0.5 % at tillering and ear emergence stages	218.4	0.33	9.78
SEm (±)	5.8	0.02	0.16
CD ($p < 0.05$)	17.3	0.05	NS
Interaction (I × Z)	NS	NS	NS

*SEm: standard error of the mean; CD: critical difference; NS: non-significant; CRI: crown root initiation.

Nutrient uptake

Irrigation scheduling significantly influenced nutrient uptake by wheat grain and straw, with the highest uptake recorded under irrigation at CRI + booting + milking stages (Table 4). Compared to irrigation at CRI alone, this treatment increased N uptake by 21.1 % in grain and 17.5 % in straw, P uptake by 27.4 % in grain and 16.7 % in straw and K uptake by 27.7 % in grain and 17.5 % in straw. Zinc uptake was also markedly enhanced, with increases of 31.5 % in grain and 17.7 % in straw over CRI-stage irrigation. These improvements reflect enhanced nutrient availability and translocation under improved soil moisture conditions.

Zinc management exerted a significant effect on nutrient uptake. Basal application of 5.0 kg Zn/ha resulted in the greatest uptake of all nutrients, increasing N uptake by 30.7 % in grain and 17.4 % in straw, P uptake by 30.8 % in grain and 20.7 % in straw and K uptake by 29.3 % in grain and 18.1 % in straw over the control (Table 4). Zinc uptake showed the largest response, increasing by 30.2 % in grain and 18.1 % in straw compared with the control. Foliar application of ZnSO₄ at tillering and ear emergence stages was intermediate but remained significantly superior to the control. The interaction between irrigation scheduling and Zn management was non-significant, indicating that the effects of Zn fertilisation were consistent across irrigation regimes.

Table 4. Nutrient uptake as influenced by various irrigation scheduling and zinc management in wheat

Treatments	Nitrogen uptake (kg/ha)		Phosphorous uptake (kg/ha)		Potassium uptake (kg/ha)		Zinc uptake (g/ha)	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Irrigation scheduling (I)								
Irrigation at CRI stage	45.0	21.1	10.6	3.0	16.6	57.7	94.1	92.6
Irrigation at CRI + booting stage	48.0	22.4	11.9	3.2	18.7	61.2	108.8	98.4
Irrigation at CRI + booting + milking stage	54.5	24.8	13.5	3.5	21.2	67.8	123.7	109.0
SEm (±)	1.4	0.3	0.5	0.1	0.8	0.7	5.1	1.2
CD ($p < 0.05$)	5.4	1.1	2.1	0.2	3.3	2.9	20.1	4.7
Zinc management (Z)								
Control	42.4	20.7	10.4	2.9	16.4	56.8	93.1	91.2
2.5 kg/ha (basal)	47.4	22.2	11.6	3.1	18.2	60.7	106.7	97.5
5.0 kg/ha (basal)	55.4	24.3	13.6	3.5	21.2	67.1	121.2	107.7
Foliar spray of ZnSO ₄ of 0.5 % at tillering and ear emergence stages	51.5	23.6	12.4	3.4	19.7	64.5	114.5	103.7
SEm (±)	1.9	0.6	0.7	0.1	1.1	1.6	6.3	2.6
CD ($p < 0.05$)	5.8	1.7	2.2	0.2	3.3	4.8	18.6	7.7
Interaction (I × Z)	NS	NS	NS	NS	NS	NS	NS	NS

*SEm: standard error of the mean; CD: critical difference; NS: non-significant; CRI: crown root initiation.

Discussion

Growth and yield

The present study demonstrated that irrigation scheduling at CRI + booting + milking stages achieved maximum dry matter accumulation, representing a 19.4 % increase over irrigation at CRI stage alone. This substantial enhancement can be attributed to optimal moisture availability during critical phenological stages, which promoted cell division and elongation in nodes and internodes, thereby facilitating photosynthetic efficiency and assimilate partitioning. These findings corroborate previous results who reported similar improvements in dry matter production under adequate irrigation regimes (23). The marked reduction in dry matter accumulation observed with CRI-only irrigation underscores the detrimental effects of water deficit during tillering and stem elongation phases, consistent with earlier observations (24). Conversely, some studies have reported diminishing returns with excessive irrigation due to waterlogging-induced hypoxia, though such conditions were not observed in the present investigation (25). Furthermore, irrigation at CRI + booting + milking stages produced more effective tillers per square metre, demonstrating the critical importance of moisture availability during tiller differentiation and establishment. This finding is consistent with previous results who

attributed enhanced tillering to improved nutrient mobilisation under optimal soil moisture conditions (26). Irrigation scheduled at CRI, booting and milking stages resulted in the highest grain and straw yield of wheat, likely due to enhanced tiller production, improved leaf photosynthetic efficiency, greater dry matter accumulation, increased crop growth rate and more effective remobilisation of assimilates during the grain-filling period (8).

Basal application of 5.0 kg Zn/ha resulted in the highest dry matter accumulation, though differences among Zn treatments were statistically non-significant at harvest. This response likely reflects zinc's fundamental role as a cofactor in numerous enzymatic systems involved in carbohydrate metabolism, protein synthesis and auxin production (27). Zinc-mediated enhancement of carbonic anhydrase activity facilitates CO₂ fixation, while its involvement in tryptophan synthesis, a precursor of indole-3-acetic acid promotes cell elongation and division (28). The control treatment's inferior performance may be associated with increased oxidative stress, as evidenced by elevated superoxide levels and enhanced lipid peroxidation under zinc-deficient conditions. These findings align with earlier findings, who documented significant improvements in vegetative growth parameters following basal Zn application (29). However, in contrast to our results, some studies have reported superior responses to foliar Zn application in calcareous soils where basal Zn availability is limited by high pH-induced precipitation (13). The observed 5.7 % increase in grain yield with basal Zn application over foliar application aligns with previous findings, who demonstrated the superiority of soil-applied Zn in enhancing wheat productivity (9). However, the combination of basal Zn application at 2.5 kg Zn/ha through ZnSO₄ and 2 foliar sprays of ZnSO₄ of 0.5 % at critical growth stages recorded the highest growth indices, grain yield, establishing it as the optimal Zn nutrition strategy for wheat cultivation (30). The relatively modest difference between basal and foliar Zn applications in our study suggests adequate soil Zn bioavailability, possibly due to favorable soil pH and organic matter content.

Irrigation use efficiency and grain quality

The inverse relationship between irrigation frequency and water use efficiency observed in this study with CRI-stage irrigation exhibiting 71 % higher water use efficiency than CRI + booting + milking stage irrigation reflects the well-established trade-off between yield maximisation and resource use efficiency. This pattern aligns with earlier findings, who documented declining water use efficiency with increasing irrigation applications (31). However, when considering total productivity and farm profitability, the substantial yield advantages of multi-stage irrigation (3812.7 vs. 2847.3 kg/ha) may justify the reduced water use efficiency, particularly in regions with assured water availability. This contrasts with water-scarce environments where deficit irrigation strategies may be more appropriate (32, 33). Zinc application enhanced water use efficiency through its effects on stomatal regulation, photosynthetic efficiency and osmotic adjustment (34). This improvement, though modest, assumes greater significance in water-limited environments where even marginal gains in water productivity translate to substantial economic benefits.

The increase in protein content under CRI + booting + milking stage irrigation, though statistically non-significant, reflects enhanced N assimilation and translocation under adequate moisture conditions. Basal Zn application at 5.0 kg/ha increased protein content over the control, likely through involvement of Zn in

protein synthesis, nucleic acid metabolism and enzyme activation. These findings corroborate those of earlier results, who reported positive correlations between Zn nutrition and grain protein concentration (35). However, some studies have reported no significant Zn effects on protein content in high-fertility soils, suggesting that Zn-protein relationships may be modulated by soil N status and overall nutrient balance (36).

Nutrient uptake dynamics

Irrigation scheduling profoundly influenced nutrient uptake patterns, with CRI + booting + milking stage irrigation increasing N, P, K and Zn uptake. These enhancements reflect improved nutrient solubilisation, root proliferation and mass flow under optimal soil moisture conditions (37). The particularly pronounced effect on Zn uptake suggests that moisture availability is a critical determinant of Zn mobility in soil-plant systems, consistent with earlier observations (10, 12). Basal Zn application at 5.0 kg/ha substantially enhanced uptake of all nutrients, this synergistic effect may be explained by the role of Zn in maintaining root membrane integrity and facilitating nutrient transporter expression (15). The enhanced P uptake observed with Zn application is particularly noteworthy, as Zn-P interactions are complex and often antagonistic at high concentrations (38, 39). The absence of a significant interaction implies that Zn availability and plant uptake were not strongly influenced by the tested irrigation regimes. Therefore, Zn fertilisation remains an effective strategy for improving wheat performance under both limited and adequate irrigation conditions. Our results suggest that at optimal Zn application rates, positive interactions predominate, facilitating overall nutrient acquisition. These findings support previous works, who reported improved nutrient use efficiency following soil Zn application (40).

Conclusion

Irrigation scheduling at CRI, booting and milk stages combined with basal application of zinc (Zn) at 5.0 kg ha⁻¹ is recommended for achieving higher wheat growth, yield and nutrient uptake, with performance comparable to foliar application of ZnSO₄ at 0.5 % applied at tillering and ear emergence stages. However, irrigation at the CRI stage alone may be preferred under limited water conditions due to higher water use efficiency. Thus, integrated irrigation scheduling and Zn management can enhance wheat productivity, water productivity and grain quality under similar agro-ecological conditions.

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Authors' contributions

Conceptualisation was carried out by SN and RK. Methodology was developed by SN and RK. Formal analysis and investigation were performed by SN, RK and D. The original draft was prepared by SN, RK and SS. Review and editing of the manuscript were done by RK, D, SK and SS. Resources were provided by RK. Supervision was undertaken by RK, D and SK. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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