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Crop Production

Effects of Irrigation Regimes and Nutrient Application Modules on Wheat Growth, Phenology and Yield Contributing Characteristics of Wheat

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Abstract

A field experiment was conducted during the rabi season of 2022–23 and 2023–24 at the Water Management Research Farm, CSKHPKV, Palampur, to assess the effect of irrigation regimes (60, 80, and 100% ETc; main plot) and nutrient modules (subplot) on wheat growth and yield in a split-plot design with three replications. Irrigation at 100% ETc produced significantly taller plants (81.7 and 81.3 cm), heavier earheads (2.54 and 2.53 g), and higher grain (1440.7 and 1428.1 kg/acre), straw yields (2155.9 and 2138.0 kg/acre) and maximised gross returns (INR 46070.8 and 45674.3/acre) during 2022–23 and 2023–24, respectively. Among nutrient modules, 75% NPK + nano-DAP + nano-Si + nano-Zn recorded taller plants (82.6 and 82.3 cm), higher test weight (43.6 and 42.7 g), grain yield (1276.7 and 1265.7 kg/acre), straw yield (1905.6 and 1889.9 kg/acre), and gross returns (INR 40798.5 and 40451.1/acre) under north-western Himalayan conditions of Himachal Pradesh.

Keywords: Growth, Irrigation, Nutrients, Wheat, Yield

Wheat is a staple food crop for more than 35% of the global population, with a significant contribution in ensuring world food security[1]. Wheat supplies more than 20% of the global protein and calories consumed by the world population[2]. Future demographic scenarios have projected the world population to reach 9.8 billion by 2050, wherein cereal demand will rise by about 70%, especially for wheat in Asia and Africa due to dietary regimes[3]. To meet the rising wheat demand, the productivity levels for the wheat crop need to be increased from the present 3.48 ton/hectare to 5 ton/hectare[4,5]. Contrary to the rising demand, wheat productivity faces significant limitations such as shrinking arable land, degraded arable lands, erratic, irregular precipitation patterns and declining availability of irrigation water resources[6,7]. Apart from current present limitations, futuristic climatic studies have projected a considerable rise in atmospheric temperature and carbon dioxide levels under the scenario of climate change in the upcoming times[8,9]. To cope with rising constraints in cereal productivity levels, agronomic practices can play a vital role in

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sustaining and enhancing wheat productivity levels. Nutrient management practices and irrigation regimes are the significant agronomic interventions affecting wheat field productivity levels. Reduced irrigation levels or reduced water volume applications can affect and certainly bring down wheat productivity levels[10,11]. Nutrient management practices based on application of nutrient nano-formulations, such as silicon, zinc and phosphorus, have been found to improve wheat biomass productivity under deficit irrigation regimes[12]. Phosphorus, being a primary macronutrient, is a foundational component of plant biological molecules such as nucleic acids, adenosine triphosphate, phospholipids and nucleotide co-enzymes[11,13]. Zinc application has been advocated to improve plant water status, stomatal functioning and physiological functioning by acting as a cofactor for a significant number of metabolic enzymes. Apart from Zn and P, Silicon have been known to counter the effects of drought on wheat growth with regulation of antioxidant enzymes, cell-membrane stability and relative leaf water content[14]. Plant nutrient nano-formulations have been reported to have considerable positive effects on crop growth and nutrient accumulation[15,16]. Exogenous application of silicon, zinc and phosphorus, especially as nano-formulations, can help crop plants curtail the malign effects of limited water application regimes in wheat. Limited scientific information has been reported on the integrated application of irrigation regimes and nutrient application modules in wheat, especially under conditions of the north-western Himalayas of Himachal Pradesh.

Therefore, the present investigation was planned to evaluate the effects of limited water application regimes and nutrient application modules on wheat growth, yield contributing characters, yield and economics of wheat under conditions of the north-western Himalayas of Himachal Pradesh. The hypothesis for the present field investigation was that the exogenous application of nutrients would alleviate the effects of drought on wheat, with considerable improvements in growth, yield, and profitability.

Materials and Methods

The present field investigation was carried out during the *rabi* season of 2022-23 and 2023-24 at Water Management Research Farm, Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The experiment site is located at 1282 meters above mean sea level with location attributes of 32° 06′ 05′′ N latitude and 76° 33′ 02′′ E longitude. The soil at the experimental site was silty clay loam in texture, acidic soil reaction, with soil availability range for nitrogen, phosphorus and potassium being 281.5, 24.6 and 176.3 kg ha^{-1}, respectively. The field experiment was conducted in a split-plot design wherein 7 nutrient application modules and 3 irrigation regimes were evaluated with three replications under main and sub-plots, respectively. The water application modules (main plot) include 60, 80 and 100% of crop water requirement (ET_C), while nutrient application modules (Sub-plot) comprised of 75 and 100% dose of recommended NPK supplemented with nano DAP + nano Si, nano DAP + nano Zn and nano DAP + nano Si + nano Zn along with 100% recommended NPK. The crop water requirement (ET_C) for various application modules was derived using CROPWAT 8.0.

The gross size of the experimental plot was 7.2 m^2 (1.8 m × 4 m), whereas the net size was 4.2 m^2 (1.2 m × 3.5 m). The field was prepared using a power tiller and a hand plough, followed by line sowing of wheat crop variety "HPW-236" at a rate of 100 kg/ha. The crop sowing was done on 17th November 2022 and 15th November 2023, respectively**.** The crop was sown at a spacing of 20 cm and at a depth of 5 cm. The nutrient sources were urea (46%), single super phosphate (16% P), muriate of potash (60% K), IFFCO-manufactured nano DAP (8% N and 16% P_2O_5) @ 4 mL L^{-1}, DVS biolife origin nano zinc (6%) @ 2 mL L^{-1} and nano silicon (5%) @ 1 mL L^{-1}. The irrigation schedules were developed based on daily climatic data as observed by the meteorological observatory of the Department of Agronomy.

To keep weed population below threshold levels, a post-emergence application of herbicide Vesta @ 400 g ha^{-1} (clodinofop propargyl 15% + metsulfuron methyl 1% WP) was done, followed by hand weeding after crop flowering. No plant protection measures were adopted for crop pests and diseases, as a significant prevalence of pests or diseases was not observed. The crop was harvested manually using sickles at physiological maturity from the net plot area, dried in the sun, tied as bundles and threshed manually.

The field data on growth parameters such as plant height and number of tillers per square meter, and yield contributing characters (earhead weight and test weight) were collected by selecting five plants randomly from the net plot area. The grain and straw yield were measured using the respective biomass from the net plot area. Gross returns were calculated by multiplying the prevailing market price by the respective yield levels. The mean values were derived by averaging recorded data to report field experimental data. The data were subjected to analysis of variance using procedures prescribed by Gomez and Gomez[17] for split-plot design.

RESULTS AND DISCUSSION

Growth Attributes

Crop plant height at 60, 90, and 120 Days After Sowing (DAS) and at harvest was significantly influenced by

Table 1. Effect of nutrient application modules and irrigation regimes on wheat plant height

Treatment	60 DAS		90 DAS		120 DAS		At harvest	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Irrigation levels								
I_1 (60% of ET_C)	19.56	19.13	39.06	38.71	66.00	65.41	71.62	70.69
I_2 (80% of ET_C)	22.09	21.85	42.54	41.96	70.91	70.32	75.65	74.55
I_3 (100% of ET_C)	24.50	24.12	46.71	46.21	79.96	78.79	81.69	81.26
SEm±	0.52	0.53	0.81	0.84	1.08	1.01	0.97	0.95
CD (P=0.05)	2.04	2.10	3.18	3.30	4.23	3.95	3.91	3.85
Fertilizer treatments								
N_1 (75% NPK + nano DAP + nano Si)	22.92	22.53	43.98	43.46	77.80	76.51	80.60	78.84
N_2 (75% NPK + nano DAP + nano Zn)	22.27	21.79	42.69	42.43	75.94	75.05	79.20	77.64
N_3 (75% NPK + nano DAP+ nano Si+ nano Zn)	23.86	23.61	45.19	44.78	79.78	79.37	82.61	82.34
N_4 (50% NPK + nano DAP + nano Si)	20.60	20.48	40.89	40.43	63.17	62.68	69.49	68.82
N_5 (50% NPK + nano DAP + nano Zn)	20.10	19.78	40.77	39.87	62.58	61.95	68.61	68.10
N_6 (50% NPK+ nano DAP+ nano Si + nano Zn)	21.21	20.60	41.35	40.93	67.89	66.99	72.34	71.91
N_7 (100% NPK)	23.40	23.11	44.54	44.19	78.86	78.00	81.38	80.82
SEm±	0.34	0.38	0.42	0.47	0.67	0.72	0.74	0.95
CD (P=0.05)	0.96	1.10	1.22	1.34	1.93	2.07	2.12	2.74

the application of nutrient application modules and irrigation regimes (Table 1). Applying irrigation at 100% of the ET_C regime led to significantly higher plant height across the observational time period, i.e., 60, 90, 120 DAS and at harvest as compared to water limiting conditions (60 and 80% of ET_C). The lowest wheat plant height was recorded when the crop was irrigated using water volume equivalent to 60% of ET_C. Lower irrigation regimes may have led to significant diversion of above-ground carbohydrates to the underground sink under water-limited conditions, leading to considerably lower above-ground growth and plant height.

Among nutrient management practices, an integrated application of 75% NPK + nano DAP + nano Si + nano Zn was observed to result in the highest plant height across all observational stages, which was at par with the 100% of recommended NPK application (Table 1). However, nutrient management practices based on 50% NPK application were found to result in considerably lower plant height for the wheat crop. Curtailed nutrient application may have limited the cell growth, elongation and division at plant physiological levels[18], leading to reduced plant height. Notable increments in wheat plant height were reported with application of inorganic fertilisers during the field investigation by Parewa *et al.* 2022[19] as compared to treatments based on abstained nutrient application. Plant height for wheat was further reported to be increased by around 43% with integrated application of NP (75% of RDF), seed treatment along with foliar sprays nano-diammonium phosphate (@0.4%)[20]. 15% increment in wheat plant height was reported by Ahmadian *et al*[21] (2021) with the application of nano-zinc when compared to the control under water-limited conditions. Similarly, the researchers further reported that the wheat plant height was increased by 26% with the application of nano-silicon when compared to the control under water-limited conditions.

Number of Tillers Per Square Meter

Irrigation regimes were found to exert a significant influence over the number of tillers per square meter at all growth intervals except at 60 DAS. The highest number of tillers per square meter was recorded under full irrigation at 100% ET_C level, followed by 80% ET_C, although it was at par with 100% ET_C, while the lowest number of tillers per square meter was recorded with 60% ET_C level.

Nutrient application practices were found to exert a significant influence over the number of tillers per square meter at 60, 90, 120 days after sowing and at harvest (Table 2). Applying 75% of the recommended NPK along with foliar spray of nano-formulations of nano DAP + nano Si + nano Zn resulted in a considerably higher number of tillers per square meter. Application of 100% recommended NPK resulted in a comparatively equivalent number of tillers per square meter when compared to 75% NPK + nano DAP + nano Si + nano Zn. Nutrient management practices based on 50% of NPK resulted in considerably lower numbers of tillers per square meter (Table 2). The lowest number of tillers per square meter was recorded for the application of 50% NPK + nano DAP + nano Zn. A considerable increase in the number of tillers per square meter can be attributed primarily to higher nutrient availability with 75% and 100% NPK based application modules. Substantially higher nutrient supply may have promoted photosynthetic activity, biomass accumulation and subsequent improved vegetative growth[22], leading to higher tiller count. In a parallel field investigation reported by Parewa *et al.* 2022[19], a notable increment in the number of tillers per square meter from 75.13 to 104.71 was observed when nutrient application was increased from 0 to 100% of the recommended NPK. Integrated application of NP (75% of RDF), seed treatment along with foliar sprays nano-diammonium phosphate (@0.4%) was found to result in 40% increment in the number of tillers per square meter as compared to the control (no nutrient application) for wheat as reported by Thakur *et al.* 2024[20]. However, irrigation regimes could not exert any significant influence over the number of tillers per square meter.

Table 2. Effect of nutrient application modules and irrigation regimes on the number of tillers per square meter

Treatment	60 DAS		90 DAS		120 DAS	
Irrigation levels	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
I_1 (60% of ET_C)	246.56	234.51	251.40	240.06	238.33	231.53
I_2 (80% of ET_C)	256.46	243.35	262.41	251.45	249.89	246.16
I_3 (100% of ET_C)	260.10	246.45	267.08	255.39	256.31	253.11
SEm±	3.66	3.28	3.69	3.19	3.91	4.58
CD (P=0.05)	NS	NS	14.48	12.52	15.35	17.98
Fertilizer treatments						
N_1 (75% NPK + nano DAP + nano Si)	262.36	250.12	268.61	256.31	257.49	252.65
N_2 (75% NPK + nano DAP + nano Zn)	258.48	246.87	264.89	253.47	252.98	248.55
N_3 (75% NPK + nano DAP+ nano Si+ nano Zn)	277.20	262.42	282.68	271.26	265.27	260.44
N_4 (50% NPK + nano DAP + nano Si)	237.71	225.61	242.97	231.55	232.59	229.09
N_5 (50% NPK + nano DAP + nano Zn)	231.66	218.54	238.31	226.89	228.12	221.85
N_6 (50% NPK+ nano DAP+ nano Si + nano Zn)	243.45	229.56	249.53	239.64	239.64	236.36
N_7 (100% NPK)	269.76	256.94	275.08	263.66	261.15	256.29
SEm±	5.01	4.62	4.94	4.75	4.48	4.16
CD (P=0.05)	14.44	13.30	14.23	13.67	12.84	11.93

Yield Attributes

Irrigation levels significantly influenced the weight of earhead during both years, i.e., 2022-23 and 2023-24, respectively. The highest ear head weight was observed under 100% ET_C, followed by 80% ET_C, while the lowest ear head weight was observed under 60% ET_C. On the other hand, test weight was not significantly influenced by irrigation levels.

The weight of ear head and test weight were significantly influenced by the effect of nutrient application modules (Table 3). Application of 75% NPK + nano DAP + nano Si + nano Zn resulted in the highest ear head weight (2.25 and 2.24 g for 2022-23 and 2023-24, respectively) and test weight (43.59 and 42.70 g for 2022-23 and 2023-24, respectively). Similarly, applying nutrient application module based on recommended dose of fertilizers (100% NPK) (2.20 and 2.18 g for ear head weight in 2022-23 and 2023-24, respectively and 43.4 and 42.4 g for test weight in 2022-23 and 2023-24, respectively) performed at par with 75% NPK + nano DAP + nano Si + nano Zn application in terms of ear head weight and test weight (Table 4). A positive effect of nutrient application on wheat test weight was reported by Parewa *et al*[19] (2022), wherein they reported almost 21% increment in test weight with 100% NPK based fertilizer application as compared to the control, wherein fertiliser application was completely abstained. Wheat test weight was reported to be increased by 6.7% with integrated application of NP (75% of RDF), seed treatment along with foliar sprays nano-diammonium phosphate (@0.4%)[20]. Ahmadian and his co-workers in 2021 reported that wheat test weight was increased by 25.8% with the application of nano-zinc as compared to control and water deficit conditions. Application of nano-silica was further reported to increase the wheat test weight by 45% when compared to the control under water deficit conditions. The lowest ear head weight

Table 3. Effect of nutrient application modules and irrigation regimes on earhead weight and test weight

Treatment	Weight of ear head (g)		Test weight (g)		Grain yield (q/ha)		Straw yield (q/ha)	
Irrigation levels	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**	**2022-23**	**2023-24**
I_1 (60% of ET_C)	1.75	1.74	41.09	40.02	22.25	20.89	33.42	31.38
I_2 (80% of ET_C)	2.01	1.99	41.77	40.67	30.35	30.04	45.46	45.01
I_3 (100% of ET_C)	2.54	2.53	42.53	41.84	36.02	35.70	53.90	53.45
SEm±	0.00	0.01	0.63	0.52	0.43	0.52	0.67	0.78
CD (P=0.05)	0.02	0.02	NS	NS	1.71	2.05	2.65	3.06
Fertilizer treatments								
N_1 (75% NPK + nano DAP + nano Si)	2.18	2.17	42.83	41.67	31.22	30.32	46.65	45.32
N_2 (75% NPK + nano DAP + nano Zn)	2.13	2.12	42.44	41.36	30.46	29.62	45.74	44.50
N_3 (75% NPK + nano DAP+ nano Si+ nano Zn)	2.25	2.24	43.59	42.70	31.92	31.64	47.64	47.25
N_4 (50% NPK + nano DAP + nano Si)	1.97	1.95	40.00	39.38	26.59	25.95	40.04	39.09
N_5 (50% NPK + nano DAP + nano Zn)	1.93	1.92	39.90	38.14	26.07	25.59	39.15	38.46
N_6 (50% NPK+ nano DAP+ nano Si + nano Zn)	2.03	2.02	40.44	40.24	28.87	28.09	43.24	42.09
N_7 (100% NPK)	2.20	2.18	43.40	42.40	31.66	30.92	47.36	46.23
SEm±	0.02	0.02	1.03	1.08	0.30	0.32	0.45	0.45
CD (P=0.05)	0.05	0.04	2.95	3.10	0.85	0.90	1.29	1.29

(1.93 and 1.92 g for 2022-23 and 2023-24, respectively) and test weight (39.9 and 38.4 g for 2022-23 and 2023-24, respectively) were recorded with the application of 50% NPK + nano DAP + nano Zn. Significant reduction in yield contributing characteristics was further reported by Kumari *et al.*[10] (2025a), under limited irrigation regimes in wheat.

Irrigating the crop at 100% of ET_C was found to result in substantially higher grain (36.02 and 35.70 q/ha for 2022-23 and 2023-24, respectively) and straw yield (53.90 and 53.45 q/ha for 2022-23 and 2023-24, respectively) levels during both the years of field investigation (Table 3). However, irrigating the crop at 80% of ET_C resulted in considerably lower levels of grain and straw yield as compared to 100% of ET_C (Table 5). The lowest yield levels were recorded for the treatment based on 60% of ET_C. Reduction in yield levels can be attributed to shorter plants, reduced number of tillers per square meter, as well as reduced earhead and test weight for wheat crop under reduced irrigation levels. In a similar study reported by Ahmadian and his co-workers in 2021, a considerable reduction in wheat yield levels was reported when the irrigation amount was reduced from 100% to 50% of the recommended amount. Decline in wheat grain yield levels with reduced irrigation amount was also reported by Getachew *et al.* 2025[3].

Among nutrient application modules, fertilizing the crop by 75% NPK + nano DAP + nano Si + nano Zn resulted in substantially higher grain of 31.92 and 31.64 q/ha and straw yield of 47.64 and 47.25 q/ha for 2022-23 and 2023-24, respectively which were found to be at par with crop fertilization based on recommended dose of fertilizers (100% NPK) (Table 5). However, the nutrient application module based on the application of 75% NPK + nano DAP + nano Zn was found to result in statistically lower levels of grain and straw yield. Similarly, nutrient application modules based on 50% NPK, i.e., 50% NPK + nano DAP + nano Si, 50% NPK + nano DAP + nano Zn and 50% NPK + nano DAP + nano Si + nano Zn performed consistently poor than 75% NPK and 100% NPK based modules. Lower yield levels with 50% NPK based modules may have been due to insufficient supply of crop nutrients to the soil solution as compared to 100% NPK based modules. However, application of nano-formulations of silicon, phosphorus and zinc was found to have positive effects in terms of yield levels[11]. Experimental findings in terms of nano-formulations can further be supported by study results reported by Ahmadian *et al.*,[21] wherein there were significant increments in wheat grain yield levels with application of silica and zinc nano-formulations.

Economic Studies

The gross returns per hectare (INR 115176.90 and 114185.8 for 2022-23 and 2023-24, respectively), as expected, were found to be the highest for the irrigation module based on 100% $ET_{C,}$ whereas the lowest gross returns were found for the lower levels of irrigation, i.e., 60% of ET_C (Table 4). However, irrigating the crop at 80% of ET_C was found to result in gross returns of INR 97071.9 and 96092.08 for 2022-23 and 2023-24, respectively. Substantially lower yield levels under lower irrigation levels (60 and 80% ET_C) can be considered to be the primary reason for reduced gross returns for 60 and 80% ET_C based irrigation regimes. The findings for the present investigation can be supported by the

Table 4. Effect of nutrient application modules and irrigation regimes on economics

Treatment	Cost of cultivation (₹/ha)		Gross returns (₹/ha)	
	2022-23	2023-24	2022-23	2023-24
Irrigation levels				
I1 (60% of ET_c)	40680.58	40680.58	71236.48	66865.1
I2 (80% of ET_c)	41288.08	41288.08	97071.9	96092.08
I3 (100% of ET_c)	42199.33	42199.33	115176.9	114185.8
Fertilizer treatments				
N1 (75% NPK + nano DAP + nano Si)	42245.73	42245.73	99787.68	96924.35
N2 (75% NPK + nano DAP + nano Zn)	42296.35	42296.35	97496.2	94826.78
N3 (75% NPK + nano DAP + nano Si + nano Zn)	43663.23	43663.23	101996.1	101127.8
N4 (50% NPK + nano DAP + nano Si)	40418.05	40418.05	85176.38	83149.88
N5 (50% NPK + nano DAP + nano Zn)	40468.68	40468.68	83441.7	81932.5
N6 (50% NPK + nano DAP + nano Si + nano Zn)	41835.55	41835.55	92340.8	89863.48
N7 (100% NPK)	38797.68	38797.68	101226.8	98842.13

results reported by Kumari and her co-workers in 2025b, wherein they emphasised reduced gross returns for wheat crop under lower irrigation regimes.

Among nutrient application modules, application of 75% NPK + nano DAP + nano Si + nano Zn resulted in the highest gross returns, which were 40798.45 and 40451.12 for 2022-23 and 2023-24, respectively (Table 4). Similarly, numerically comparable gross returns were reported with the application of the recommended dose of fertilisers, i.e., 100% of NPK, which were 40490.71 and 39536.85 for 2022-23 and 2023-24, respectively. The lowest gross returns (INR 33376.68 and 32773.00 for 2022-23 and 2023-24, respectively) were reported with the application of 50% NPK + nano DAP + nano Zn. Nutrient application modules based on 50% of NPK application resulted in considerably lower gross returns as compared to 50% NPK based modules. Lower yield levels under reduced nutrient application-based modules have been found responsible for correspondingly lower gross returns.

CONCLUSION

The field investigation concluded that reducing the irrigation water supply can substantially bring down growth and yield contributing characteristics of wheat, which can be considerably countered by integrated application of primary macronutrients (75% NPK) along with nano-formulations of micronutrients such as phosphorus (DAP@ 4 ml l^{-1}), silicon (Si @ 1 ml l^{-1}) and zinc (Zn @ 2 ml l^{-1}). The benign effects of integrated nutrient application were reflected with considerably improved plant height, earhead weight, grain and straw yield, along with substantially improved levels of gross returns.

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AUTHORS CONTRIBUTION

GC: Conceptualization, Data Acquisition, Formal analysis, Manuscript Writing – reviewing and editing AK: Conceptualization, Project Administration, Methodology, Supervision, Resources; SM: Project Administration, Methodology, Supervision, Resources; SS: Project Administration, Supervision RK: Project Administration, Supervision; TS: Formal analysis, Manuscript Writing – reviewing and editing