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Growth and Yield Response of Rice-Wheat to Moisture Regimes and Soil–foliar Amendments

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Abstract

The pot experiment was conducted during *kharif* and *rabi* 2024-2025 at the Irrigation and Water Management Farm, CSKHPKV, Palampur, to evaluate soil and foliar amendments under different irrigation regimes on the growth and yield of rice-wheat. The experiment was laid out in a two-factor CRD with irrigation: I1, I2 and I3 corresponding to 70, 90, 100 % well watered condition (WWC) in rice and 60, 80, 100 % in wheat, respectively and amendments A1:no amendments; A2:hydrogel @ 4 kg/ha (soil application); A3:nano-Zn @ 2 mL/L (foliar spray); A4:nano-Si @ 1 mL/L (foliar spray); A5:hydrogel + nano-Zn; A6:hydrogel + nano-Si. 100% WWC produced significantly taller plants (103.49 cm), dry matter accumulation (773.79 g/m^2), grain yield (275.81 g/m^2) and straw yield (505.43 g/m^2) during *kharif* and 88.18 cm, 970.04 g/m^2, 411.93 g/m^2 and 592.37 g/m^2 during *rabi* season, respectively. Among soil and foliar amendments, the combined application of hydrogel + nano-Si recorded maximum growth and yield, which were statistically comparable to the sole foliar application of Si. Furthermore, a significant interaction was found between both irrigation and amendment treatments.

Keywords: Growth, Hydrogel, Irrigation, Silicon, Yield, Zinc

Rice (*Oryza sativa* L.) in *kharif* and wheat (*Triticum aestivum* L.) in *rabi* together constitute the rice-wheat cropping system, one of the most extensively practised and food security critical double cropping sequences across South and South-East Asia[1]. This system feeds more than one billion people across the Indo-Gangetic Plains and the north-western Himalayan region, contributing substantially to both regional and national food security[2]. Rice and wheat together supply more than 50% of the dietary energy consumed by the world's population, making their sustained productivity indispensable for global food security[3]. However, the productivity of the rice–wheat system faces mounting challenges attributable to erratic and declining precipitation, increasing frequency of drought episodes, and shrinking availability of irrigation water resources[4,5]. Water deficit is widely recognised as the most critical

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abiotic stress constraining cereal productivity under both field and controlled conditions[6]. In the context of accelerating climate change, futuristic projections indicate a continued rise in atmospheric temperature and unpredictable precipitation patterns, expected to further intensify moisture stress in cereal production systems across the north-western Himalayas[7].

Moisture stress adversely affects a cascade of physiological and biochemical processes in both rice and wheat, including reduced cell division and elongation, impaired stomatal conductance, decline in photosynthetic activity, and disruption of assimilate partitioning to developing grains[6,8]. These adverse responses ultimately manifest as reduced plant height, lower dry matter accumulation, fewer effective tillers, and significant yield losses[9,10,11]. Soil amendments capable of improving the water retention capacity of the root zone have therefore attracted considerable research attention as potential tools for mitigating deficit irrigation effects. Hydrogels are super absorbent polymeric materials that absorb and retain several hundred times their own weight of water, releasing it gradually in response to soil matric potential gradients, thereby sustaining moisture availability to the crop root zone over prolonged dry intervals[12]. The application of hydrogels has been reported to enhance germination, seedling establishment, and vegetative growth of cereals under water-limited conditions by maintaining adequate rhizosphere moisture and reducing plant water stress[12,13].

In addition to soil-applied amendments, foliar application of micronutrients in nano-formulated form has emerged as a promising strategy to alleviate the deleterious effects of drought on cereal crops. Silicon (Si) is a beneficial quasi-essential element that improves drought tolerance in cereals by enhancing cell membrane stability, regulating stomatal conductance, improving photosynthetic efficiency, and stimulating antioxidant enzyme activity[14,15]. Nano formulations of Si are characterised by a higher surface-area-to-volume ratio compared to conventional Si sources, enabling more efficient foliar uptake and translocation within the plant[16]. Zinc (Zn) is an essential micronutrient that functions as a cofactor for metalloenzymes involved in carbohydrate metabolism, protein synthesis, and auxin regulation; its deficiency under drought severely impairs plant growth and grain development[17]. Ahmadian *et al.*,[18] reported significant improvements in wheat plant height, dry matter accumulation, test weight, and grain yield with foliar application of nano zinc and nano silica under deficit irrigation. Combined application of nano Si and nano Zn has been suggested to produce synergistic improvements in plant water status and biomass productivity under moisture-limited environments[19].

Despite the promising individual effects of hydrogels, nano Si, and nano Zn, limited scientific information is available on their integrated application under varying irrigation regimes for the rice–wheat cropping system, particularly under the agro-climatic conditions of the north-western Himalayas of Himachal Pradesh. The present investigation was therefore conducted to evaluate the effects of different moisture regimes and soil-foliar amendment combinations on the growth, yield attributes, and productivity of rice and wheat under pot culture conditions. The hypothesis underlying the investigation was that the combined soil application of hydrogel with either nano Si or nano Zn would effectively alleviate the adverse effects of moisture stress, resulting in significant improvements in growth, dry matter accumulation, and grain yield across varying sufficient irrigation condition levels.

MATERIALS AND METHODS

The present experiment was conducted during the *kharif* and *rabi* seasons of 2024-2025 at the Irrigation and Water Management Research Farm of the Department of Soil Science, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The area lies at 32° 06′ 05′′ N latitude and 76° 33′ 02′′ E longitude at an elevation of 1282 meters above mean sea level in the Kangra district of Himachal Pradesh, India.

A pre-sowing composite soil sample was assessed for its physical and chemical properties. The soil was found to have a silty clay loam texture, a low pH (5.42), and an organic carbon content of 0.78%, soil available nitrogen, phosphorus and potassium content of 283.1, 27.3 and 179.3 kg ha^{-1}, respectively. The 18 treatment combinations were imposed in a completely randomised design with factorial arrangement and three replications for each treatment, with the first and second replication repeated twice and therefore 90 pots were used during the pot experiment. The treatment comprised of three irrigation regimes as factor A [I_1:70% WWC (762 mL of water per pot); I_2:90% WWC (980 mL of water per pot); I_3:100% WWC (1089 mL of water per pot) in rice and I_1:60% WWC (528 mL of water per pot); I_2:80% WWC (704 mL of water per pot); I_3:100% WWC (880 mL of water per pot) in wheat] and six soil and foliar amendments in each crop as factor B [A_1: No amendments; A_2: Hydrogel; A_3: Nano Zn; A_4: Nano Si; A_5: Hydrogel + Nano Zn; A_6: Hydrogel + Nano Si]. The doses of nano Zn @ 2mL/L, nano Si @ 1mL/L as foliar spray and hydrogel@4kg/ha (Soil applied) were used. WWC represents well-watered conditions at soil field capacity (FC) @31% calculated by the gravimetric method.

The pots with a 10 kg capacity were selected for the experiment. The pots were filled with 10 kg of air-dried sieved soil from the experimental field mixed with FYM. Variety *Him Palam Lal Dhan* 1 (HPR 2795) for direct-seeded rice and Variety HPW-368 of wheat were used for sowing. Ten seeds were sown at a depth of 5 cm. Two weeks after germination, five healthy plants were left per pot by thinning. Sowing was done on 18th June, 2024, and 19th November 2024 for the *kharif* and *Rabi* seasons of 2024-25. The plants were watered based on the gravimetric method as per the protocol mentioned by Imakumbili (2019)[20] for different treatments. The water treatment for the pots of the well-watered group (100% WWC) was maintained for optimum water level throughout the experiment. The watering of the drought-stressed groups was done by determining the FC every day at the same time by weighing the pots and replacing water in the pots with the same weight. The nutrient sources were Urea (46% N), single super phosphate (16% P) and muriate of potash (60% K). 50% of the recommended nitrogen and the entire quantity of phosphorus and potassium were applied at the time of sowing. The remaining nitrogen was applied in two equal splits at crown root initiation and the booting stage. In addition, AI Nidhi hydrogel (Pusa Hydrogel) supplied by KCH India Private Limited was used as the soil amendment, and DVS biolife origin nano zinc (6%) @ 2 mL/L and nano silicon (5%) @ 1 mL/L were applied as foliar application. Nano-fertiliser-based foliar application was done twice at the active tillering stage and the grain filling stage. Weed management was carried out using Vesta at the rate of 0.4 kg/ha. The plants were harvested manually on 5th October, 2024, and 27th April, 2025, for the *rabi* season of 2024–25.

RESULTS AND DISCUSSION

Plant height of rice at physiological maturity was significantly influenced by different irrigation regimes (WWC levels) and soil–foliar amendments (Table 1). Full irrigation (100% WWC) recorded significantly taller plants, followed by 90% WWC, whereas the lowest plant height was observed under 70% WWC. This might be due to the maintenance of adequate and continuous moisture availability to the plant, which promoted good establishment of roots and sustained metabolic activities. Similarly, researchers have reported the production of taller rice plants due to the maintenance of an optimal irrigation regime Azarpour *et al*.,[21], Chowdhury *et al*[22].

Among soil and foliar amendments, the tallest plants for rice were recorded with the combined application of hydrogel + foliar application of nano-Si. The treatment was found to be statistically at par with the sole foliar application of nano-Si (Table 2). The beneficial influence of silicon application on plant height is associated with improved water relations, maintenance of leaf turgor, and enhanced physiological efficiency under water-limited conditions. Silicon

has been reported to improve drought tolerance in wheat by regulating stomatal conductance, improving photosynthetic performance, and stabilising cell membranes, thereby sustaining vegetative growth under moisture stress. This could be attributed to an adequate silicon supply, which may have improved the photosynthetic activity that enabled the rice plant to accumulate sufficient photosynthates. 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. In conjunction, Roy *et al.*,[12] recorded a higher plant height with the application of hydrogel in rice, and Rijula *et al.*,[23] reported improved rice growth parameters with foliar application of a silicon-based biostimulant under Palampur conditions.

Dry matter accumulation of the wheat crop was significantly influenced by the different irrigation regimes. Among different water regimes, the maximum dry matter accumulation was registered with full irrigation (100% WWC), followed by 90% WWC and the lowest with 70% WWC (Table 1). The higher dry matter accumulation may be attributed to the maintenance of adequate moisture in the rhizosphere under full irrigation, which promoted better root growth, enhanced nutrient mobilisation, and a higher photosynthetic rate through improved stomatal conductance. These results also conform to the findings of Vishuddha *et al.*,[24] Zhan-Jiang *et al.*,[25] and Kumar *et al.*,[2] who reported higher dry matter accumulation with higher irrigation levels.

Table 1. Effect of irrigation regimes, soil and foliar amendments on growth and yield parameters of rice

Treatment	Plant Height (cm)	Dry Matter Accumulation (g/m^2)	Grain Yield (g/m^2)	Straw Yield (g/m^2)	Biological Yield (g/m^2)	Harvest Index (%)
Irrigation Regimes						
I_1 (70% WWC)	96.41	539.16	171.87	340.87	512.73	33.55
I_2 (90% WWC)	100.28	681.93	236.35	450.05	686.40	34.37
I_3 (100% WWC)	103.49	773.79	275.81	505.43	781.24	35.18
SEm±	0.60	4.56	3.30	4.60	5.82	0.42
CD (P=0.05)	1.71	13.07	9.48	13.19	16.69	1.21
Soil and Foliar Amendments						
A_1 (No amendments)	97.12	643.51	196.34	377.95	574.29	34.28
A_2 (Hydrogel)	97.25	644.90	200.51	388.91	589.42	33.99
A_3 (Nano Zn)	99.98	665.03	222.77	428.56	651.32	33.95
A_4 (Nano Si)	102.72	684.43	251.80	466.36	718.16	34.91
A_5 (Hydrogel + Nano Zn)	100.04	665.67	233.59	447.60	681.19	34.09
A_6 (Hydrogel + Nano Si)	103.25	686.22	263.05	483.32	746.37	34.99
SEm±	0.84	6.44	4.67	6.50	8.23	0.60
CD (P=0.05)	2.42	18.48	13.40	18.66	23.61	NS

The effects of different soil and foliar amendments were significant on dry matter accumulation. The maximum dry matter accumulation was recorded with the combined application of hydrogel (4 kg ha^{-1}) + foliar application of nano-Si (1 mL/L), and both treatments were statistically at par. Higher accumulation of photosynthates might have given higher dry matter production, as this aligns with the study done by Rani and Narayanan[15].

The grain, straw, and biological yield of rice were all significantly influenced by the various water and soil–foliar amendment combinations applied (Table 1). Application of full irrigation (100% WWC) increased the grain yield, straw yield and biological yield significantly over 90% WWC and 70% WWC. The lowest yield levels were recorded for the treatment based on 70% of WWC during 2024–25. The highest grain, straw, and biological yield under full irrigation indicate that regular distribution of water supports the root zone for better root growth, enhanced assimilate production, translocation to developing grains, and improved partitioning efficiency[13].

Among soil and foliar amendments, the highest grain, straw and biological yield for rice were obtained with the combined application of hydrogel (4 kg ha^{-1}) + foliar application of nano-Si (1 mL/L). This treatment was found to be statistically at par with the sole foliar application of nano-Si (Table 2). The lowest grain yield was recorded with no amendments and was statistically comparable to the application of hydrogel alone. In a similar study reported by Kheyri *et al.*[26], the Si and Zn application by both foliar (nano) and soil significantly increased yields compared with the control. With respect to irrigation regimes, a significantly higher harvest index was recorded under 100% WWC, although it was statistically at par with the harvest index observed under 90% WWC. The lowest harvest index was observed under 70% WWC. However, soil and foliar amendments had no significant effects on the harvest index of rice during *Kharif* 2024. A statistically significant interaction was observed between irrigation regimes and soil and foliar amendments. Application of hydrogel + nano-Si under full irrigation resulted in the highest grain and straw, and the biological yield of rice under the pot experiment (Table 2).

Table 2. Interactive effects of irrigation regimes, soil and foliar amendments on yield of Rice

Amendments	Grain Yield (g/m^2)				Straw Yield (g/m^2)				Biological Yield (g/m^2)			
	Irrigation Levels											
	I_1 (70% WWC)	I_2 (90% WWC)	I_3 (100 %WWC)	Mean	I_1 (70% WWC)	I_2 (90% WWC)	I_3 (100 %WWC)	Mean	I_1 (70% WWC)	I_2 (90% WWC)	I_3 (100 %WWC)	Mean
A_1	155.57	214.29	219.16	196.34	296.32	396.24	441.28	377.95	451.90	610.52	660.43	574.29
A_2	163.15	217.34	221.05	200.51	316.00	418.37	432.36	388.91	479.15	635.71	653.41	589.42
A_3	167.75	216.46	284.09	222.77	336.43	443.59	505.65	428.56	504.18	660.05	789.74	651.32
A_4	182.36	264.88	308.17	251.80	360.39	486.74	551.95	466.36	542.75	751.62	860.12	718.16
A_5	171.00	230.79	298.97	233.59	345.78	453.60	543.43	447.60	516.77	684.39	842.40	681.19
A_6	191.37	274.35	323.43	263.05	390.27	501.77	557.93	483.32	581.63	776.12	881.37	746.37
Mean	171.87	236.35	275.81		340.87	450.05	505.43		512.73	686.40	781.24	
Irrigation × amendments												
SE (m)			±8.09				±11.27				±14.26	
CD (P=0.05)			23.21				32.31				40.89	

Similarly, in wheat, plant height at physiological maturity was significantly influenced by different irrigation regimes (WWC levels) and soil–foliar amendments (Table 3). Full irrigation (100% WWC) recorded significantly taller plants, followed by 80% WWC, whereas the lowest plant height was observed under 60% WWC. Lower irrigation regimes may have led to significant diversion of above-ground carbohydrates to below-ground sinks under water-limited conditions, resulting in considerably reduced above-ground growth and plant height. The decrease in wheat plant height caused by deficit water stress can be attributed to a reduction in relative turgidity and protoplasm dehydration, which is accompanied by a decline in photosynthesis and the reduced production of photosynthetic materials, impaired cell development, and restricted cell division[8].

Among soil and foliar amendments, the tallest plants for wheat were recorded with the combined application of hydrogel + foliar application of nano-Si. The treatment was found to be statistically at par with the sole foliar application of nano-Si (Table 4). The beneficial influence of silicon application on plant height is associated with improved water relations, maintenance of leaf turgor, and enhanced physiological efficiency under water-limited conditions. Silicon has been reported to improve drought tolerance in wheat by regulating stomatal conductance, improving photosynthetic performance, and stabilising cell membranes, thereby sustaining vegetative growth under moisture stress.

Dry matter accumulation of the wheat crop was significantly influenced by the different irrigation regimes. It was significantly higher under full irrigation

Table 3. Effect of irrigation regimes, soil and foliar amendments on growth and yield parameters of wheat

Treatment	Plant Height (cm)	Dry Matter Accumulation (g/m^2)	Grain Yield (g/m^2)	Straw Yield (g/m^2)	Biological Yield (g/m^2)	Harvest Index (%)
Irrigation regimes						
I_1 (60% WWC)	81.82	754.21	309.79	471.50	781.30	39.60
I_2 (80% WWC)	86.16	879.88	378.65	558.31	936.96	40.41
I_3 (100% WWC)	88.18	970.04	411.93	592.37	1004.30	41.01
SEm±	0.47	3.39	2.53	2.69	3.37	0.22
CD (P=0.05)	1.34	9.73	7.26	7.71	9.68	0.63
Soil and foliar amendments						
A_1(No amendments)	82.77	850.04	342.80	517.88	860.68	39.72
A_2 (Hydrogel)	82.90	851.44	344.70	520.22	864.92	39.72
A_3 (Nano Zn)	85.02	867.17	369.05	539.91	908.95	40.55
A_4 (Nano Si)	87.76	883.66	383.66	558.96	942.62	40.67
A_5 (Hydrogel + Nano Zn)	85.58	869.20	373.38	544.18	917.56	40.69
A_6 (Hydrogel + Nano Si)	88.29	886.76	387.18	563.21	950.38	40.70
SEm±	0.66	4.80	3.58	3.80	4.77	0.31
CD (P=0.05)	1.90	13.75	10.27	10.91	13.68	NS

than under deficit irrigation (60% and 80% of WWC). The limited water availability negatively impacted the leaf characters like leaf area, leaf size, number and duration, whereas the irrigation regimes enhanced these traits Abdelaal *et al*[27]. Among the soil and foliar amendments, the combined application of hydrogel (4 kg ha^{-1}) along with foliar application of nano-Si (1 mL/L) resulted in considerably higher dry matter accumulation, which was statistically comparable to that observed under the sole foliar application of nano-Si (1 mL/L).

The data of grain, straw, and biological yield of wheat, as influenced by irrigation schedules and amendment treatments (Table 3), revealed that irrigating the crop at 100% of WWC was found to result in substantially higher grain, straw and biological yield levels over 80% of WWC and 60% of WWC during 2024-25. The lowest yield levels for grain, straw and biological yield were recorded for the treatment based on 60% of WWC. The reduction in yield caused by drought stress may be attributed to factors such as reduced cell division and growth, impaired photosynthesis, membrane degradation, incompatibility of water and nutrient uptake, and their disrupted transmission Hasanuzzaman *et al*[6]. The highest grain, straw and biological yield under full irrigation indicates that

Table 4. Interactive effects of irrigation regimes, soil and foliar amendments on yield attributes of wheat

Amendments	Grain Yield (g/m²)				Straw Yield (g/m²)				Biological Yield (g/m²)			
	Irrigation levels											
	I_1 (60% WWC)	I_2 (80% WWC)	I_3 (100 %WWC)	Mean	I_1 (60% WWC)	I_2 (80% WWC)	I_3 (100 %WWC)	Mean	I_1 (60% WWC)	I_2 (80% WWC)	I_3 (100 %WWC)	Mean
A_1 (No amendments)	272.727	360.390	395.292	342.80	434.52	540.04	579.08	517.88	707.25	900.43	974.37	860.68
A_2 (Hydrogel)	274.351	362.825	396.916	344.70	441.56	545.18	573.92	520.22	715.91	908.01	970.83	864.92
A_3 (Nano Zn)	316.558	380.682	409.903	369.05	477.27	556.82	585.62	539.91	793.83	937.50	995.53	908.95
A_4 (Nano Si)	334.416	391.234	425.325	383.66	498.38	573.86	604.65	558.96	832.79	965.10	1029.97	942.62
A_5 (Hydrogel + Nano Zn)	321.429	383.929	414.773	373.38	472.40	556.01	604.14	544.18	793.83	939.94	1018.91	917.56
A_6 (Hydrogel + Nano Si)	339.286	392.857	429.383	387.18	504.87	577.92	606.82	563.21	844.16	970.78	1036.21	950.38
Mean	309.79	378.65	411.93		471.50	558.31	592.37		781.30	936.96	1004.30	
Irrigation × amendments SE (m)			±6.20				±6.59				±8.26	
CD (P=0.05)			17.79				18.90				23.70	

optimal soil moisture supports enhanced assimilate production, translocation to developing grains, and improved partitioning efficiency. Decline in wheat yield levels with reduced irrigation amount was also reported by Getachew *et al.*,[9] and Gangmei *et al*[28].

Among soil and foliar amendments, the combined application of hydrogel (4 kg/ha) + foliar application of nano-Si (1 mL/L) (3.24 g/plant for 2024) resulted in substantially higher grain, straw and biological yield for wheat. The treatment was found to be statistically at par with the sole foliar application of nano-Si (Table 3). Si has been proven to be beneficial for the healthy growth and development of many plant species, particularly Gramineae[29]. The beneficial effects of Si are particularly distinct in plants exposed to various environmental stresses. Si could improve plant photosynthesis under drought stress conditions Hattori *et al*[14]. These experimental findings regarding nano-formulations are further corroborated by the results of Ahmadian *et al.*,[18] who observed significant increments in wheat grain yield with the application of silica and zinc nano-formulations.

With respect to irrigation regimes, a significantly higher harvest index was recorded under 100% WWC, although it was statistically at par with the harvest index observed under 80% WWC. The lowest harvest index was observed under 60% WWC. However, soil and foliar amendments had no significant effects on the harvest index of wheat during *Rabi* 2024-25. Significant interaction effects were observed between irrigation regimes and soil and foliar amendments. The combined application of hydrogel (4 kg ha^{-1}) + nano-Si (1 mL/L) at full irrigation (100% WWC) resulted in statistically the highest grain, straw and biological yield for *kharif* 2024 (Table 4).

CONCLUSION

The present study demonstrated that a reduction in soil moisture levels markedly impaired the growth and yield of both rice and wheat. However, the adverse effects of moisture stress could be effectively alleviated through the application of nano-silicon and nano-zinc, highlighting the importance of integrated amendment strategies under varying moisture conditions. Hydrogel applied alone failed to bring about a significant enhancement in rice–wheat crop productivity.

CONFLICT OF INTEREST

The Authors declare no competing interests

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AUTHORS CONTRIBUTIONS

V.: Conducted the experiment, analyzed the data and wrote the original manuscript. AK: Conceptualized the research programme, designed the work, supervised the study and reviewed the manuscript. K, HP and GC: Reviewed and edited the manuscript. SM and SKS: Supervised the study and reviewed the manuscript.