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Effect of zinc applications on physiological parameters in *kharif* rice (*Oryza sativa* L.) genotypes

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Abstract

A field experiment in rice investigation was conducted during *kharif* seasons at college farm, Navsari Agricultural University, Navsari to study the effect of variety and zinc application on rice. The experiment was laid out in a randomized block design with factorial concept and replicated thrice. The experiment consisted of three varieties viz., IET-25450 (V₁), BPT-5204 (V₂) and IET-24766 (V₃), three soil base zinc application (S₁) control (00 kg ZnSO₄ ha⁻¹), (S₂) 10 kg ZnSO₄ ha⁻¹ at the time of transplanting and (S₃) 20 kg ZnSO₄ ha⁻¹ at the time of transplanting and two foliar Zn application (F₁) 0% Zn EDTA and (F₂) 1% Zn EDTA spray at tillering and grain filling stage.

Varieties differed significantly in plant height, leaf area and leaf area index. Among the varieties, IET-24766 gave significantly highest plant height (111.54 cm), leaf area (47.76 cm²), leaf area index (1.93) followed by IET-25450 and BPT-5204 and soil base zinc application of 20 kg ZnSO₄ ha⁻¹ at the time of transplanting as well as foliar zinc application of 1% Zn EDTA spray at tillering and grain filling stage resulted in highest values in plant height (108.72 cm and 107.74 cm respectively), leaf area (45.56 cm² and 45.06 cm² respectively), leaf area index (2.05 and 1.97 respectively) during in pooled analysis.

Keywords: Rice, varieties, zinc sulphate, Zn-EDTA foliar spray, growth parameters, *kharif* season

Introduction

Rice (*Oryza sativa* L.) stands as the world's most vital food crop, serving as the primary dietary staple for over half of the global population and contributing 35% to 75% of the total caloric intake for more than 3 billion people across Asia. India, recognized as one of the original centers of rice domestication and cultivation, dedicates approximately 44.6 million hectares to this crop, yielding around 90.0 million tonnes. This volume constitutes 52% of the nation's total food grain production, operating at an average productivity of about 2.1 tons per hectare (Anonymous, 2017) [3]. Beyond its role as a fundamental energy source rich in carbohydrates, rice also serves as an important source of dietary protein.

Despite its agronomic and caloric significance, polished rice is inherently a poor source of essential micronutrients, particularly zinc (Zn). Severe zinc deficiency in lowland rice ecosystems is a documented constraint across major global production zones, including India, Brazil, and the Philippines. Biochemically, zinc functions as an essential catalytic cofactor for numerous enzymes that govern crucial plant metabolic pathways (Fageria *et al.* 2011) [7]. These include glutamate dehydrogenase, which regulates nitrogen metabolism, and alcohol dehydrogenase, which maintains anaerobic metabolic pathways under waterlogged conditions.

A global assessment by the Food and Agriculture Organization (FAO) indicates that approximately 30% of arable soils worldwide are zinc-deficient (Zinzala *et al.* 2019) [20, 22]. Soil-borne zinc deficiencies restrict overall grain yield and compromise the ultimate nutritional quality of the harvest. Lowland rice fields are uniquely susceptible to this nutritional disorder; over 50% of global rice-growing areas are prone to zinc deficiency, making it one of the most critical nutritional stresses limiting rice production in Asia (Zinzala *et al.* 2019) [20, 22]. Consequently, widespread soil zinc depletion not only drives agricultural yield stagnation but also directly correlates with systemic human micronutrient deficiencies.

Planting materials and treatments

Experimental Site and Agro-Climatic Profile

The field experiment was conducted over two consecutive crop cycles (2017 and 2018) at the College Farm, Navsari Agricultural University, Navsari, Gujarat, India. The regional climate is typically tropical, characterized by deep, clayey, waterlogged lowland soils during the *khari*f monsoon window.

Experimental Design and Treatment Combinations

The trial was organized using a randomized block design (RBD) with a factorial concept, replicated three times. The experimental framework evaluated three distinct factors: varieties viz., IET-25450 (V_1), BPT-5204 (V_2) and IET-24766 (V_3), three soil base zinc application (S_1) control (00 kg $ZnSO_4$ ha⁻¹), (S_2) 10 kg $ZnSO_4$ ha⁻¹ at the time of transplanting and (S_3) 20 kg $ZnSO_4$ ha⁻¹ at the time of transplanting followed by two foliar Zn application (F_1) 0% Zn EDTA and (F_2) 1% Zn EDTA spray at tillering and grain filling stage. Standard agronomic practices and recommended fertilizer schedules were maintained across all treatments.

Sampling and Physiological Measurements

Five representative plants per plot were permanently tagged to monitor chronological crop development at 30, 60, and 90 days after transplanting (DAT), as well as at physiological harvest.

- **Plant Height (cm):** Measured linearly from the soil line to the tip of the longest extended leaf blade or panicle apex.
- **Leaf Area (cm²):** Quantified using a Handheld Laser Leaf Area Meter (Model CI-203, CID Bio-Science).
- **Leaf Area Index (LAI):** Calculated based on the mathematical relationship:

$$LAI = \frac{\text{Leaf area per plant (LA)}}{\text{Land area occupied by the plant (P)}}$$

Statistical Modeling

Data were analyzed using the standard Analysis of Variance (ANOVA) technique for factorial experiments (Gomez and Gomez, 1984) [11]. The significance of treatment effects was assessed using the F-test at a 5% probability level ($\alpha = 0.05$). Variance dispersion was quantified via the Standard Error of Mean (S.E.m. $\pm$), and treatment distinctions were resolved through Critical Difference (CD) formulations: C.D. = S.E. (d) $\times$ t 0.05, edf

Results and Discussion

Plant height

Effect of different variety on plant height at 60 DAT, 90 DAT and at harvest

An evaluation of the chronological growth data presented in Table 1 indicates that plant height was significantly influenced by the chosen rice varieties across both individual experimental years and within the pooled analysis. As expected, vertical growth progressed continuously with increasing crop age.

Among the evaluated cultivars, genotype IET-24766 (V_3) consistently demonstrated superior structural development, establishing the maximum mean plant heights across all observations at 60 DAT (98.28, 99.64 and 98.96 cm, respectively), 90 DAT (110.96, 112.04 and 111.50 cm,

respectively) and at harvest (111.01, 112.07 and 111.54 cm, respectively) were recorded with variety IET-24766 (V_3). Conversely, the lowest vertical baseline throughout the consecutive crop seasons and in the integrated data was systematically recorded for variety BPT-5204 (V_2) at 60 DAT (91.64, 92.66 and 92.15 cm, respectively), 90 DAT (97.83, 98.90 and 98.36 cm, respectively) and at harvest (97.95, 98.94 and 98.45 cm, respectively).

Effect of soil base Zn application on plant height at 60 DAT, 90 DAT and at harvest

Data profiles compiled across individual crop year and verified through integrated pooled calculations (Table 1) reveal that basal soil applications of zinc sulfate ($ZnSO_4$) at the time of transplanting exerted a statistically significant influence on the vertical growth of rice at 60 DAT, 90 DAT, and physiological harvest.

The maximum growth response across both experimental seasons and within the pooled analysis was systematically achieved with the highest basal application rate of 20 kg $ZnSO_4$ ha⁻¹ (S_3) at 60 DAT (95.44, 96.57 and 96.00 cm, respectively), 90 DAT (108.08, 109.21 and 108.65 cm, respectively) and at harvest (108.18, 109.25 and 108.72 cm, respectively). Statistical analysis showed that while the 20 kg $ZnSO_4$ ha⁻¹ (S_3) treatment gave the highest plant height, it remained statistically at par with the moderate dose of 10 kg $ZnSO_4$ ha⁻¹ (S_2). Crucially, both soil base zinc treatments (S_3 and S_2) demonstrated significant statistical superiority over the unfertilized control plot 00 kg $ZnSO_4$ ha⁻¹ (S_1), which consistently recorded the absolute lowest vertical growth parameters across all testing intervals at 60 DAT (89.38, 90.43 and 89.91 cm, respectively), 90 DAT (100.17, 101.18 and 100.67 cm, respectively) and at harvest (100.26, 101.21 and 100.73 cm, respectively).

Effect of foliar Zn application on plant height at 60 DAT, 90 DAT and at harvest

The data presented in Table 1 demonstrate that foliar zinc applications administered at the tillering and grain filling stage significantly affected the plant height of rice throughout both individual experimental year and within the combined pooled analysis.

Targeted canopy nutrition using foliar zinc sprays during critical vegetative growth stages also significantly improved plant height. Administering a 1% Zn-EDTA foliar spray (F_2) at the tillering and grain filling stage stimulated vertical growth, resulting in significantly maximum plant heights at 60 DAT (94.24, 95.46 and 94.85 cm), 90 DAT (107.13, 108.22 and 107.67 cm) and at harvest (107.23, 108.26 and 107.74 cm, respectively). In contrast, plants that did not receive the micronutrient spray showed restricted vertical development to control 0% Zn EDTA (F_1) at 60 DAT (90.32, 91.38 and 90.85 cm, respectively), 90 DAT (101.47, 102.53 and 102.00 cm, respectively) and at harvest (101.56, 102.56 and 102.06 cm, respectively).

Interaction effect on plant height at 60 DAT, 90 DAT and at harvest

The interaction effects in respect of plant height between variety and soil base Zn application ($V \times S$), variety and foliar Zn application ($V \times F$), soil base Zn application and foliar Zn application ($S \times F$) and variety, soil base Zn application and foliar Zn application ($V \times S \times F$) were did not show any significant effect in individual years of study and in pooled analysis at 60, 90 DAT and at harvest.

The first-order and second-order interaction effects—specifically, the combinations of variety and soil-applied zinc (V x S), variety and foliar-applied zinc (V x F), soil-applied zinc and foliar-applied zinc (S x F), as well as the three-way interaction of variety, soil, and foliar zinc applications (V x S x F) did not exert a statistically significant influence on the plant height of rice. This lack of significance was consistent across both individual years of field experimentation and within the combined pooled analysis at all evaluated developmental stages, including 60 DAT, 90 DAT and at harvest. These results demonstrate that the structural elongation response of the crop to the individual main factors functioned independently, meaning that the vertical phenotypic expression of each genotype under specific zinc delivery methods did not rely on synergistic or mutually restrictive cross-factor dependencies.

Leaf area

Effect of different variety on leaf area at 60 DAT, 90 DAT and at harvest

The data presented in Tables 2 demonstrate that varietal treatments had a significant effect on leaf area during both years of investigation, as well as in the pooled analysis.

Among the evaluated genotypes, variety IET-24766 (V_3) established significantly higher leaf area magnitudes during consecutive years and in the pooled data over the remaining treatments. This performance was sustained chronologically at 60 DAT (44.72, 44.79, and 45.25 cm², respectively), 90 DAT (47.69, 47.82, and 47.76 cm², respectively), and at harvest (46.54, 46.68, and 46.61 cm² respectively). In contrast, the lowest phenotypic values for this functional canopy parameter were documented for BPT-5204 (V_2), which yielded minimum baselines at 60 DAT (36.90, 37.95 and 37.42 cm², respectively), 90 DAT (39.82, 39.95 and 39.88 cm², respectively) and at harvest (38.64, 38.44 and 38.69 cm², respectively) across individual and combined years.

Effect of soil base Zn application on leaf area at 60 DAT, 90 DAT and at harvest

Statistical analysis presented in Tables 2 demonstrates that basal soil applications of ZnSO₄ at transplanting exerted a highly significant influence on the leaf area of rice across both individual year of experiment and within the integrated pooled data.

Basal incorporation of 20 kg ZnSO₄ ha⁻¹ (S_3) maximized the mean leaf area across both individual years and the pooled analysis at 60 DAT (42.51, 43.59 and 43.05 cm²), 90 DAT (45.49, 45.62 and 45.56 cm², respectively) and at harvest (44.34, 44.46 and 44.40 cm²). While the S_3 treatment remained statistically at par with the moderate application rate of 10 kg ZnSO₄ ha⁻¹ (S_2), both treatments significantly outperformed the unfertilized control (S_1), which recorded the minimum functional leaf area at 60 DAT (38.64, 39.66 and 39.15 cm², respectively), 90 DAT (41.57, 41.71 and 41.64 cm², respectively) and at harvest (40.39, 40.51 and 40.45 cm², respectively).

Effect of foliar Zn application on leaf area at 60 DAT, 90 DAT and at harvest

Data in Tables 2 reveal that foliar zinc applications administered at the tillering and grain filling stage significantly influenced the leaf area of rice across both individual experimental years and within the integrated pooled analysis.

Foliar application of 1% Zn-EDTA (F_2) resulted in a significantly higher mean leaf area across both experimental years and the pooled analysis at 60 DAT (42.00, 43.06 and 42.53 cm², respectively), 90 DAT (44.95, 45.16 and 45.06 cm², respectively). Conversely, the lowest functional leaf area was consistently documented in the control plots (F_1) 0% Zn EDTA at 60 DAT (39.00, 40.06 and 39.53 cm², respectively), 90 DAT (41.94, 42.0 and 41.97, respectively) and at harvest (40.78, 40.88 and 40.83, respectively) during individual crop cycles and within the combined dataset.

Interaction effect on leaf area at 60 DAT, 90 DAT and at harvest

The first-and second-order interaction effects among the experimental factors specifically variety x soil zinc application (V x S), variety x foliar zinc application (V x F), soil zinc application x foliar zinc application (S x F), and the three-way variety x soil zinc application x foliar zinc application (V x S x F) did not exert any statistically significant influence on the leaf area of rice. This non-significant response remained completely consistent across both individual years of investigation and within the integrated pooled analysis at 60 DAT, 90 DAT, and at harvest.

Leaf area index

Effect of different variety on leaf area index at 60 DAT, 90 DAT and at harvest

The results presented in Tables 3, 4, and 5 reveal that varietal treatments exerted a highly significant effect on the leaf area index of rice across both individual years of investigation and within the pooled analysis.

Across both experimental years and the pooled analysis, the rice genotype IET-24766 (V_3) consistently exhibited a significantly superior leaf area index relative to all other treatments at 60 DAT (1.59, 1.62 and 1.61, respectively), 90 DAT (1.92, 1.94 and 1.93, respectively) and at harvest (1.71, 1.73 and 1.72, respectively). Conversely, the minimum mean leaf area index was systematically recorded in variety BPT-5204 (V_2) at 60 DAT (1.34, 1.35 and 1.35, respectively), 90 DAT (1.61, 1.63 and 1.62, respectively) and at harvest (1.43, 1.45 and 1.44, respectively) during both individual year and within the integrated pooled data.

Effect of soil base Zn application on leaf area index at 60 DAT, 90 DAT and at harvest

The statistical analysis presented in Tables 3, 4, and 5 demonstrates that the leaf area index of rice was significantly influenced by varying levels of basal soil zinc application at transplanting across both individual experimental cycles and within the integrated pooled data.

Basal application of 20 kg ZnSO₄ ha⁻¹ (S_3) statistically maximized the mean leaf area index across both individual years and the pooled analysis at 60 DAT (1.67, 1.70 and 1.69, respectively), 90 DAT (2.04, 2.06 and 2.05, respectively) and at harvest (1.80, 1.82 and 1.81, respectively) relative to all other treatments. This treatment, alongside the moderate zinc rate, exhibited marked statistical superiority over the unfertilized control (S_1), which recorded the minimum leaf area index at 60 DAT (1.25, 1.27 and 1.26, respectively), 90 DAT (1.50, 1.52 and 1.51, respectively) and at harvest (1.36, 1.38 and 1.37, respectively) during both individual crop cycles and within the integrated pooled data.

Effect of foliar Zn application on leaf area index at 60 DAT, 90 DAT and at harvest

Data presented in Tables 3, 4, and 5 reveal that foliar zinc applications administered at the tillering and grain filling stage significantly influenced the leaf area index of rice across both individual experimental years and within the integrated pooled analysis.

Foliar application of 1% Zn-EDTA (F_2) resulted in a significantly higher mean leaf area index across both experimental years and the pooled analysis at 60 DAT (1.62, 1.64 and 1.63, respectively), 90 DAT (1.96, 1.99 and 1.97, respectively) and at harvest (1.73, 1.75 and 1.74, respectively). Conversely, the minimum leaf area index was consistently documented in the control plots (F_1 : 0% Zn-EDTA) at 60 DAT (1.31, 1.33 and 1.32, respectively) 90 DAT (1.57, 1.59 and 1.58, respectively) and at harvest (1.42, 1.43 and 1.42, respectively) during individual year and within the integrated pooled data.

Interaction effect on leaf area index at 60 DAT, 90 DAT and at harvest

The interaction effects in respect of leaf area index between variety and soil base Zn application ($V \times S$), variety and foliar Zn application ($V \times F$), soil base Zn application and foliar Zn application ($S \times F$) and variety, soil base Zn application and foliar Zn application ($V \times S \times F$) were did not show any significant effect in individual years of study and in pooled analysis at 60 DAT but at 90 DAT the interaction effects in respect of leaf area index between variety and soil base Zn application ($V \times S$), variety and foliar Zn application ($V \times F$) and soil base Zn application and foliar Zn application ($S \times F$) were show significant effect except variety, soil base Zn application and foliar Zn

application ($V \times S \times F$) in individual years of study and in pooled analysis.

Regarding the variety $\times$ soil zinc ($V \times S$) interaction, the treatment combination V_3S_3 (IET-24766 + 20 kg ha^{-1} $ZnSO_4$) statistically maximized the leaf area index across both year of experimental and in the pooled analysis at 90 DAT (2.26, 2.29 and 2.27, respectively) and at harvest (1.99, 2.02 and 2.01, respectively). Conversely, the minimum leaf area index was consistently documented under the V_2S_1 combination (BPT-5204 + 00 kg $ZnSO_4 ha^{-1}$) during both individual years and within the integrated pooled dataset (1.33, 1.35 and 1.34, respectively).

With respect to the variety $\times$ foliar zinc ($V \times F$) interaction at 90 DAT, the treatment combination V_3F_2 (IET-24766 + 1.0% Zn EDTA) statistically maximized the leaf area index across both individual years and the pooled analysis (2.15, 2.17 and 2.16, respectively). Conversely, the minimum leaf area index was consistently documented under the V_2F_1 combination (BPT-5204 + 0.0% Zn-EDTA) during both experimental cycles and within the integrated pooled data (1.39, 1.40 and 1.39, respectively).

Treatment receiving interaction effect of ($S \times F$) soil Zn application (20 kg $ZnSO_4 ha^{-1}$) and foliar Zn application (1.0% Zn EDTA) (S_3F_2) produced significantly higher leaf area index during first and second year of experiment as well as in pooled data at 90 DAT (2.22, 2.25 and 2.23, respectively) and at harvest (1.94, 1.97 and 1.95, respectively). Conversely, minimum mean leaf area index were recorded in S_1F_1 Control at 90 DAT (00 kg $ZnSO_4 ha^{-1}$ + 0.0% Zn EDTA) and at harvest in both years and in pooled data at 90 DAT (1.36, 1.37 and 1.36, respectively) and at harvest (1.25, 1.26 and 1.25, respectively).

Table 1: Plant height at 60 DAT, 90 DAT and at harvest

	Plant height (cm) at 60 DAT			Plant height (cm) at 90 DAT			Plant height (cm) at harvest		
	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
V_1	91.64	92.66	92.15	104.11	105.19	104.65	104.22	105.22	104.72
V_2	86.93	87.95	87.44	97.83	98.90	98.36	97.95	98.94	98.45
V_3	98.28	99.64	98.96	110.96	112.04	111.50	111.01	112.07	111.54
S.Em. $\pm$	1.67	1.66	1.16	2.19	2.22	1.54	2.19	2.22	1.54
C.D.	4.79	4.78	3.28	6.29	6.39	4.34	6.30	6.40	4.34
S_1	89.38	90.43	89.91	100.17	101.18	100.67	100.26	101.21	100.73
S_2	92.03	93.25	92.64	104.65	105.73	105.19	104.74	105.77	105.26
S_3	95.44	96.57	96.00	108.08	109.21	108.65	108.18	109.25	108.72
S.Em. $\pm$	1.67	1.66	1.16	2.19	2.22	1.54	2.19	2.22	1.54
C.D.	4.79	4.78	3.28	6.29	6.39	4.34	6.30	6.40	4.34
F_1	90.32	91.38	90.85	101.47	102.53	102.00	101.56	102.56	102.06
F_2	94.24	95.46	94.85	107.13	108.22	107.68	107.23	108.26	107.74
S.Em. $\pm$	1.36	1.36	0.95	1.78	1.81	1.26	1.79	1.82	1.26
C.D.	3.91	3.90	2.69	5.13	5.22	3.57	5.14	5.22	3.57
$V \times S$									
S.Em. $\pm$	2.89	2.88	1.98	3.78	3.85	2.62	3.79	3.85	2.63
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
$V \times F$									
S.Em. $\pm$	2.36	2.35	1.64	3.09	3.14	2.17	3.10	3.15	2.17
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
$S \times F$									
S.Em. $\pm$	2.36	2.35	1.64	3.09	3.14	2.17	3.10	3.15	2.17
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
$V \times S \times F$									
S.Em. $\pm$	4.08	4.07	2.80	5.35	5.44	3.71	5.36	5.45	3.71
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	7.60			8.92			8.92		

Table 2: Leaf area at 60 DAT, 90 DAT and at harvest

	Leaf area (cm ²) at 60 DAT			Leaf area (cm ²) at 90 DAT			Leaf area (cm ²) at harvest		
	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
V ₁	39.89	40.94	40.41	42.84	42.97	42.90	41.66	41.77	41.72
V ₂	36.90	37.95	37.42	39.82	39.95	39.88	38.64	38.74	38.69
V ₃	44.72	45.79	45.25	47.69	47.82	47.76	46.54	46.68	46.61
S.Em.±	0.89	0.89	0.62	1.02	1.02	0.71	0.97	0.96	0.67
C.D.	2.57	2.57	1.76	2.93	2.93	2.00	2.78	2.76	1.90
S ₁	38.64	39.66	39.15	41.57	41.71	41.64	40.39	40.51	40.45
S ₂	40.35	41.43	40.89	43.27	43.41	43.34	42.12	42.23	42.17
S ₃	42.51	43.59	43.05	45.49	45.62	45.56	44.34	44.46	44.40
S.Em.±	0.89	0.89	0.62	1.02	1.02	0.71	0.97	0.96	0.67
C.D.	2.57	2.57	1.76	2.93	2.93	2.00	2.78	2.76	1.90
F ₁	39.00	40.06	39.53	41.94	42.00	41.97	40.78	40.88	40.83
F ₂	42.00	43.06	42.53	44.95	45.16	45.06	43.78	43.91	43.85
S.Em.±	0.73	0.73	0.51	0.83	0.83	0.58	0.79	0.78	0.55
C.D.	2.10	2.10	1.45	2.39	2.39	1.65	2.27	2.26	1.56
V x S									
S.Em.±	1.55	1.55	1.06	1.76	1.77	1.21	1.67	1.66	1.15
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
V x F									
S.Em.±	1.26	1.26	0.88	1.44	1.44	1.00	1.37	1.36	0.95
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x F									
S.Em.±	1.26	1.26	0.88	1.44	1.44	1.00	1.37	1.36	0.95
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
V x S x F									
S.Em.±	2.19	2.19	1.50	2.49	2.50	1.71	2.37	2.35	1.62
C.D.	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV%	9.24			9.93			11.00		

Table 3: Leaf area index at 60 DAT

	V			S			F		Y
	V ₁	V ₂	V ₃	S ₁	S ₂	S ₃	F ₁	F ₂	
Y1	1.47	1.34	1.59	1.25	1.48	1.67	1.31	1.62	1.47
Y2	1.49	1.35	1.62	1.27	1.50	1.70	1.33	1.64	1.49
Pooled	1.48	1.35	1.61	1.26	1.49	1.69	1.32	1.63	1.48

		V	S	F	V x S	V x F	S x F	V x S x F	Y
		S.Em.±	C.D.	S.Em.±	C.D.	S.Em.±	C.D.	S.Em.±	C.D.
Y1	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	0.09	0.09	0.07	NS	NS	NS	NS	
Y2	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	0.08	0.08	0.06	NS	NS	NS	NS	
Pooled	S.Em.±	0.02	0.02	0.02	0.03	0.03	0.03	0.05	0.017
	C.D.	0.06	0.06	0.05	NS	NS	NS	NS	NS
Interaction with year	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	NS	NS	NS	NS	NS	NS	NS	
C.V.%		8.20							

Plant height increased with advancement of crop age and maximum plant height was recorded with IET-24766 followed by IET-25450 and BPT-5204. However, the percent increase in plant height was highest up to 60 DAT thereafter increases at decreasing rate during both years. The increases in plant height among varieties are mainly due to differences in their genetic makeup (Singh *et al.* 2013) [18]. Similar results were also reported by Arif *et al.* (2018) [4], Kumar and Singh (2018) [12], and Oahiduzzamana *et al.* (2016) [14]. The leaf area and leaf area index tested varieties increased up to 90 DAT, there after it decreased. It might be due to the start senescence and drying of leaves. The higher leaf area and leaf area index was recorded under the IET-24766 in comparison to other varieties. It might be due to wider and longer leaves, greater source size and more number of tillers per hill. Similar results were also reported by Gautam *et al.* (2008) [9], Dore *et al.* (2018) [6], Ali *et al.* (2014) [2] and Shukla *et al.* (2014) [17].

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Table 4: Leaf area index at 90 DAT

	V			S			F		Y
	V ₁	V ₂	V ₃	S ₁	S ₂	S ₃	F ₁	F ₂	
Y1	1.77	1.61	1.92	1.50	1.76	2.04	1.57	1.96	1.77
Y2	1.79	1.63	1.94	1.52	1.78	2.06	1.59	1.99	1.79
Pooled	1.78	1.62	1.93	1.51	1.77	2.05	1.58	1.97	1.78

	V ₁			V ₂			V ₃		
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃
Y1	1.59	1.78	1.93	1.33	1.58	1.92	1.59	1.91	2.26
Y2	1.61	1.81	1.96	1.35	1.60	1.95	1.60	1.93	2.29
Pooled	1.60	1.79	1.94	1.34	1.59	1.93	1.60	1.92	2.27

	V ₁		V ₂		V ₃	
	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂
Y1	1.64	1.90	1.39	1.83	1.69	2.15
Y2	1.66	1.92	1.40	1.86	1.71	2.17
Pooled	1.65	1.91	1.39	1.85	1.70	2.16

	F ₁			F ₂		
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃
Y1	1.36	1.50	1.86	1.65	2.01	2.22
Y2	1.37	1.51	1.88	1.67	2.04	2.25
Pooled	1.36	1.51	1.87	1.66	2.02	2.23

		V	S	F	V x S	V x F	S x F	V x S x F	Y
Y1	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	0.09	0.09	0.07	0.15	0.12	0.12	NS	
Y2	S.Em.±	0.03	0.03	0.03	0.05	0.04	0.04	0.08	
	C.D.	0.09	0.09	0.07	0.16	0.13	0.13	NS	
Pooled	S.Em.±	0.02	0.02	0.02	0.04	0.03	0.03	0.05	0.018
	C.D.	0.06	0.06	0.05	0.10	0.09	0.09	NS	NS
Interaction with year	S.Em.±	0.03	0.03	0.03	0.05	0.04	0.04	0.08	
	C.D.	NS	NS	NS	0.22	NS	NS	NS	
C.V.%		7.35							

Table 5: Leaf area index at harvest

	V			S			F		Y
	V ₁	V ₂	V ₃	S ₁	S ₂	S ₃	F ₁	F ₂	
Y1	1.59	1.43	1.71	1.36	1.57	1.80	1.42	1.73	1.58
Y2	1.60	1.45	1.73	1.38	1.58	1.82	1.43	1.75	1.59
Pooled	1.59	1.44	1.72	1.37	1.58	1.81	1.43	1.74	1.59

	V ₁			V ₂			V ₃		
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃
Y1	1.45	1.60	1.71	1.21	1.40	1.68	1.43	1.70	1.99
Y2	1.46	1.61	1.73	1.22	1.42	1.70	1.45	1.72	2.02
Pooled	1.46	1.60	1.72	1.22	1.41	1.69	1.44	1.71	2.01

	V ₁		V ₂		V ₃	
	F ₁	F ₂	F ₁	F ₂	F ₁	F ₂
Y1	1.49	1.69	1.25	1.61	1.52	1.90
Y2	1.50	1.70	1.26	1.64	1.53	1.93
Pooled	1.49	1.70	1.26	1.62	1.53	1.91

	F ₁			F ₂		
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃
Y1	1.25	1.35	1.65	1.48	1.78	1.94
Y2	1.26	1.37	1.67	1.50	1.80	1.97
Pooled	1.25	1.36	1.66	1.49	1.79	1.95

		V	S	F	V x S	V x F	S x F	V x S x F	Y
Y1	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	0.08	0.08	0.06	0.14	0.11	0.11	NS	
Y2	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	0.08	0.08	0.07	0.14	0.11	0.11	NS	
Pooled	S.Em.±	0.02	0.02	0.02	0.03	0.03	0.03	0.05	0.016
	C.D.	0.05	0.05	0.04	0.09	0.08	0.08	NS	NS
Interaction with year	S.Em.±	0.03	0.03	0.02	0.05	0.04	0.04	0.07	
	C.D.	NS	NS	NS	NS	NS	NS	NS	
C.V.%		7.38							

Plant height increased with advancement of crop age and maximum plant height was recorded with IET-24766 followed by IET-25450 and BPT-5204. However, the percent increase in plant height was highest up to 60 DAT thereafter increases at decreasing rate during both years. The increases in plant height among varieties are mainly due to differences in their genetic makeup (Singh *et al.* 2013)^[18]. Similar results were also reported by Arif *et al.* (2018)^[4], Kumar and Singh (2018)^[12], and Oahiduzzamana *et al.* (2016)^[14]. The leaf area and leaf area index tested varieties increased up to 90 DAT, there after it decreased. It might be due to the start senescence and drying of leaves. The higher leaf area and leaf area index was recorded under the IET-24766 in comparison to other varieties. It might be due to wider and longer leaves, greater source size and more number of tillers per hill. Similar results were also reported by Gautam *et al.* (2008)^[9], Dore *et al.* (2018)^[6], Ali *et al.* (2014)^[2] and Shukla *et al.* (2014)^[17].

An inspection of the data revealed that plant height continued to increase with advancement in age but rapid increase in height was recorded up to 90 DAT thereafter it increased with slow rate. The slow growth of plant after 90 DAT might be due to diversion of photosynthates towards sink *i.e.* the grain and reproductive parts. The application of 20 kg ZnSO₄ ha⁻¹ at the time of transplanting was recorded significantly taller plant over rest of other treatment. This was might be due to availability of zinc by two ways *i.e.* soil by xylem and foliar applied zinc by phloem. As a result of high photosynthetic and hormonal activity, the meristematic growth in the apical region resulted in the sufficient elongation of the plants due to Zn application. Ghatak *et al.* (2005)^[10], Fageria *et al.* (2003)^[8], Shivay *et al.* (2010)^[16] have reported a positive response of plant height in rice to Zn application. Zn-induced availability of growth regulators such as gibberellins, kinetin, and indole-3-acetic acid and enhancement in the ability of plant to cope with an adverse environment. This result corroborates the finding of Meena *et al.* (2018)^[13], Alam and Kumar (2015)^[1], Boonchuay *et al.* (2013)^[5] and Zinzala *et al.* (2016)^[21].

It is apparent from the data that the leaf area and leaf area index increased up to 60 DAT and after that it started declined from 90 DAT. Between 30-60 DAT the rate of leaf formation was higher and after 60 DAT the rate of leaf drying was very high which led to decrease the leaf area and leaf area index. It was further noticed that higher leaf area and leaf area index was recorded in (S₃) 20 kg ZnSO₄ ha⁻¹ at the time of transplanting and it showed significant superiority over rest of the treatments at 60, 90 DAT and at the time of harvesting. The maximum leaf area and LAI is obtained due to providing sufficient amount of zinc through appropriate sources ZnSO₄ that are essentially required to photosynthesis, sufficient cell expansion and elongation rate of leaves due to increase in both number and duration of epidermal cells. This is also due to increase of plant height as well as number of tillers. Similar observations were made by Dore *et al.* (2018)^[6], Singh *et al.* (2012)^[19], and Rehman *et al.* (2012)^[15].

Conclusions

This study demonstrates that combining soil zinc applications with targeted foliar sprays is an effective strategy for managing zinc limitations in lowland paddy systems. The rice genotype IET-24766 showed high genetic responsiveness, developing an optimal crop height,

individual leaf area, and functional canopy index. To maximize the Leaf Area Index and maintain a functional canopy through late growth stages, the recommended treatment is an integrated application of 20 kg ZnSO₄ ha⁻¹ soil base incorporation combined with 1% Zn-EDTA foliar sprays at the tillering and grain-filling stages.

Future Research Directions

To build on these physiological findings, future molecular studies should investigate the regulation of zinc transporter gene families and carbonic anhydrase expression levels. This will help clarify the genetic mechanisms behind variation in zinc use efficiency across different rice genotypes.

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