International Journal of Plant & Soil Science

Volume 37, Issue 1, Page 134-143, 2025; Article no.IJPSS.129361
ISSN: 2320-7035

Comparative Performance of Zinc Sources on Productivity of Rice (*Oryza sativa*) in Zinc Stressed Soils of Cauvery Delta Zone

T. Muthukumararaja [a++], R. Sumithra [a#*], P. Poonkodi [a†], S. Sathiyamurthi [a++] and S. Kalaisudarson [b++]

[a] *Department of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Annamalai University, Annamalai Nagar-608002, India.*
[b] *Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar-608002, India.*

Authors' contributions

This work was carried out in collaboration among all authors. Authors TM and RS designed the study, performed the statistical analysis, wrote the protocol, and developed the first draft of the manuscript. Authors PP and SS managed the data analysis. Authors RS and SK managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i15261

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/129361

Original Research Article

Received: 11/11/2024
Accepted: 13/01/2025
Published: 16/01/2025

ABSTRACT

Rice (*Oryza sativa*) cultivation is a cornerstone of India's economy and food security, with the nation ranking second only to China in annual production. Despite considerable advancements in recent years, rice yields remain below their maximum potential. Enhancing rice productivity through

++*Assistant Professor;*
#*Ph. D Scholar;*
†*Professor and Head;*
**Corresponding author: E-mail: sumithrar1425@gmail.com;*

Cite as: *Muthukumararaja, T., R. Sumithra, P. Poonkodi, S. Sathiyamurthi, and S. Kalaisudarson. 2025. "Comparative Performance of Zinc Sources on Productivity of Rice (Oryza Sativa) in Zinc Stressed Soils of Cauvery Delta Zone". International Journal of Plant & Soil Science 37 (1):134-43. https://doi.org/10.9734/ijpss/2025/v37i15261.*

precise and advanced mineral nutrition techniques offers a promising solution for overcoming nutrient deficiencies in soils and improving crop yields. Zinc, an essential micronutrient, plays a crucial role in enzyme activation, protein synthesis, and overall plant metabolism. However, zinc deficiency is a widespread issue in many agricultural soils, particularly affecting rice crops, leading to reduced growth and yield. Addressing this deficiency through the application of appropriate zinc formulations is vital for improving rice productivity in zinc-deficient soils. A pot experiment was carried out in department of soil science and agricultural chemistry, Annamalai University, Chidambaram, Tamilnadu during kharif of 2023 and included four sources of zinc and four levels of zinc levels to study their comparative performances and improve the yield of rice. Growth characters *viz.,* plant height, number of tillers hill^{-1}, leaf area index, chlorophyll content, dry matter production, yield characters *viz.*, no of panicles pot^{-1}, no. of grains panicle^{-1}, panicle length and test weight and grain and straw yield were recorded. The results indicated that the application of zinc lysinate at 5 kg ha^{-1}, either individually or in combination, produced the highest growth and yield parameters, with grain (43.01 g pot^{-1}) and straw (58.87 g pot^{-1}) yields surpassing those of other treatments, demonstrating its potential to improve rice productivity in zinc-deficient soils.

Keywords: Zinc formulations; stressed soil; rice; productivity.

1. INTRODUCTION

Rice (*Oryza sativa* L.) stands as a vital staple crop globally, providing sustenance for a significant portion of the world's population. For the 2022-2023 agricultural year, the total rice production in India reached approximately 130.8 million grown at 44.7 million hectares of area, with an average yield of 2.93 tonnes per hectare. In Tamil Nadu, rice production was recorded at around 8.14 million tonnes, spread over an area of approximately 2 million hectares, with productivity averaging 4.1 tonnes per hectare (The Directorate of Economics and Statistics, 2021-2022). Maximizing rice yields is imperative for sustainable agriculture and food security. In Tamil Nadu, rice production predominantly relies on alluvial soils, renowned for their fertility. Despite their richness, these soils are vulnerable to nutrient depletion through leaching and erosion, hampering rice growth and yield potential. Proper application of organic manures and inorganic fertilizers, tailored to crop requirements, is crucial for optimizing productivity.

Zinc (Zn) is a vital micronutrient essential for the growth and productivity of rice, playing a critical role in various physiological and biochemical processes such as enzyme activation, protein synthesis, and hormone regulation. However, zinc deficiency poses a significant challenge to rice cultivation. Zinc-deficient plants often exhibit reduced tillering, stunted growth, leaf discoloration such as bronzing or brown spots, and delayed maturity, ultimately leading to reduced grain yield and quality (Alloway, 2008). In addition, zinc-deficient soils limit the plant's physiological performance, compounding productivity losses. Forty-seven per cent of Indian soils and fifty percent of Tamil N adu soils are deficient in zinc (Arunachalam et al., 2013). In Cauvery Delta Zone (CDZ), next to N, the deficiency of zinc is occurring widely. Heavy textured soils of old delta are more deficient in Zn (80.4%) than the new delta soils (47.4%) (Hafeez et al., 2013). This issue is exacerbated in waterlogged and flooded conditions, common in rice fields, which further hinder zinc availability to plants.

Zinc availability in soil depends on soil properties such as pH and redox potential, contents of CO_3^{2-} and HCO_3^{-}, oxides of Fe and Al, and organic matter and inherent Zn status in the upper soil layer (Tuyogon et al., 2016). Addressing these deficiencies is critical to ensuring optimal rice productivity. In rice, zinc deficiency is a widespread issue, particularly in flooded or waterlogged soils common in the alluvial soils of Cauvery Delta Zone (CDZ). The zinc deficient soils in this region not only limit rice growth but also significantly reduce yield potential, making the management of zinc nutrition a key concern for rice farmers (Rahale et al. 2019). Proper management of zinc nutrition provides several direct benefits to farmers, such as enhanced crop yields, improved grain quality with higher market value, increased resilience to abiotic stresses such as waterlogging, and reduced reliance on other fertilizers, which can lower costs (Kumar et al., 2021; Hossain et al., 2022; Saeed et al., 2023). Additionally, balanced zinc application promotes sustainable farming by preventing nutrient runoff and preserving soil health for future crops (Cakmak, 2008; Singh et al., 2017).

To mitigate zinc deficiencies, different sources of zinc fertilizers are available, each with varying efficiency in improving zinc availability to rice plants. Traditional zinc sulfate ($ZnSO_4$) is widely used and cost-effective, while newer zinc compounds like Zinc HEDP (Hydroxyethylidene diphosphonic acid), Zinc oxide (ZnO), and Zinc lysinate are being explored for their potential to enhance zinc uptake and improve rice productivity under zinc-stressed conditions. These sources differ in terms of their solubility, zinc release rates, and interactions with soil properties, which may influence their efficacy in zinc-deficient soils (Dasgupta et al. 2024). For instance, Zinc HEDP offers slow-release benefits, ensuring prolonged availability, while Zinc lysinate enhance zinc uptake under highly stressed soil conditions.

In the Cauvery Delta Zone, where rice is a staple crop and soil zinc deficiency is prevalent, understanding the comparative performance of different zinc sources is critical for optimizing rice yields and improving farmers' livelihoods. By selecting the appropriate zinc source based on soil and crop requirements, farmers can achieve higher productivity, better economic returns, and sustainable agricultural practices. This study aims to evaluate the effects of various zinc fertilizers-Zinc sulfate, Zinc HEDP, Zinc oxide, and Zinc Lysinate-on the productivity of rice in zinc-stressed soils.

2. MATERIALS AND METHODS

A pot experiment was carried out in pot culture yard of Department of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Annamalai University, Chidambaram during kharif season of 2023. The experimental site is geographically located at 11° 24’ N latitude and 79° 41’ E longitude, 6 km away from Bay of Bengal, at an altitude of 5.79 m above mean sea level. The soil for this experiment was collected from the Thiruvalaputhur village, Mayiladhuari district. The soil was slightly alkaline in pH (7.78), non-saline (EC- 0.31 dSm^{-1}), organic carbon (5.92 g kg^{-1}), CEC (13.6) low in available nitrogen (166 kg ha^{-1}) and medium in available phosphorus (13 kg ha^{-1}) and potassium (176.4 kg ha^{-1}) and deficient in zinc (0.52 mg kg^{-1}). The soil samples were dried in shade, powdered with wooden mallet and sieved to pass through 2 mm sieve, thoroughly homogenized and used for the pot experiments. Twenty kilograms of air-dried homogenized soil was filled in one foot cement pots. The experiment includes four sources of zinc (S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1}). The experiment was laid out in completely randomized block design with three replications. The locally common short duration rice variety ADT-43 was planted at a spacing of 12.5 x 15 cm. The recommended fertilizer dose of 100, 50, and 50 kg ha^{-1} of N, P_2O_5, and K_2O, respectively, is referred to as the standard (100%). Half of the N and K dose was applied basally in the form of urea (46% N) and MOP (60% K_2O) and the remaining 50% was split into two equal amounts and top dressed at tillering and panicle initiation stages. Phosphorus was applied basally in the form of superphosphate (SSP, 16% P_2O_5). Zinc sources and their levels are applied at basal respective to their treatments pots.

Growth characters *viz.,* plant height, number of tillers $plant^{-1}$, leaf area index, chlorophyll content and dry matter production was recorded from all plants from each pot at all crop developmental stages - tillering, panicle initiation and harvest. Yield characters *viz.,* Number of panicles $plant^{-1}$, No. of grains $panicle^{-1}$, Panicle length and 1000 seed weight, grain and straw yield were recorded during harvest. Grains were separated by hand threshing, winnowed, cleaned, and sun dried to bring the moisture content to the standard level (14%). The straw was sun dried and measured. The Statistical analysis for all parameters was done by procedure described by Sheoran et al. (1998) at 5% significant level.

3. RESULTS AND DISCUSSION

3.1 Growth Characters

Growth characters *viz.,* plant height, no. of tillers $plant^{-1}$, chlorophyll content and dry matter production were significantly influenced by different zinc sources with varying levels over control at all critical stages of rice (Tables 1-4).

Among the different sources of zinc formulation used, highest plant height (57.44, 82.76 and 97.09 cm), no. of tillers $plant^{-1}$ (9.1, 10.7 and 10.2), Leaf area index (1.26 and 2.33) chlorophyll content (36.97 and 39.17) and dry matter production (13.16, 39.31 and 89.32 g pot^{-1}) at maximum tillering, panicle initiation and harvest were recorded with zinc lysinate which is on par with $ZnSO_4$, respectively. Plant height, no. of tillers plant^{-1}, chlorophyll content and dry matter production increased linearly with increased dose of zinc from 0 to 5 kg ha^{-1}, while increase in dose from 5 to 7.5 kg ha^{-1} showed a decrease which is significantly on par with 5 kg ha^{-1}. The maximum plant height (60.91, 87.91 and 101.73cm), no. of tillers plant^{-1} (10.9, 11.7 and 10.6), Leaf area index (1.30 and 2.48) chlorophyll content (41.19 and 43.39) and dry matter production (13.05, 44.85 and 103.76 g pot^{-1}) were noticed with soil application of Zn @ 5 kg ha^{-1} at maximum tillering, panicle initiation and harvest, respectively. In interaction effect, application of zinc lysinate @ 5 kg ha^{-1} recorded the highest plant height of 62.98, 88.82 and 102.87cm, no. of tillers plant^{-1} of 12.0, 13.4 and 12.4, leaf area index of 1.38 and 2.68, chlorophyll content of 42.12 and 44.53 and dry matter production of 13.58, 46.68 and 104.68 g pot^{-1} at maximum tillering, panicle initiation and harvest, respectively.

The application of zinc along with the recommended dose of fertilizers (RDF) likely enhanced nutrient use efficiency, providing a continuous supply of nutrients throughout the crop growth period and supporting essential physiological processes for optimal plant development. This is supported with findings of Goneium (2016) and Guo et al. (2016). Zinc also played a crucial role in the synthesis of growth hormones and auxin metabolism, which promoted cell division, differentiation, and the formation of lateral buds, ultimately increasing the number of tillers. This is evident with findings of Imran et al. (2015) and Reddy et al. (2023). Studies have shown that chelated forms of zinc, like zinc lysinate, offer superior bioavailability and mobility, resulting in improved nutrient uptake and growth during critical stages such as tillering and panicle initiation (Pathak et al., 2014, Yadav et al., 2015 and Saeed et al., 2018). Furthermore, zinc application contributed to increased chlorophyll content, which is essential for maintaining chloroplast structure and function, leading to more efficient photosynthesis. The improved photosynthetic rate enabled the plant to generate more energy, primarily in the form of carbohydrates, resulting in greater plant height, increased tiller numbers, and higher dry matter accumulation. This is linings with findings of Islam et al. (2016) and Liu et al. (2017).

Nitrogen, critical for plant growth due to its role in producing amino acids, proteins, and enzymes necessary for cell division and elongation, was more efficiently utilized with the aid of zinc. This allowed more nutrients to be available for vegetative growth. Additionally, the combined application of zinc and RDF facilitated zinc distribution within the rice plant through the xylem and phloem, enhancing vegetative tissue formation and improving photosynthetic activity, which in turn promoted overall plant growth and dry matter production. These findings align with the results reported by Kadam et al. (2018).

3.2 Yield Parameters

The application of different zinc formulation and varying levels, in conjunction with the recommended doses of NPK fertilizers, had a significant impact on yield parameters such as no. of panicles per plant, panicle length, no. of grain per panicle and 1000g seed weight as shown in Table 5.

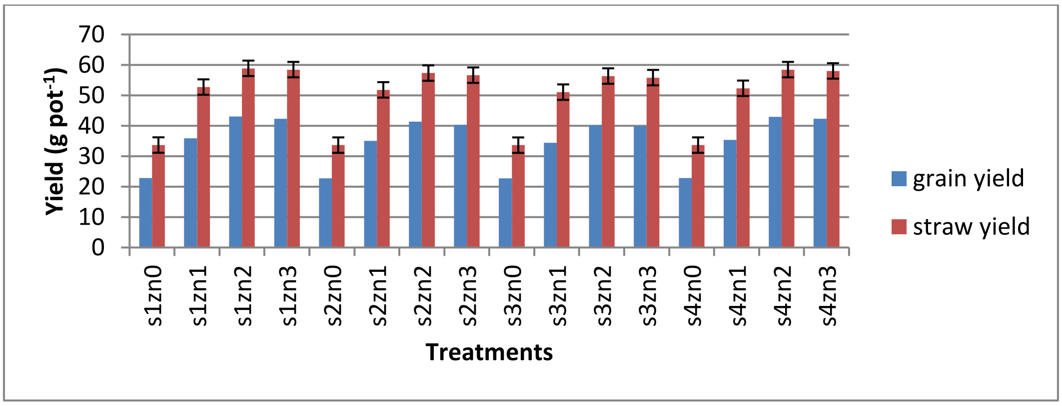

Fig. 1. Effect of zinc sources on yield (g pot^{-1}) of rice
(S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1})

Table 1. Effect of zinc sources on plant height (cm) at different stages of rice

	Maximum Tillering					Panicle initiation					Harvest				
	Zn_0	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**
S_1	48.71	56.73	62.98	61.34	57.44	73.71	80.83	88.82	87.68	82.76	88.65	95.12	102.87	101.72	97.09
S_2	47.05	55.78	60.12	57.74	55.17	72.92	79.68	87.62	86.14	81.59	88.68	93.78	101.15	100.01	95.91
S_3	47.67	54.02	57.76	56.23	53.92	72.23	77.71	86.86	85.23	80.51	88.39	92.06	100.75	99.25	95.11
S_4	46.69	56.23	62.78	61.17	56.72	72.94	80.14	88.32	87.38	82.20	88.27	94.18	102.14	101.21	96.45
Mean	47.53	55.69	60.91	59.12		72.95	79.59	87.91	86.61		88.5	93.79	101.73	100.55	
Factors	SE(d)		C.D.			SE(d)		C.D.			SE(d)		C.D.		
S	0.57		1.71			0.18		0.38			0.28		0.56		
Zn	0.57		1.71			0.18		0.38			0.28		0.56		
S X Zn	1.15		2.34			0.37		0.75			0.55		1.13		

(S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1})

Table 2. Effect of zinc sources on number of tillers $plant^{-1}$ at different stages of rice

	Maximum Tillering					Panicle initiation					Harvest				
	Zn_0	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**
S_1	5.2	8.1	12.0	11.2	9.1	7.1	10.1	13.4	12.1	10.7	7.0	9.4	12.4	12.0	10.2
S_2	4.9	7.1	10.0	9.2	7.8	6.5	9.1	11.0	10.3	9.2	6.0	8.3	10.0	9.2	8.4
S_3	4.1	7.0	9.6	8.5	7.3	5.6	8.3	9.6	8.8	8.1	5.0	7.2	8.1	7.7	7.0
S_4	5.0	7.9	11.8	10.7	8.9	6.8	9.9	12.8	11.7	10.3	6.5	9.9	12.0	11.7	10.0
Mean	4.8	7.5	10.9	9.9		6.5	9.4	11.7	10.7		6.125	8.7	10.6	10.2	
Factors	SE(d)		C.D.			SE(d)		C.D.			SE(d)		C.D.		
S	0.18		0.36			0.20		0.41			0.19		0.38		
Zn	0.18		0.36			0.20		0.41			0.19		0.38		
S X Zn	0.35		0.72			0.40		0.82			0.38		0.77		

(S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1})

Table 3. Effect of zinc sources on leaf area index and chlorophyll content at different stages of rice

	Leaf area index										Chlorophyll content									
	Maximum Tillering					Panicle initiation					Maximum Tillering					Panicle initiation				
	Zn_0	Zn_1	Zn_2	Zn_0	Zn_0	Zn_0	Zn_0	Zn_0	Zn_3	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Mean
S_1	1.11	1.19	1.38	1.35	1.26	1.72	2.24	2.68	2.66	2.33	28.52	35.24	42.12	41.98	36.97	30.12	38.04	44.53	43.97	39.17
S_2	1.10	1.14	1.26	1.21	1.18	1.67	1.95	2.48	2.46	2.14	27.62	33.96	40.53	40.18	35.57	29.02	37.26	42.82	41.78	37.72
S_3	1.00	1.14	1.24	1.13	1.13	1.63	1.91	2.23	2.22	2.00	28.43	32.15	40.00	39.18	34.94	29.23	34.15	42.04	41.68	36.78
S_4	1.12	1.17	1.32	1.21	1.21	1.75	2.21	2.54	2.51	2.25	27.86	35.12	42.09	41.45	36.63	29.26	37.83	44.15	43.08	38.58
Mean	1.08	1.16	1.30	1.23		1.69	2.08	2.48	2.46		28.11	34.12	41.19	40.70		29.41	36.82	43.39	42.63	
Factors	SE(d)		C.D.			SE(d)		C.D.				SE(d)		C.D.			SE(d)		C.D.	
S	0.01		0.03			0.03		0.07				0.30		0.61			0.31		0.64	
Zn	0.01		0.03			0.03		0.07				0.30		0.61			0.31		0.64	
S X Zn	0.02		0.06			0.07		0.15				0.60		1.22			0.63		1.29	

(S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1})

Table 4. Effect of zinc sources on dry matter production (g pot^{-1}) at different stages of rice

	Maximum Tillering					Panicle initiation					Harvest				
	Zn_0	Zn_1	Zn_2	Zn_3	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Mean	Zn_0	Zn_1	Zn_2	Zn_3	Mean
S_1	12.27	13.32	13.58	13.46	13.16	27.48	36.94	46.68	46.13	39.31	58.23	89.92	104.68	104.46	89.32
S_2	11.72	12.36	12.87	12.74	12.42	25.87	35.36	43.87	43.36	37.12	56.74	87.68	103.43	103.03	87.72
S_3	11.67	12.03	12.31	12.23	12.06	24.75	34.87	42.41	42.23	36.07	56.56	86.43	102.41	102.12	86.88
S_4	12.21	13.29	13.42	13.38	13.08	27.41	36.48	46.44	46.13	39.12	58.11	89.63	104.52	104.31	89.14
Mean	11.97	12.75	13.05	12.95		26.38	35.91	44.85	44.46		57.41	88.42	103.76	103.48	
Factors	SE(d)		C.D.			SE(d)		C.D.			SE(d)		C.D.		
S	0.08		0.16			0.25		0.52			0.17		0.34		
Zn	0.08		0.16			0.25		0.52			0.17		0.34		
S X Zn	0.16		0.31			0.51		1.03			0.33		0.68		

Table 5. Effect of zinc sources on yield characters of rice

	Number of panicles plant^{-1}					No. of grains panicle^{-1}					Panicle length (cm)					1000 seed weight (g)				
	Zn_0	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**	**Zn_0**	**Zn_1**	**Zn_2**	**Zn_3**	**Mean**
S_1	15.6	17.6	19.6	18.9	17.9	86.4	106.2	117.8	116.3	106.6	17.8	19.6	21.3	21.2	20.0	15.1	15.3	15.5	15.4	15.3
S_2	14.3	16.5	18.4	17.9	16.8	85.8	104.6	116.4	114.3	105.3	17.6	18.4	20.3	20.2	19.1	15.0	15.1	15.3	15.2	15.2
S_3	14.1	16.0	18.0	17.1	16.3	85.6	103.2	114.6	113.3	104.2	17.4	18.1	19.2	19.0	18.4	14.9	15.0	15.2	15.1	15.1
S_4	15.2	17.1	19.2	18.3	17.5	86.5	105.9	117.2	115.9	106.4	17.6	19.1	21.0	20.8	19.6	15.1	15.2	15.4	15.3	15.3
Mean	14.8	16.8	18.8	18.1		86.0	104.9	116.5	114.9		17.6	18.8	20.5	20.3		15.0	15.2	15.4	15.3	
Factors	SE(d)		C.D.			SE(d)		C.D.			SE(d)		C.D.			SE(d)		C.D.		
S	0.05		0.11			0.22		0.44			0.16		0.32			0.01		0.03		
Zn	0.05		0.11			0.22		0.44			0.16		0.32			0.01		0.03		
S X Zn	0.11		0.22			0.43		0.89			0.32		0.65			0.03		0.05		

(S_1- Zinc Lysinate, S_2- Zinc HEDP, S_3- Zinc oxide, S_4- Zinc sulphate) and four levels of zinc (Zn_0- 0kg Zn ha^{-1}, Zn_1- 2.5 kg Zn ha^{-1}, Zn_2- 5 kg Zn ha^{-1}, Zn_3- 7.5 kg Zn ha^{-1})

With respect different sources of zinc used the highest yield parameters *viz.,* no. of panicle plant^{-1} of 17.9, panicle length of 20.0 cm, no. of grains panicle^{-1} of 106.6 and 1000 seed weight of 15.3 g was recorded with zinc lysinate application. Regarding the levels of zinc, yield parameters showed a linear increase with increasing dose from 0 to 5 kg Zn ha^{-1} where further increase showed a decrease. The maximum yield parameters of no. of panicles per plant (18.8), panicle length (20.5 cm), no. of grains per panicle (116.5) and 1000 seed weight (15.4 g) were achieved with soil application of zinc @ 5 kg ha^{-1} which is on par with 7.5 kg Zn ha^{-1}. With considering the interaction effect between zinc sources and its levels, they showed a significant improvement in yield characters of rice. Specifically, the combination of applying zinc lysinate @ 5 kg ha^{-1} resulted in the highest no. of panicles per plant of 19.6, panicle length of 21.3 cm, no. of grain per panicle of 117.8 and 1000 seed weight of 15.5g.

The results indicated that soil application of zinc plays a crucial role in influencing various physiological and biochemical processes, directly affecting yield-related traits. The number of panicles per plant is closely linked to productive tillers, as each tiller develops into a panicle. Zinc application increases tiller production, which significantly boosts the number of panicles per plant. Panicle length is a key yield trait, as longer panicles generally contain more grains. This is corroborative with findings of Dore et al*.* (2018) and Islam et al. (2021). Zinc application promotes the synthesis of DNA, RNA, proteins, gibberellins, and other hormones necessary for cell division and elongation, leading to the elongation of the panicle axis and an increase in panicle length. Additionally, zinc enhances enzymatic activities that support proper flowering, pollination, and grain filling, resulting in a higher number of well-developed grains per panicle. Zinc also facilitates the efficient translocation of nutrients through the xylem and phloem, ensuring a consistent nutrient supply for grain filling, which leads to an increased number of grains and improved test weight in the rice crop. This is evident with fiindings of Muthukumararaja and Sriramachandrasekhran (2012) Saeed et al. (2018) and Patel et al. (2022).

3.3 Yield (g pot^{-1})

The individual and combined application different sources of zinc and levels exerted a significant influence on grain and straw yield of rice in zinc stressed soil (Fig. 1). Among Zn sources, application of zinc lysinate recorded significantly the highest grain yield (36.02 g pot^{-1}) and straw yield (50.93 g pot^{-1}), which is on par with zinc sulphate. Among the different levels of zinc applied, soil application of Zn @ 5 kg ha^{-1} recorded the highest grain yield of 41.86 g pot^{-1} and straw yield of 57.74 g pot^{-1} and it was at par with 7.5 kg ha^{-1} of zinc application. In combined effect, the maximum grain yield of 43.01 g pot^{-1} and straw yield of 58.87 g pot^{-1} in was recorded with application of zinc lysinate @ 5 kg ha^{-1}. Soil application of zinc improves the grain and straw yield of rice by enhancing root development, nutrient uptake, tillering, photosynthesis, nutrient translocation, grain filling, and nitrogen utilization. Zinc also increases stress tolerance, regulates hormonal balance, and promotes biomass accumulation, all of which contribute to higher yields in both grain and straw. Zinc lysinate, a chelated form of zinc, offers superior solubility and bioavailability, making it an efficient source of zinc for plants, particularly in soils with high pH or other limiting conditions. Its quick absorption helps plants maximize their potential, improving overall productivity in zinc-deficient soils (Saeed et al., 2018; Yadav et al., 2020). This is evident with findings of Muthukumararaja and Sriramachandrasekhran (2012), Imran et al. (2015), Sudha and stain (2015), Das et al. (2019) and Coffin and Slaton (2020),(Ghoneim, 2016).

4. CONCLUSION

The study underscores the crucial impact of zinc application on enhancing rice growth and yield. Zinc lysinate was identified as the most effective source, delivering grain and straw yields comparable to zinc sulfate. The optimal yield was achieved with soil application of zinc at 5 kg ha^{-1}, with combined treatments of zinc lysinate at this rate showing excellent results. These findings highlight the necessity of selecting the appropriate zinc source and application rate to ensure sustainable rice production in zinc-deficient regions. Future studies should explore the broader effectiveness of zinc lysinate across various soil types and climates, assess its long-term impact on soil health, and investigate the benefits of combining zinc with other micronutrients for better rice productivity and stress resilience.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Alloway, B. J. (2008). Zinc in soils and crop nutrition. *International Zinc Association*, 2nd Edition.

Arunachalam, P., Kannan, P., Prabukumar, G., & Mahalingam, G. (2013). Zinc deficiency in Indian soils with special focus to enrich zinc in peanut. *African Journal of Agricultural Research, 8*, 6681-6688.

Cakmak, I. (2008). Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant and Soil*, *302*(1-2), 1-17.

Coffin, M. D., & Slaton, N. A. (2020). Effect of low-use-rate zinc fertilization on rice growth and grain yield. *Agrosystems, Geosciences & Environment, 3*(1), e20016.

Das, A., Singh, S. K., Kumar, M., & Kumar, O. (2019). Evaluation of different methods of zinc application on growth, yield and biofortification of zinc in rice (*Oryza sativa L.*). *Journal of the Indian Society of Soil Science, 67*(1), 92-102.

Dasgupta, R., Bhargaw, A., Hadimani, A., Meghana, G. B., Shetty, M. G., & Ghosh, S. K. (2024). Zn Check: Revolutionizing plant nutrition with amino acid-based zinc chelation. *Asian Journal of Soil Science and Plant Nutrition, 10*(2), 301-310.

Directorate of Economics and Statistics (2021-22). Second Advance Estimates of Production of Food Grains. Dept Agric Farmers Welfare, Govt of India.

Dore, S., Kumar, R., Rana, V., Singh, J., & Tiwari, V. (2018). Effect of zinc fertilization on growth, yield, and quality of rice (*Oryza sativa L.*) under different methods of application. *International Journal of Current Microbiology and Applied Sciences, 7*(2), 2595-2603.

Ghoneim, A. M. (2016). Effect of different methods of Zn application on rice growth, yield and nutrients dynamics in plant and soil. *Journal of Agriculture and Ecology Research International, 6*(2), 1-9.

Guo, J. X., Feng, X. M., Hu, X. Y., Tian, G. L., Ling, N., Wang, J. H., Shen, Q. R., & Guo, S. W. (2016). Effects of soil zinc availability, nitrogen fertilizer rate and zinc fertilizer application method on zinc biofortification of rice. *Journal of Agricultural Science, 154*(4), 584-597.

Hafeez, B., Khanif, Y. M., & Saleem, M. (2013). Role of zinc in plant nutrition: A review. *American Journal of Experimental Agriculture, 3*(2), 374-391.

Hossain, M. M., Islam, M. S., & Ahmed, S. (2022). Zinc nutrition and its role in improving rice growth under abiotic stress conditions. *Journal of Plant Nutrition*, *45*(5), 707-719.

Imran, M., Kanwal, S., Hussain, S., Aziz, T., & Maqsood, M. A. (2015). Efficacy of zinc application methods for concentration and estimated bioavailability of zinc in grains of rice grown on a calcareous soil. *Pakistan Journal of Agricultural Sciences, 52*(1).

Islam, M. R., Sultana, A., Jahiruddin, M., & Islam, S. (2021). Effect of soil application of zinc on growth, yield and zinc concentration in rice varieties. *European Journal of Agriculture and Food Sciences, 3*(6), 117-122.

Islam, M. R., Yesmin, N., Malika, M., Huda, A., & Rahman, M. M. (2016). Effect of zinc supplied from two different sources on the growth, yield and zinc uptake of rice (*cv. BRRI dhan49*). *Asian-Australasian Journal of Bioscience and Biotechnology, 1*(2), 230-234.

Kadam, S. S., Kumar, A., & Arif, M. (2018). Zinc mediated agronomic bio-fortification of wheat and rice for sustaining food and health security: A review. *International Journal of Chemical Studies, 6*, 471-475.

Kumar, S., Singh, P., & Sharma, R. (2021). Impact of zinc fertilization on rice productivity and its nutritional quality in zinc-deficient soils. *Field Crops Research*, 264, 108053.

Liu, D. Y., Zhang, W., Yan, P., Chen, X. P., Zhang, F. S., & Zou, C. Q. (2017). Soil application of zinc fertilizer could achieve high yield and high grain zinc concentration in maize. *Plant and Soil, 411*, 47-55.

Muthukumararaja, T. M., & Sriramachandrasekharan, M. V. (2012). Effect of zinc on yield, zinc nutrition and zinc use efficiency of lowland rice. *Journal of Agricultural Technology, 8*(2), 551-561.

Patel, P. S., Singh, S. K., Patra, A., & Jatav, S. S. (2022). Root dipping, foliar and soil application of zinc increase growth, yields, and grain zinc in rice (*Oryza sativa L.*) grown in moderate zinc soil of inceptisol order. *Communications in Soil Science and Plant Analysis, 53*(15), 1917-1929.

Pathak, H., Raj, A. K., & Choudhary, B. (2014). Effect of zinc application on crop growth and yield in zinc-deficient soils. *Agricultural Science Research Journal*, *4*(12), 441-446.

Rahale, C. S. (2019). Evolving appropriate zinc fertilization strategy for rice-rice (*Oryza sativa*) cropping system in Cauvery Delta Zone. *Oryza, 56*(3), 294-304.

Reddy, B. N. K., Mehera, B., & Kumar, P. (2023). Effect of poultry manure, vermicompost and zinc on growth and yield of rice. *International Journal of Plant and Soil Science, 35*(12), 46-50.

Saeed, M., Ahmad, M., & Shah, A. H. (2018). Comparative efficiency of different zinc sources on wheat growth, yield, and zinc uptake. *Pakistan Journal of Agricultural Sciences*, *55*(2), 253-260.

Saeed, M., Ahmad, M., & Shah, A. H. (2023). Role of zinc supplementation in enhancing yield and quality of rice under waterlogging stress. *Agricultural Science and Technology Journal*, *14*(2), 220-229.

Sheoran, O. P., Tonk, D. S., Kaushik, L. S., Hasija, R. C., & Pannu, R. S. (1998). Statistical software package for agricultural research workers. In Hooda, D. S., & Hasija, R. C. (Eds.), *Recent Advances in Information Theory, Statistics & Computer Applications* (pp. 139-143). CCS HAU, Hisar.

Singh, B., Singh, P., & Suman, A. (2017). The role of zinc in enhancing crop productivity under nutrient-deficient soils. *Journal of Soil Science and Plant Nutrition*, *17*(2), 374-384.

Sudha, S., & Stalin, P. (2015). Effect of zinc on yield, quality and grain zinc content of rice genotypes. *International Journal of Farm Sciences, 5*(3), 17-27.

Tuyogon, D., Somayanda, I. M., Larazo, W., & Johnson-Beebout, S. E. (2016). Enriching rice grain zinc through zinc fertilization and water management. *Soil Science Society of America Journal, 80*, 121-134.

Yadav, B. K., Suman, A., & Yadav, S. (2015). Effect of different sources of zinc on growth, yield, and zinc uptake by rice. *Journal of Plant Nutrition and Soil Science*, *178*(3), 354-360.

Yadav, B. K., Suman, A., & Yadav, S. (2020). Impact of chelated zinc forms on rice yield and nutrient uptake in zinc-deficient soils. Journal of Plant Nutrition, *43*(4), 497-506.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/129361