

Original Research Article

Comparative Performance of Zinc Sources on Productivity of Rice in Zinc Stressed Soils of Cauvery

Delta Zone

Comment [MS1]: Add scientific name of rice too.

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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 precise and advanced mineral nutrition techniques offers a promising solution. 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.

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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. Forty-seven per cent of Indian soils and fifty percent of Tamil Nadu 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).

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). 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).

To address 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 commonly used, but newer zinc compounds such as Zinc HEDP (Hydroxyethylidene diphosphonic acid), Zinc oxide (ZnO), and Zinc glycinate 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). 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. 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.

Comment [MS4]: While the introduction discusses the knowledge gap regarding the physiological mechanisms of *Oryza sativa* responses to Zn, it lacks specific emphasis on the **practical applications** of these findings. Highlighting how the results could directly benefit farmers or improve agricultural practices in real-world settings would strengthen the manuscript. This would address how growers might optimize inputs to enhance soil health, crop resilience and yield. Write more about the Zinc stress in soils as well as plants. Cite more reference as you increase the matter.

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 Thiruvallaputhur 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 experiment includes four sources of zinc (S₁- Zinc Lysinate, S₂- Zinc HEDP, S₃- Zinc oxide, S₄- Zinc sulphate) and four levels of zinc (Zn₀- 0kg Zn ha⁻¹, Zn₁- 2 kg Zn ha⁻¹, Zn₂- 5 kg Zn ha⁻¹, Zn₃- 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, P₂O₅, and K₂O, 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% K₂O) 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% P₂O₅). 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. (Table 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 ZnSO₄, respectively. Plant

Comment [MS5]: Mention the dimensions of the pot and quantity of the soil used per pot. And number of pots used to conduct the experiment.

Comment [MS6]: Mention the source of procurement of the Zinc sources. Mention the method of applying treatments to the pots.

Comment [MS7]: Mention the source of procurement of the rice variety. The selection of seeds for sowing was based on strict quality criteria, ensuring that only seeds exhibiting strong health and free from damage were chosen' – how did you choose the seeds, elaborate. Write the characters of the variety.

Comment [MS8]: 1. Expand on the current field practices and problems associated/limited with using nitrogenous and phosphatic chemical fertilizers.

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). 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 in line 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.

Comment [MS9]: Discuss more about how the treatments influence growth parameters of this particular variety.

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		

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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		

Comment [MS11]: Write details and abbreviation in the under the table

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

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	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		

Comment [MS13]: Write details and abbreviation in the under the table

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		

Comment [MS14]: Write details and abbreviation in the under the table

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 findings of Muthukumararaja and Sriramachandrasekhran (2012) 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 (Figure 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. 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).

Comment [MS15]: Add more discussion about how this experiment influence yield attributing characters under stressed conditions.

Comment [MS16]: Correlate the yield with other studies of stressed Zinc conditions.

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		

Comment [MS17]: Write details and abbreviation in the under the table

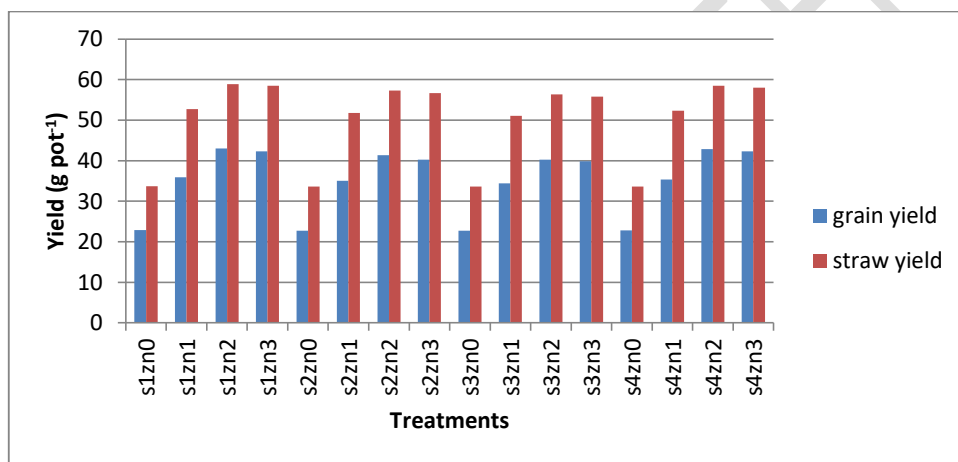


Figure 1: Effect of zinc sources on yield (g pot⁻¹) of rice

Comment [MS18]: Where figures for growth parameter footnote mentioning abbreviation the figures. For more clarity add duncan above bars in the figure.

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.

Comment [MS19]: Add more conclusion. Conclude briefly and Mention the scope for further studies as well. It would be beneficial to mention the need for further studies to explore the long-term effects of Zn individual and in combination on soil health and sustainability.

Comment [MS20]: Add the limitations of the current study
Add COMPETING INTERESTS, acknowledgement and conflicts.

UNDER PEER REVIEW

REFERENCES:

1. Directorate of Economics and Statistics (2021-22). Second Advance Estimates of Production of Food Grains. Dept Agric Farmers Welfare, Govt of India.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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.
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.
10. 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).
11. 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.
12. 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. *BRR1 dhan49*). *Asian-Australasian Journal of Bioscience and Biotechnology*, 1(2), 230-234.
13. 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.

14. 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.
15. 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.
16. 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.
17. 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.
18. 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.
19. 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.
20. 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.
21. 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.

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