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Impact of Biofortification with Application of $FeSO_4$ and $ZnSO_4$ on Growth, Yield, and Economics of Pearl Millet (*Pennisetum glaucum* L.)

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Abstract

A field experiment entitled "Role of Biofortification with Iron and Zinc in Yield and Quality of Pearl millet (*Pennisetum glaucum* L.)" was conducted during the Kharif season of 2024 at the Agricultural Research Farm, Vivekananda Global University, Jaipur. The study consisted of nine treatments, arranged in a Randomized Block Design (RBD) with three replications. In pearl millet, parameters such as plant height (cm), dry matter accumulation (g m−2), chlorophyll content (mg g^{-1}), and yield-attributing traits including the number of effective tillers per plant, ear head length (cm), ear head girth (mm), and grain weight per ear head (g) were significantly enhanced by the treatment involving soil application of ZnSO4 @ 25 kg/ha combined with a 0.5% FeSO4 foliar spray at the tillering stage (20–25 DAS), referred to as T7. The highest grain yield (2422.25 kg ha^{-1}), stover yield (6669.26 kg ha^{-1}) and biological yield (9091.51 kg ha^{-1}) were recorded under treatment T7. The highest, gross return (Rs. 87932.44), net returns (Rs. 54707.5 ha^{-1}) and benefit-cost (B:C) ratio (1.65) were observed in T7, demonstrating the economic viability of Iron and Zinc management practice in pearl millet cultivation.

Keywords: Biofortification, Economics, $FeSO_4$, Growth traits, Pearl millet, Yield attributes, $ZnSO_4$

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Introduction

Pearl millet (*Pennisetum glaucum* L.), one of the most resilient cereals cultivated in arid and semi-arid regions, plays a vital role in ensuring food and nutritional security of millions of smallholder farmers in Asia and Africa. It is widely grown under rainfed conditions owing to its tolerance to drought, heat, and poor soils [1]. In India, pearl millet is a staple cereal in Rajasthan, Gujarat, Maharashtra, and Haryana, where it constitutes a key component of food, fodder, and livestock feed systems. Despite its high adaptability, pearl millet yields remain relatively low compared to other cereals due to nutrient deficiencies, particularly micronutrients such as zinc (Zn) and iron (Fe), which limit growth, yield, and quality [2, 3]. Zinc deficiency is a major soil fertility problem in India, affecting about 45% of arable soils, particularly in calcareous and alkaline conditions. Similarly, iron deficiency is widespread in sandy and alkaline soils, limiting chlorophyll synthesis and photosynthetic efficiency [4]. Both Zn and Fe are not only essential for plant metabolic processes but also critical for human nutrition. Pearl millet is a promising crop for biofortification—the process of enriching staple crops with essential micronutrients to alleviate hidden hunger (micronutrient malnutrition), particularly among rural populations dependent on cereals for dietary energy [5, 6]. Previous studies have shown that application of $ZnSO_4$ and $FeSO_4$, either through soil or foliar spray, significantly enhances crop growth, yield attributes, and nutrient concentration in grains [7–9]. Soil application ensures long-term availability, while foliar application provides a rapid correction of deficiencies during critical growth stages [10]. Integrated approaches involving both soil and foliar application have been reported to be most effective in maximizing micronutrient uptake and utilization efficiency [11]. However, comprehensive research on their combined effect in pearl millet, particularly under Rajasthan conditions, is limited. This study was therefore conducted to evaluate the impact of biofortification through soil and foliar application of $ZnSO_4$ and $FeSO_4$ on growth traits, yield attributes, yield, and economics of pearl millet under field conditions.

Materials and Methods

The field experiment was conducted during the Kharif season of 2024 at the Agronomy Research Farm, Vivekananda Global University, Jaipur (Rajasthan, India). The site lies in the semi-arid region with sandy loam soils, low organic carbon (0.32%), available nitrogen (205 kg ha^{-1}), medium phosphorus (21 kg ha^{-1}), and low available zinc (0.51 ppm) and iron (2.34 ppm). The soil pH was slightly alkaline (pH 7.9) The experimental season received 485 mm rainfall, mostly concentrated between July and September. The average maximum and minimum temperatures during crop growth were 34.5°C and 24.1°C, respectively, suitable for pearl millet cultivation.

Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with nine treatments replicated thrice. The treatments were as follows: T1: Control (RDF only), T2: RDF + Soil application $ZnSO_4$ @ 25 kg ha^{-1}, T3: RDF + Soil application $FeSO_4$ @ 20 kg ha^{-1}, T4: RDF + 0.5% $ZnSO_4$ foliar spray at tillering (20–25 DAS), T5: RDF + 0.5% $FeSO_4$ foliar spray at tillering (20–25 DAS), T6: RDF + Soil application $ZnSO_4$ @ 25 kg ha^{-1} + 0.5% $ZnSO_4$ foliar spray, T7: RDF + Soil application $ZnSO_4$ @ 25 kg ha^{-1} + 0.5% $FeSO_4$ foliar spray, T8: RDF + Soil application $FeSO_4$ @ 20 kg ha^{-1} + 0.5% $ZnSO_4$ foliar spray, T9: RDF + Soil application $FeSO_4$ @ 20 kg ha^{-1} + 0.5% $FeSO_4$ foliar spray

RDF (Recommended Dose of Fertilizers): 60:30:30 N\:P_2O_5\:K_2O kg ha^{-1}

Observations Recorded- Growth traits: Plant height (cm), dry matter accumulation (g m^{-2}), and chlorophyll content (mg g^{-1} fresh weight). Yield attributes and yield traits: Effective tillers per plant, ear head length (cm), girth (mm), grain weight per ear head (g), test weight (g), grain yield (kg ha^{-1}), stover yield (kg ha^{-1}), biological yield (kg ha^{-1}), and harvest index (%). Economics: Cost of cultivation, gross returns, net returns, and B\:C ratio.

Statistical Analysis- The data were analyzed using ANOVA for RBD. Critical differences (CD) at 5% probability were calculated for comparing treatment means.

Table 1 Impact of biofortification with application of $FeSO_4$ and $ZnSO_4$ on growth traits of pearl millet

S.No	Treatment	plant height (cm)				Dry matter accumulation (gram per square meter)				Chlorophyll content (mg per g) at 65 DAS
		At 25 DAS	At 45 DAS	At 65 DAS	At harvest	At 25 DAS	At 45 DAS	At 65 DAS	At harvest	
T1	Control	20.94	52.95	161.26	172.74	22.44	166.84	610.16	715.67	2.56
T2	RDF + Soil application $ZnSO_4$ @25kg/ha	24.04	59.68	167.93	179.17	22.68	174.23	646.34	798.95	2.44
T3	RDF + Soil application $FeSO_4$@ 20kg/ha	24.93	56.02	164.9	174.22	23.13	168.94	634.57	804.42	2.54
T4	RDF + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	23.00	57.23	163.2	175.74	22.48	172.91	629.22	805.9	2.66
T5	RDF+ 0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	22.00	59.37	170.22	179.56	22.49	176.22	644.97	794.43	2.78
T6	RDF+ Soil application $ZnSO_4$ @25kg/ha +0.5% $ZnSO_4$ Foliar sprat at tillering stage (20- 25 DAS)	25.72	64.44	177.44	190.28	23.94	192.03	704.38	902.45	2.87
T7	RDF+Soil application $ZnSO_4$ @25kg/ha +0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	26.66	66.68	179.69	192.92	24.26	194.25	706	904.86	2.76
T8	RDF+ Soil application $FeSO_4$@ 20kg/ha + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20- 25 DAS)	24.95	62.76	173.13	184.42	23.94	185.24	676.12	896.24	2.68
T9	RDF+ Soil application $FeSO_4$ @ 20kg/ha + 0.5% $FeSO_4$ spray at tillering stage (20-25)	25.28	61.39	172.16	182.87	23.14	184.34	668.94	868.96	0.095
	C.D.	1.092	2.426	4.984	8.367	0.474	8.687	27.342	34.302	0.031
	SE(m)	0.361	0.802	1.648	2.767	0.157	2.873	9.042	11.344	2.56

Results and Discussion

Effect on Growth Traits

Plant height, dry matter accumulation, and chlorophyll content were significantly influenced by $ZnSO_4$ and $FeSO_4$ application. At harvest, the tallest plants (192.92 cm) were recorded with T7 (RDF + $ZnSO_4$ soil + $FeSO_4$ foliar), followed by T6 (190.28 cm). The control (172.74 cm) recorded the lowest height. Similar trends were observed for dry matter accumulation, with T7 (904.86 g m^{-2}) and T6 (902.45 g m^{-2}) being superior. Chlorophyll content, an indicator of photosynthetic efficiency, was highest (2.87 mg g^{-1}) in T6, followed by T7 (2.76 mg g^{-1}), while the control recorded the lowest (2.56 mg g^{-1}). Foliar supplementation during tillering might have improved chlorophyll synthesis by increasing Fe and Zn availability, as both are cofactors in chlorophyll biosynthesis and enzymatic functions [12]. These results confirm earlier findings of [13, 14], who reported significant improvement in growth traits of cereals with combined soil and foliar micronutrient application.

Table 2 Impact of biofortification with application of $FeSO_4$ and $ZnSO_4$ on Yield attributes and Yield traits of pearl millet

S.No.	Treatments	Yield attributes					Yield traits			
		Number of effective tillers per plant	Length of ear head (cm)	Girth of ear head (mm)	Grain weigh per ear head (g)	Test weight (g)	Grain yield	Stover yield	Biological yield	Harvest index
T1	Control	1.2	13.94	55.47	5.96	8.14	1910.22	5004.13	6914.35	27.62
T2	RDF + Soil application $ZnSO_4$ @25kg/ha	1.4	14.85	62.93	7.28	9.22	2095.22	5522.46	7617.68	27.5
T3	RDF + Soil application $FeSO_4$@ 20kg/ha	1.3	14.1	58.49	7.57	8.66	2116.29	5892.25	8008.54	26.42
T4	RDF + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	1.5	15.44	61.16	7.47	8.94	2115.46	5644.2	7759.66	27.26
T5	RDF+ 0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	1.75	16.16	66.47	7.63	9.87	2145.36	5745.03	7890.39	27.18
T6	RDF+ Soil application $ZnSO_4$ @25kg/ha +0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	2.04	18.34	73.94	8.48	10.76	2394.95	6494.17	8889.12	26.94
T7	RDF+Soil application $ZnSO_4$ @25kg/ha +0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	2.22	18.94	79.16	8.59	10.95	2422.25	6669.26	9091.51	26.64
T8	RDF+ Soil application $FeSO_4$@ 20kg/ha + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	1.94	18.22	71.17	8.38	10.25	2304.14	6656.23	8960.37	25.71
T9	RDF+ Soil application $FeSO_4$ @ 20kg/ha + 0.5% $FeSO_4$ spray at tillering stage (20-25)	2.1	16.96	69.48	8.16	10.1	2216.23	6466.43	8682.66	25.52
CD (P=0.05)		0.063	0.745	3.546	0.42	0.43	98.714	256.781	250.351	1.22
SEm ±		0.021	0.246	1.173	0.139	0.14	32.645	84.92	82.793	0.404

Effect on Yield Attributes and Yield Traits

Yield attributes such as effective tillers, ear head length, girth, grain weight per ear, and test weight improved with micronutrient biofortification. Maximum effective tillers (2.22 $plant^{-1}$), ear head length (18.94 cm), and ear girth (79.16 mm) were observed in T7, closely followed by T6. These improvements translated into higher grain weight per ear (8.59 g) and test weight (10.95 g). Grain yield was significantly higher in T7 (2422 kg ha^{-1}), followed by T6 (2395 kg ha^{-1}). This represented a yield increase of nearly 26.7% over control. Stover yield also improved under Zn and Fe treatments, contributing to higher biological yield. However, harvest index remained statistically non-significant, indicating that increased yield was primarily due to higher total biomass production. These findings align with those of [15, 16], who demonstrated the synergistic effect of Zn and Fe biofortification on yield traits of pearl millet and wheat

Effect on Economics

Economic analysis revealed that the highest gross returns (Rs. 87,932 ha^{-1}) and net returns (Rs. 54,707 ha^{-1}) were recorded under T7, with a benefit-cost ratio (1.65). T6 also recorded a high B:C ratio (1.57). Although treatments involving both soil and foliar applications increased cost of cultivation marginally, the higher yields more than compensated for the added input cost. This indicates that combined biofortification strategies are economically viable, which is consistent with findings of [17].

Table 3 Impact of biofortification with application of $FeSO_4$ and $ZnSO_4$ on economics of pearl millet.

S. No.	Treatments	Economics			
		Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	B: C
T1	Control	28395	66469.25	38074.25	1.34
T2	RDF + Soil application $ZnSO_4$ @25kg/ha	29275	70656.57	41381.57	1.41
T3	RDF + Soil application $FeSO_4$@ 20kg/ha	30375	74085.45	43710.45	1.44
T4	RDF + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	31000.45	75080	44079.55	1.42
T5	RDF+ 0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	32610.1	78820	46209.9	1.42
T6	RDF+ Soil application $ZnSO_4$ @25kg/ha +0.5% $ZnSO_4$ Foliar sprat at tillering stage (20-25 DAS)	32944.72	84825.22	51880.5	1.57
T7	RDF+Soil application $ZnSO_4$ @25kg/ha +0.5% $FeSO_4$ Foliar spray at tillering stage (20-25 DAS)	33224.94	87932.44	54707.5	1.65
T8	RDF+ Soil application $FeSO_4$@ 20kg/ha + 0.5% $ZnSO_4$ Foliar sprat at tillering stage (20 25 DAS)	33475.1	84928.85	51453.75	1.54
T9	RDF+ Soil application $FeSO_4$ @ 20kg/ha + 0.5% $FeSO_4$ spray at tillering stage (20-25)	32941.57	84448.43	51506.86	1.57
	C.D.	1,526.84	2,791.66	1,501.35	0.055
	SE(m)	504.938	923.224	496.509	0.018

Conclusion

The study demonstrated that biofortification of pearl millet through combined soil and foliar application of $ZnSO_4$ and $FeSO_4$ significantly improved growth traits, yield attributes, grain and stover yield, and economic returns. Among treatments, T7 (RDF + $ZnSO_4$ soil + $FeSO_4$ foliar) proved most effective, closely followed by T6 (RDF + $ZnSO_4$ soil + $ZnSO_4$ foliar). Thus, integrated application of Zn and Fe is recommended for pearl millet cultivation in micronutrient-deficient soils to enhance productivity, profitability, and nutritional quality, thereby contributing to food and nutritional security.

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